The Impact of Transformable Area Systems on Factory Planning Theory and Practice

A Study of Automobile Manufacturing Plants

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Abstract

Transformable areas are the missing link to the Fourth Industrial Revolution.

For more than 150 years, factories have been based on terrestrial areas. It has not been recognised that areas play a major role in the transformability of factories, and thus, the transformability of areas has not yet been increased. Factory lifecycles, factory structures and terrestrial areas are not sufficiently considered in current factory planning, which does not adequately reveal the limitations of today's factories or the potential impacts of new factory concepts that are based on systems that make areas transformable – 'transformable area systems'.

The purpose of this research is to demonstrate that the limited transformability of terrestrial areas leads to limitations and negative developments of today's factory characteristics and capabilities, and to the limited potential of 'Industry 4.0', to define the requirements of transformable area systems and to indicate their potential.

The research methodology is based on elements of grounded theory, on the research and analysis of literature and technologies, and on semi-structured expert interviews. Furthermore, a model for factory planning has been developed and applied in order to research and assess newly developed factory concepts.

Terrestrial areas make today's factories unsustainable, inefficient and difficult to transform. Furthermore, a genuine Fourth Industrial Revolution cannot be achieved as long as factories are constructed upon terrestrial areas that create numerous rigid factory objects and structures. This can be changed with transformable area systems which significantly and permanently increase the transformability of factories; this will have a considerable impact on factories throughout their lifecycles.

This research reveals gaps in factory planning theory and the limitations of today's factories and 'Industry 4.0', and demonstrates that restrictions relating to terrestrial areas can be overcome using transformable area systems in order to reach the Fourth Industrial Revolution.

Author's Declaration

I declare that the work in this thesis was carried out in accordance with the regulations of the University of Gloucestershire and is original except where indicated by specific reference in the text. No part of the thesis has been submitted as part of any other academic award. The thesis has not been presented to any other education institution in the United Kingdom or overseas.

Any views expressed in the thesis are those of the author and in no way represent those of the University.

Signed ___________________________________ Date 31 May 2018

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Sometimes one must break away from the system in order to improve it, but one person is never successful only because of herself/himself.

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This research was conducted simultaneously with my job as project leader in the factory planning and process optimisation consulting business, and is dedicated to Mario Vogel.

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Abbreviations

In this thesis, many specialist terms are used. Some of them are long. Several of them (and their abbreviations) have been specifically created for this thesis. Therefore, the author recommends printing the abbreviations and glossary so that they can be referred to when reading the thesis.

*Explanations of the designations with * can be found in the glossary.*

BFPC	basic factory planning case
BFPS	basic factory planning stage (new)*
BME	basic movement event (new)*
eBFPC	enhanced basic factory planning case (enhanced/developed further)*
etc.	et cetera
EPO	European Patent Office
FO	factory object*
FOs/FSs	factory objects and (factory) structures
	(also factory objects/factory structures)*
FPP	factory planning process*
FS	factory structure*
GPTO	German Patent and Trademark Office
IQ	interview question
MAS	movable area size (new)
OEM	Original Equipment Manufacturer
	(In this thesis an OEM is an automobile manufacturer, not a supplier.)*
RFO	rigid factory object*
RFS	rigid factory structure*
RO	research objective

s&d	supply and disposal*
SMEs	small and medium-sized enterprises
	(SME stands for small and/or medium-sized enterprise)
SOP	start of production
TAS	transformable area system (new)*
marTAS	maritime transformable area system (new)*
terTAS	terrestrial transformable area system (new)*
TBC	transformable building content
TBS	transformable building system*
TFC	TAS-based factory concept (new)*
marTFC	maritime TAS-based factory concept (new)*
terTFC	terrestrial TAS-based factory concept (new)*
terTFC_bw	terrestrial TAS-based factory concept beside waters (new)*
TFO	transformable factory object*
TFS	transformable factory structure*
UHP	united huts plant
USPTO	United States Patent and Trademark Office

Glossary

Single inverted commas are used to highlight important words, word combinations and translations.

Accelerators and acceleration units (new): Accelerators refer to characteristics of factory objects and structures (FOs/FSs) that accelerate the planning, implementation and/or transformation of factories. Pre-producibility, for instance, is an accelerator. If pre-producibility can be combined with an FO or FS, an acceleration unit is created. The development of acceleration units follows the same logic as the development of transformation units which are developed through the combination of a transformation enabler (see below) with an FO or FS. The development of transformation units is described in Hernández (2002).

Active transformability of areas (new): Terrestrial areas can only be transformed through area works (e.g. excavations). Area systems and transformable area systems (TASs) enable autonomous movements. Consequently, these technical systems can perform active transformations and enable the active transformability of areas.

Anticipations: estimations, forecasts and assumptions

Area: An area provides the basis for a factory. In this thesis a factory is either based on terrestrial areas or on transformable area system (TAS). The term 'terrestrial area' stands for land, land plot, land parcel, site, building land and areal. TASs are technical systems that substitute terrestrial areas. TASs can be based on terrestrial areas and/or on waters. The term 'terrestrial' is used to indicate terrestrial area-based TASs and TAS-based factory concepts (TFCs), and 'maritime' to indicate water-based TASs and TFCs (see below).

Area system (new): An area system refers to a technical system that substitutes terrestrial areas but does not meet diverse minimum requirements in terms of system characteristics and functions/capabilities that are required to be classified as a TAS. Both area system and TAS are new designations.

BFPSs – Basic factory planning stages (new) are real-world factory development stages that are passed through by today's (OEM) factories and are generally valid if no exceptional cases or special events such as economic crises, booms or other extreme market changes (e.g. extensive labour or product market shifts) occur.

BMEs – Basic movement events (new) are events by which factory project cases can be broken down and described in more detailed. Movements are always basic elements of implementations and transformations, while diverse works accompany BMEs, which means that further factory planning processes (FPPs) (see below) can be required. BMEs are specific FPPs.

The terms **company** and **enterprise** are used synonymously.

Difficulty factors (new) are required actions which make the planning and implementation or re-planning and transformation of factories difficult, laborious, time-consuming and expensive. Difficulty factors generally require several FPPs.

eBFPCs – enhanced basic factory planning cases are roughly defined types of factory projects that follow different patterns and can involve different BMEs and difficulty factors (BMEs and difficulty factors also enhance these cases). EBFPCs can help factory planners to orientate themselves and manage factory projects more effectively (particularly in combination with BFPSs).

Extension areas refer to (reserved or unreserved) on-site areas which can be used for building extensions. Reserved floor spaces within buildings are also designated as extension areas. Extension areas can be located off-site (e.g. adjacent/neighbouring land and/or not adjacent parcels) but must be acquired and can require approval processes before they can be used. **Exchange areas** are further types of extension areas which are explained throughout the thesis.

The terms **factory**, **plant** and **location** are used synonymously; the term 'factory' is primarily used. The term 'location' can also be used to indicate an area free of FOs/FSs. The designation 'plant' is mainly used to emphasise an automotive OEM plant, which is a huge (multi-)factory which involves several production sections at one location.

A **factory boundary** (or **plant boundary**) defines the physical border of a factory.

(Developed) Factory concepts (new): The traditional factory, the modern factory, the terrestrial TAS-based factory concept (terTFC), the terrestrial TAS-based factory concept beside waters (terTFC_bw) and the maritime TAS-based factory concept (marTFC) are newly developed factory concepts that are relevant to this research project.

FOs/FSs – Factory objects and structures: The term **factory object(s) (FO(s))** relates to systems, subsystems and elements that are or belong to building, production, logistics and s&d (supply and disposal) systems. FOs are s&d infrastructure elements (e.g. a section of a pipe), machines, conveyors, production plants, production lines, buildings and the like, while the term **factory structure(s) (FS(s))** relates more to building structures and to technical infrastructures/infrastructure networks. These terms are used either in combination or alone. A building, for instance, is an FO, but it is constructed out of diverse building structures. The term ‘facility’ refers likewise to FOs, but is not used synonymously for the term factory, plant or location (see subsection 2.1.1 for further information). The designation ‘factory structure(s)’ can be used to refer to a factory’s overall structure. The factory structure can also comprise areas and substructures (see below). **Rigid factory objects and structures (RFOs/RFSs)** are mainly understood as objects and structures that are area-related or, in other words, bound with the area/ground. The designation ‘rigid’ is also used to indicate that FOs/FSs are not transformable. ‘Inhibitor’ and ‘fixed point’ can be used synonymously with RFO/RFS while **transformable factory objects and structures (TFOs/TFSs)** can also become inhibitors, which is explained throughout the thesis (TFOs/TFSs are at least modular and mobile/movable). Descriptions about FOs/FSs refer often to FOs/FSs that are ground-based or, in other words, placed on the ground or on floors.

Factory planning is a field of study that involves theories that are related to the planning, implementation (re-planning) and transformation of factories.

Factory planning process models are phase models that involve different factory planning project phases and numerous factory planning processes (FPPs).

FPP – Factory planning processes are processes that require time, financial and further resources and are required for the planning and implementation and/or re-planning and transformation of factories.

Fundamental enablers (new) are overarching supra enablers, as they determine the transformability of areas, substructures and superstructures. Fundamental enablers impact on transformation enablers/units and accelerators/acceleration units (see below).

The **general structure** (general factory structure) involves the dimensions, shapes, positions and connections of the main FOs/FSs (e.g. buildings, s&d plants and technical infrastructures). Furthermore, the general structure involves the arrangement and linking principle of all FOs/FSs; this relates to the whole factory and its main flows. Possible area-related factory developments which involve effective transformation (e.g. extension) directions and dimensions are determined by the general structure, since it involves the area size and shape (besides other area-related characteristics). The general structure of a factory is visible in its factory layouts (Hernández, 2002).

A **Greenfield** project is a planning and implementation project for a new factory built upon a "green" field without any prior construction disturbances (Metzger, 1995, pp. 117–118) or restrictions that are "imposed by prior work ... [or] existing structures"; in contrast, a **Brownfield** project must operate within restrictions such as existing buildings, foundations and technical infrastructures (Gupta, 2014, p. 23). Within a Brownfield project, a factory is transformed in order to meet changing requirements (Grundig, 2015).

Human-globe system: The human-globe system is the entire system (of systems) that we live in. It involves all of the systems and system elements of our globe that people have an impact on, and vice versa: the environment, the current adjustment of our economic system, capitalism, profit-orientation, short-term thinking, different forms of egotism of individuals and groups, and further aspects that form our human-globe system. Groups are, for instance, divisions, factories, companies, mergers, regions, states, countries and world powers.

Ideal planning and implementation or re-planning and transformation: An ideal planning and implementation or re-planning and transformation happens in real-time and tends to reduce the duration of FPPs to virtually zero through the use of pre-producible, pre-testable and highly transformable objects and structures which enable fast and effortless implementations and transformations.

OEM – Original equipment manufacturer: In this thesis an OEM is an automobile manufacturer and not a supplier. The designation OEM is thus not used ambiguously. An OEM plant is a factory of an automobile manufacturer, not of a supplier.

Off-site (ex-plant or external)**:** outside the factory/plant boundary

On-site (in-plant or internal)**:** inside the factory/plant boundary

(Planning) **Premises** are presupposed factory-related conditions and factory characteristics (e.g. a factory's capacity and products) that are defined by strategy and/or factory planners at the beginning of a factory project (e.g. based on anticipations) and that are updated throughout this project. It is possible that some premises are not changed. The aim is to define premises that will be valid in the future (e.g. at the point in time when the operation of the implemented or transformed factory begins). Premises are, in simple terms, (initial and continuously updated) planning assumptions.

The term **production** can involve manufacturing, assembly, logistics and further areas and processes.

The use of the designation **production depth** implies shifts of vertical production scopes between OEM plants and supplier factories (vertical integration), even though other OEM plants can impact not only the horizontal production scope (horizontal integration) but also the production depth, while it is also conceivable that suppliers produce product models, types and/or variants and thus have an impact on the horizontal integration.

A **production network** consists of two or more factories. Production networks (and supply chains) can exist at only one location, not necessarily over several locations (e.g. over one or several countries). A production network can comprise factories of the same hierarchical level (e.g. two OEM plants) at several locations or different hierarchical levels (e.g. an OEM plant and several supplier factories) at one or several locations. The designation **supply chain** refers also to a production network, while in this thesis a supply chain consists of one or more OEMs and one or more suppliers. However, the designation 'production network' is mainly used, which usually includes supply chains.

A **production plant** refers to a linked system that consists mainly of machines and can comprise different apparatus, tools, instruments, jigs and fixtures and other objects and structures. The designation production plant is not used synonymously with the terms factory, plant or location.

Short-term: one year or less; **medium-term:** one to five years; **long-term:** more than five years (please consider the information in brackets)

The term **substructure(s)** refers to all FOs/FSs up to the zero or ground level of a factory. Any FO/FS that is surrounded by and/or based on soil or located below ground level is a substructure (e.g. foundations, pits and technical infrastructures*). As a rule, the area(s) is therefore in some way involved when the term substructure(s) is used (at least as a basis for a substructure(s)). It is not necessary for the term area(s) to be explicitly mentioned when the term substructure(s) is used and vice versa. *If such an FO/FS emerges above ground level, it is mainly still a substructure (see below).

Superstructure(s): The zero or ground level is the border and interface between sub- and superstructures. Technical infrastructures, for instance, can be sub- or/and superstructures, depending on their position(s) and sphere of influence. If a machine, for instance, is connected to a pipe at ground level and this pipe is not positioned anywhere above this level, it (the pipe) is a substructure. The machine belongs generally to superstructures while its foundation belongs to substructures. Generally and more roughly: All FOs/FSs above ground level are superstructures while all FOs/FSs below ground level are substructures.

TAS – Transformable area system (new): A TAS refers to a technical system that substitutes terrestrial areas and involves diverse minimum requirements in terms of system characteristics and functions which improve the transformability of areas in comparison to the transformability of terrestrial areas and (basic) area systems that do not comprise these requirements. Maritime transformable area systems (marTASs) and terrestrial transformable area systems (terTASs) are differentiated.

TBS – Transformable building system: A TBS is a building system which is based on modular building structures. TBSs are modular, mobile (or movable/transportable), scalable and pluggable. TBSs are different than traditional buildings (e.g. early factory buildings built out of bricks), which are buildings that are not non-destructively transformable after their construction.

Technical infrastructure: any transportation and supply and disposal (s&d) infrastructure

Transformability (transformation ability) is both a characteristic and a capability of factories. It can enable factory transformations such as building extensions and moves/relocations of FOs/FSs. The transformability of factories can be assessed with transformation enablers (e.g. modularity and mobility) (Hernández, 2002; Wiendahl, Reichardt and Nyhuis, 2015) and fundamental enablers.

One difference between transformability and **flexibility** is the time required to perform a change. Transformability involves factory structures while flexibility refers to a complementary characteristic to the transformability by which FOs/FSs can be adapted without a structural transformation (VDI 5201, 2017).

The higher the **transformation velocity** of a factory, the shorter the duration of transformation. Transformation velocity can be used synonymously for implementation velocity; implementation velocity is not always mentioned, because it can be covered through the designation transformation velocity.

1 Introduction

This chapter provides an introduction to the research.

Section 1.1 discusses why this research is relevant, briefly explains the research methodology and summarises the contribution of the research. Section 1.2 encompasses the research aim(s) and research objectives (ROs). Section 1.3 covers the scope and assumptions of this research, and section 1.4 describes the research contribution. Section 1.5 explains the thesis structure.

1.1 General Background

Factories are required for the production of goods while factory planning is the field of study that is required for the planning, implementation and transformation of factories (Grundig, 2015).

Product markets in the world were mainly separated and relatively simple in the 1970s. The same applied to factories, but this situation has changed. The number of competitors in the automotive industry has increased since the 1980s, and the working environment inside and outside factories has become tougher. Technical, economic and further developments or changes of the factory environment lead to enormous complexity and difficulties in factory planning (Hernández, 2002; Burggräf, 2012). These changes lead to an increased number of factory transformations. Increasing product complexities (Graf, 2006) and continuous shortening of product lifecycles (Schenk, Wirth and Müller, 2014) are influencing production systems (Wagner *et al.*, 2012), while the latter influence factory objects and structures (FOs/FSs) (Schenk, Wirth and Müller, 2010) and finally whole factories and (factory) areas (Grundig, 2015). Today, innovations in drive technologies play an important role (Bernhart and Zollenkop, 2011; Wallentowitz and Freialdenhoven, 2011; Karle, 2017).

Volatile markets with short-term changes in consumer desires with respect to product models, types, variants and quantities impact on factory operation periods, which were once stable and largely fixed with regard to their requirements and durations (Westkämper, Balve and Wiendahl, 1998). Therefore, a large number of different solutions have been established over recent decades to increase the transformability of factories and to speed up factory planning, implementation and transformation processes in order to meet changing market requirements (Hernández, 2002; Heinecker, 2006). Westkämper *et al.* (2000) recognise the importance of the transformability of factories. FOs/FSs must be constructed in a manner that enables rapid transformations at different points in time to meet the ever-changing market and further requirements of the factory environment in these times of unprecedented globalisation. Unfortunately, terrestrial areas and substructures remain untransformable, despite diverse 'Industry 4.0'-developments.

'Industry 4.0' does not seriously consider dynamics in factory planning that impact on FOs/FSs (particularly on areas and substructures), despite the recognition that factory configurations impact upon possible future transformations with regard to production volumes and flexibilities (Friese, 2008). The factory planning literature generally considers factories statically, and therefore conveys the impression that requirements for factories can be handled adequately. Theories are developed without adequate considerations of the limitations of today's factories while the most relevant problems in factory planning are not identified.

Westkämper and Zahn (2009) discuss the limitations of the transformability of factories but have not recognised the overarching problems in factory planning in sum. Today's problems in factory planning are the complexity of the factory environment, changes of this complexity, and the inability of current factories to implement these changes, as their transformability is limited and decreases further during the planning, implementation and numerous transformations which occur during a factory's lifecycle.

Wiendahl, Reichardt and Nyhuis (2009) recognise that the transformability of the factory layout/general structure is important but insufficient. Despite this, the development of (practical) solutions that are capable of increasing the transformability of the general structure has not been recognised in factory planning. Instead, theoretical solutions are developed and partly reinvented time and again. Despite the development of these factory planning theories, ‘united huts plants’ (UHPs) still exist; even new factories turn into this status, which means that there is a considerable gap between theory and practice. Numerous authors attempt to handle the problems in factory planning with the development of new theories (e.g. Heger, 2006; Velkova, 2013), without questioning whether this is possible at all. The transformability of today’s factories is insufficient and the development of theories cannot change this fact. Thus, it is not factory planning theories that need to be primarily developed, but the transformability of factories must be significantly increased in order to meet today’s factory requirements.

Factory planning authors and practitioners have been able to develop transformable solutions such as transformable buildings and movable production cells, but they have failed to improve the transformability of areas. Consequently, the transformability of today’s factories is barely capable of meeting current factory requirements (especially over time).

The transformability of areas and substructures in factory planning is highly beneficial but currently limited. The negative characteristics of today’s factories increase over time, while the required capabilities (e.g. transformability) decrease. Thus, factory requirements can hardly or not at all be met. This leads to inability to transform. This evokes the need to significantly and permanently increase the transformability of factories, which can be achieved if areas are made transformable. This is possible with transformable area systems (TASs), while it is necessary to develop a TAS-requirement profile. TASs form the basis for the conceptual development of ‘TAS-based Factory Concepts’ (TFCs).

A reliable theoretical building which describes the limitations of today’s factories and factory planning theories, a requirement profile for TASs, and the impacts of TASs(/TFCs) on factory planning theory and practice is not currently available. Factory planning lacks a model (and associated concepts); this is developed and applied in this research (RO1), and is required to reach the other ROs. Therefore, the model is both a research result and a part of the methodology.

Semi-structured expert interviews have provided the majority of the data and evidence for this research, and elements of grounded theory have helped to shape and combine the gathered data. A new model and associated concepts were developed and applied (RO1) in order to research and assess the capabilities and limitations of today's factories (RO2) and TFCs (RO4), which are both developed factory concepts. Furthermore, this model and associated concepts were required for the definition of the TAS-requirement profile (RO3) which was developed based on the limitations of today's factories (RO2). These limitations emerged from the interviews and provided the data required to develop this profile.

In brief, the limitations of today's factories (RO2) were researched and assessed in order to develop the TAS-requirement profile (RO3). TFCs were researched and assessed to define their capabilities and limitations or, in other words, impacts (RO4). The model and associated concepts (RO1) were required to achieve RO2, RO3 and RO4.

Basic factory planning stages (BFPSs) are factory development stages which reflect a factory's lifecycle and have an impact on the complexity (and other characteristics) of factories and factory projects, and on the transformability (and other capabilities) of factories – and thus on factory planning processes (FPPs). The concept of BFPS(s) is a key component of the new model and theory development in this research. The model and associated concepts are capable of indicating the impacts of recurring real-world factory project cases within the BFPSs of all developed factory concepts.

The new model has been developed and applied (RO1), the capabilities and limitations of today's factories researched and assessed (RO2), the first requirement profile for TASs developed (RO3) and the impacts of TFCs researched and assessed (RO4).

Impacts/effects of factory projects were explicitly and implicitly known by the interviewees. Nevertheless, all impacts/effects – particularly in combination – cannot be known (e.g. due to diverse chain reactions). Factory planners know that cases/situations exist in which it is either hardly possible to plan a project or in which they are incapable of planning a project, but they do not entirely know the reasons for this. Furthermore, factory planners do not know that cases/situations exist in which it cannot be known at all what needs to be done and why. Thus, only a stepwise planning is possible (which has less to do with planning). Factory planning theory lacks explanations for these occurrences; these will be explained in this thesis.

In factory planning theory, the impacts/effects that accompany progressed BFPSs are unknown. Someone who does not know the impacts/effects cannot detect the causes. The interviewees provided impacts/effects of real-world factory project cases in factories, and made it clear that terrestrial areas are the reason why today's factories become unstructured, increase in complexity and lose their transformability throughout the BFPSs (while further negative consequences occur).

In this thesis, problems with regard to today's factory solutions (also Industry 4.0) and factory planning theories are analysed and discussed, and conclusions drawn. Basic problems in factory planning with regard to today's factory and factory planning solutions could be identified. The capabilities and limitations of the traditional and the modern factory, which both represent today's factories, are in principle comparable, while tremendous benefits of TFCs were identified. Today's factories (and FOs/FSs) are largely static. Dynamics lead to challenges for both factory planning and factories. Dynamics and dynamic factory developments have, before this research, not been sufficiently considered against the backdrop of static factories, even though it is logical that statics and dynamics are challengers. Terrestrial areas are behind the limitations of both today's factories and Industry 4.0-developments.

This research casts a new light on how industrial structures can be planned, implemented and transformed. Specific advantages and new degrees of freedom that are provided by TASs/TFCs are identified, described and validated. TASs significantly and permanently increase the transformability of factories which increases FPP-capabilities.

Transformability is the most important capability of factories. The problem is that the importance of the transformability of areas is underrated in factory planning, as numerous essential aspects such as factory developments and their consequences are underestimated or not considered, which leads to a considerable gap in theory. This gap is closed by this research, as the dynamics of factory planning and of factories, factory developments and their consequences are now considered.

1.2 Purpose of the Research

1.2.1 Research Aim

The aim of this research is to demonstrate the relevance and significance of the active transformability of areas for factory planning, and to demonstrate that the limited transformability of terrestrial areas is the root cause that leads finally to UHPs and evokes the need for TASs.

1.2.2 Research Objectives

The ROs are:

(1) To develop and apply a new model (and associated concepts) to enable the assessment of today's real-world automobile factory requirements and of the capabilities and limitations of newly developed factory concepts.

(2) To research and assess the capabilities and limitations of today's factories with regard to the technical and spatial transformability, transformation velocity, and factory planning processes (FPPs).

(3) To develop the first requirement profile for transformable area systems (TASs), develop TAS-based factory concepts (TFCs) and identify how they differ in comparison to one another, and to today's factories.

(4) To research and assess the impacts of TFCs on the technical and spatial transformability, transformation velocity, and on FPPs.

The transformability and FPP-capabilities of the developed factory concepts determine their implementation and transformation velocity, and how the planning, implementation and transformation of factories can be performed. Although transformability, FPPs and other concepts are not always able to be completely differentiated, they must be separated in order to show their impacts.

The ROs have been translated into the following research questions:

(1) What concepts are required to assess today's real-world automobile factory requirements and the capabilities and limitations of newly developed factory concepts?

(2) What are the limitations of today's factories with regard to the technical and spatial transformability, transformation velocity, and FPPs?

(3) How can the transformability of areas be increased?

(4) What would be the impacts on the technical and spatial transformability, transformation velocity, and on FPPs if areas were transformable?

Existing works

(a) are concerned with factory planning theory, e.g. with the description, assessment and planning of the transformability and of transformations of factories (e.g. Hernández, 2002)

(b) provide (technical) solutions for factory planning practice, e.g. transformable FOs/FSs (e.g. Heinecker, 2006)

(c) deal with production networks and/or corporate strategies that enable high-level transformability by means of strategic measures, e.g. adaptations of horizontal and vertical integration through flexibility and capacity strategies for production networks (e.g. Friese, 2008)

This thesis is primarily concerned with factory planning theory and practice; relevant issues of (c) are considered where required.

This thesis provides original knowledge about TASs and TFCs, and about current factories and factory planning theories.

1.3 Scope and Assumptions

Factories and factory planning theories in the automotive sector are the main foci of this research project. This research emphasises terrestrial areas, construction sites and related processes, as well as area systems, their sites, and related processes to identify and define the importance of areas and substructures for factories and factory planning. The planning, implementation and transformation of factories are in the foreground, where the transformability and FPP-capabilities of the developed factory concepts are decisive.

The research is based on a simplified model of one factory at one location with a continuous lifecycle, as well as its environment. Possibilities with regard to horizontal integration are excluded. Digital factory is not analysed. (Advantages provided by a digital factory-based planning are not questioned in this thesis.) Nevertheless, required input data and possibilities to obtain these data with different factory concepts are considered.

Case analyses from the automotive sector, particularly automobile manufacturers (which are designated as OEMs) and supplier factories (which are designated as SMEs) as well as other sectors (e.g. diverse SME factories) were used as a basis for wider generalisations. The developed model can be applied to OEM and SME factories, as the general patterns with regard to factory developments and capabilities are identical. Nevertheless, the impacts of the enhanced basic factory planning cases (eBFPCs) are specific to automotive OEM factories, which means that impacts of these cases in SME factories can differ (eBFPCs are cases which come closer to real-world factory project cases than the BFPCs that are described in the literature). Except for the eBFPCs, the complexity of their impacts, and the possibilities to handle them, this does not change the general validity, reliability, meaning and importance of the research results for SMEs. Thus, the model (RO1) and research results which refer to today's factories (RO2) are generally valid for both OEM and SME factories, while the SME-related exceptions and factory developments are mainly a subject for future research.

Further points:

- 'Re-planning/re-plan' is used as an umbrella term for the planning of all Brownfield projects (e.g. extension planning and reduction planning).
- Numerous scenario techniques are available and can be differentiated, which is not done in this research as they are all based on anticipations.
- Spatial and technical transformability (not physical transformations) are independent of a human resistance to change. Thus, organisational transformability as a purely human-related part of transformability

(Hernández, 2002; Spath *et al.,* 2008) can be viewed separately and is not considered.

- The physical degradation over time of FOs/FSs is largely overlooked.
- When the designation OEM plant/factory is used, an OEM factory of the automotive industry is meant. These factories involve s&d plants, indirect/service buildings (e.g. canteens) and areas, office buildings (i.e. departments) and factory sections, which are common for automotive OEM factories. The sections '(stamping/)press shop', 'body shop', 'paint shop' and 'assembly shop' (including 'end-of-line') in particular are considered, but not in all examples. Other sections (e.g. for parts and tool manufacturing or for the production of gearboxes and engines) are not considered, as objects which require specific substructures are involved within other sections too.
- There is no differentiation between car and truck (or other commercial vehicle) factories, as their basic characteristics are basically comparable. When the term 'automotive' or 'automobile' is used, car and truck factories can be meant.
- Economic viability and profitability are reflected, but not analysed. What is meant are initial investments and the respective return on investment (e.g. the reimbursement of implementation/transformation activities).
- The research is occurring against the backdrop of fully developed factory concepts. TFCs have no pilot status, are fully operational and are environmentally safe. TASs are assumed as serial/series products which are, for instance, produced in shipyards or comparable industrial structures.
- The factory concept comparison is mainly based on the physical capabilities and limitations of the developed factory concepts (under consideration of spatial, technical, nature-related, physical/chemical and human-related possibilities), while non-material FPPs are also considered (e.g. approval processes). Rating criteria are factory implementation and transformation

durations, which should be brief, while required factory configurations, which should involve optimal flows, should always be achievable.

- Maritime law and related legal framework conditions cannot be deeply considered within the scope of this thesis (particularly as diverse laws and regulations for TASs and TFCs do not exist). Therefore, maritime approval processes and permits are mainly based on assumptions. Terrestrial law and related legal framework conditions are considered to the required extent. Approval processes and permits are considered on a high level with an attempt to generate generally valid statements (which, of course, cannot cover all variations). Moreover, different countries and states are assumed to have the same standards, norms and approval requirements.

The author strives to uncover possibilities for improvement. The focus lies on the development of sustainable and transformable factory solutions that enable permanently efficient and green factories. The transformability of areas plays an important role in this regard.

1.4 Research Contribution

This thesis contributes decisively to the developing knowledge of factory planning theory and practice. The following points highlight the research novelty:

- In this research, (elementary) limitations of factory planning theories are revealed, and
- a new model and associated concepts are developed and applied.
- Complexity, dynamics (e.g. the development of a factory environment) and real transformation requirements which occur over time are now seriously considered, and today’s real-world automobile factory requirements are recognised.
- Limitations of today’s factories and of ‘Industry 4.0’ are now known.

- The developments of real-world factory characteristics and capabilities are reflected on in the light of the dynamics which occur throughout a factory's lifecycle. It is demonstrated that the limited transformability of terrestrial areas leads to limitations and negative developments of today's factory characteristics and capabilities, and to the limited potential of 'Industry 4.0'.

  The development of today's factories is now considered; for instance it has been described how today's factories develop structurally, and why.

- Area systems are given names. These systems are typified and classified, and a first theory of these systems developed. The minimum requirements that form TASs are defined and their potential is indicated, the same as the potential of TFCs.

- Impacts of TASs and TFCs are identified and described (this is also relevant for other industrial and non-industrial structures). The way in which the characteristics and capabilities of TFCs develop is explained.

  TASs significantly and permanently increase the transformability of factories; this has a considerable impact on FPPs, and on factory characteristics and capabilities.

- The differences of the developed factory concepts are revealed.

- The importance of the transformability of areas is now known in factory planning: Areas play a major role in the transformability of factories, and for factory development, i.e. the development of factory characteristics and capabilities.

This thesis demonstrates that terrestrial areas are behind the limitations of both today's factories and Industry 4.0-developments, and that this can be changed through TASs.

This research reveals gaps in factory planning theory and the limitations of today's factories and 'Industry 4.0', and demonstrates that restrictions relating to terrestrial areas can be bypassed using TASs in order to reach the Fourth Industrial Revolution.

TASs are the missing key component of the Fourth Industrial Revolution.

1.5 Thesis Structure

In chapter 2 (literature and technology review), the current status of factory planning literature, factory- and area system-related technologies is provided. The main differences between terrestrial areas and area systems can be understood after reading this chapter. Chapter 2 concludes with a summary of existing gaps in knowledge relevant to this thesis, and required actions.

The 'conceptual framework' (chapter 3) describes the surroundings and elements of a factory that are required to reflect and analyse the activities that take place in real-world factories (e.g. the relocation of FOs). Chapter 3 provides the environment in which the new model for factory planning plays its part. The conceptual framework and the model enable the analyses of the developed factory concepts, as they form the theoretical world in which this research takes place (i.e. a system model). This system-related view of a factory enables its analysis, as the relevant elements and the relations and interactions between these elements can be analysed against the backdrop of the system model.

In chapter 4, the 'research methodology' (including the foundations of the research), design, process and methods are explained and justified. In addition, research ethics are explained, and the new model along with associated concepts and their development are briefly described.

Chapter 5 describes the 'new model for factory planning', its functionality, all concepts, and how they interact. Furthermore, details of the model and concept development are described.

Chapter 6 provides the majority of 'research results'. An improvement of factory planning requires a holistic view. This view is provided throughout section 6.1, is relevant for all developed factory concepts, and contains background and data which are required for their analysis. High-level problems in factory planning are recognised and combined. Real-world factory dynamics under consideration of

FOs/FSs (particularly areas and substructures) show what makes factory planning and the use of factories problematic when areas and substructures are static. The model and associated concepts (primarily the eBFPCs, difficulty factors and BFPSs) explain in which cases which transformation requirements occur and how these requirements change when area conditions of a factory change throughout the BFPSs because areas become increasingly overbuilt. BFPSs are passed through by each factory (if its lifecycle is long enough) and impact negatively on their transformability (as well as other capabilities), efficiency and sustainability. This section provides data to understand relevant aspects of factory planning and why there are a large number of transformations, especially why areas and substructures are often impacted. The impacts of dynamic requirements throughout the lifecycles of today's factories are recognisable because real-world factory project cases and real-world factory developments are considered. Section 6.1 validates the functionality of the new model and associated concepts, and provides an outlook on what is to come in section 6.2.

Section 6.2 is concerned with the capabilities and limitations of today's factories (RO2) and section 6.3 with those of TFCs (or, in other words, their impacts) (RO4). Firstly, both sections provide basics of transformability- and FPP-related capabilities and limitations of these factory concepts, based on the application and validation of the newly developed concepts. The developed model is then applied and validated (RO1). Thus, the previously mentioned basics are considered against the backdrop of the BFPSs. Finally, both sections end with a description of consequences. Why the transformability of terrestrial areas is a problem becomes evident throughout sections 6.1 and 6.2. Here, it becomes furthermore evident that today's factories pass through the BFPSs. Limitations of today's factories lead to the TAS-requirement profile (subsection 6.3.1) (RO3).

A final comparison and rating of the developed factory concepts is conducted in sections 6.4, 6.5 and 6.6. Durations of different factory project cases for each factory concept are qualitatively compared. Furthermore, a factory lifecycle is considered in which it is shown how the factory concepts can handle different factory configurations over time. These sections are based on the previous sections and verify the RO2- and RO4-results and the functionality of the model (RO1), and provide further results for RO3 (differences between factory concepts) which also verify the thesis results.

Chapter 7 discusses the research methodology and the findings regarding the ROs, identifies the contribution of this study to current research, and answers the research questions.

2 Literature and Technology Review

This chapter reviews existing literature and technologies. Essential terms are explained and differentiated where required. Furthermore, new designations are defined.

Section 2.1 is concerned with the definition of terms, and with the evolution and requirements of factories. Furthermore, modern factory and production concepts are presented. Factory planning theories are described in section 2.2. An overview of the technical status quo of factories, areas and area systems is presented in section 2.3. The chapter is summarised and concluded in section 2.4.

The main theories used in this research project are related to factory planning. The purpose of factory planning is to plan and implement a factory against the backdrop of numerous framework conditions that satisfy corporate, social and 'national economic'-related targets (Kettner, Schmidt and Greim, 1984, p. 3). Furthermore, factory planning theories are used to re-plan and transform factories (Hernández, 2002).

Factory planning is a field of study combining different elements of economic and engineering sciences (Zürn, 2010, p. 30). Spur and Stöferle (1994, p. 14) describe the multidisciplinary nature of factory planning and introduce the term 'factory sciences'. Economic, technical, natural and social sciences, labour studies and humanities have points of contact with factories. Further views on factory planning show that sciences of industrial economics, business sciences and engineering sciences (including industrial engineering and management) are considered. Factory planning considers processes relevant for construction and production purposes that are included in FPP models. Peripheral aspects in the legal field are also relevant, and can interfere with and even prohibit required activities. Human factors also play an important role, along with the related working environment and social aspects. Factory planning consequently provides a basis for process improvements where the transformability of factories plays a key role as it can enable a factory's future functionality (Westkämper, Balve and Wiendahl, 1998; Helbing, 2010; Grundig, 2015).

Transformability determines the degree to which factory structures can be transformed (Hernández, 2002). Project management also plays a significant role in factory planning (Claussen, 2012). FPP models are based on application-specific phase models. In addition to FPP models, BFPCs, factory planning approaches, factory planning with scenarios, methods for the assessment and planning of transformability and of transformations, and further factory planning theories are discussed.

Besides the current status of factory planning theories, the technical status quo of factories (including areas) is considered. The same applies to utility models, patent applications, approved patents and implemented inventions/technical products/ solutions with regard to FOs/FSs, terrestrial and maritime area systems, and to further floating structures, maritime solutions, their technical backgrounds, possible combinations of these backgrounds and solutions, and to maritime developments (e.g. market developments).

2.1 Factory Definition, Evolution and Requirements

2.1.1 Definition of Terms

A factory is a place where tasks are accomplished that lead to products through the conversion of production factors (Felix, 1998, p. 32). Chryssolouris *et al*. (2014, p. 500) argue:

> "[Both] manufacturing and production . . . [can] be understood as functions for the generation of products . . . whereas the factory represents the physical and logical means of performing production and manufacturing processes. An industrial manufacturing site [(that can also be designated as production site, production centre, plant or factory)] includes the buildings, the manufacturing facilities, and the ground on which they are located."

Factories provide further physical structures such as technical infrastructure (Schenk, Wirth and Müller, 2010) and working space for people (Claussen, 2012) while the technologies required to run and control a factory are developing and increasing in complexity (Chryssolouris, Papakostas and Mavrikios, 2008). These technologies are required to meet numerous and ever-growing factory requirements against the backdrop of different factory influencing factors, a selection of which is visible in figure 1.

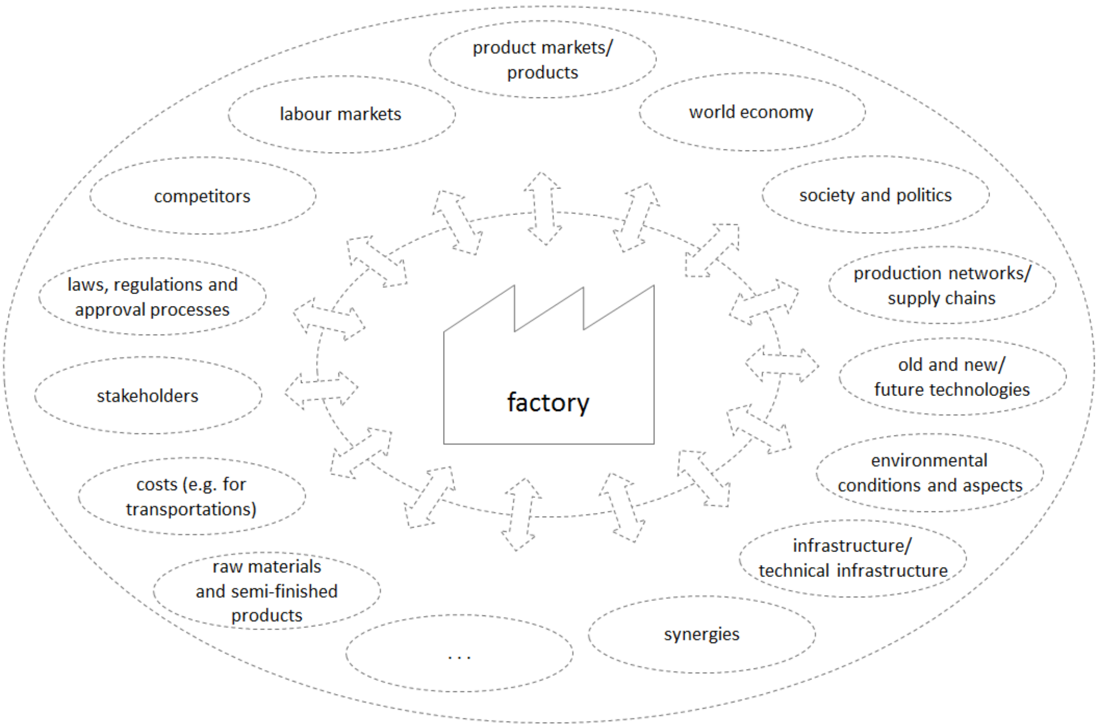


Figure 1: Factory influencing factors (based on Schmigalla, 1995; Hernández, 2002; Hildebrand, 2005; Helbing, 2010; Schenk, Wirth and Müller, 2010 and Wiendahl, Reichardt and Nyhuis, 2015)

A factory can be distinguished into sections and departments. Factories are also discussed in the context of production networks. The VDI 5200 (2011, p. 7) defines a production network as “A locally, regionally, interregionally or internationally configured grouping of locations for one or even several companies.” A production network covers all factories that are connected to one another through flows of material or goods. ‘Horizontal integration’ refers to a co-operation or working-relationship between factories of the same hierarchical level/tier (Friese, 2008).

'Vertical integration' is the designation for a linked supply chain between factories of different hierarchical levels (Graf, 2006).

One plant can comprise numerous factories of different suppliers, and those of different OEMs. The SMART Hambach Plant, for instance, has an integrated supply chain and is often praised for its lean production flows (Klug, 2010). Negative aspects such as the exertion of pressure on suppliers and different intransparent processes (e.g. transportations) are often undisclosed (Sredic, 2011). The percentage of suppliers which are located at locations other than Hambach is unknown. Furthermore, SMART Hambach is not representative of an automotive OEM plant, as the products are rather simple compared to those of other automotive OEM plants, which are more complex and involve larger dimensions. Lean production approaches with regard to production networks have been considered for decades (Wildemann, 1997), but their real benefit is questionable against the backdrop of fragmented factories (Sredic, 2011). Co-operating factories within production networks are generally spread all over the world, so that production flows and consequently value addition are fragmented, which leads to a vast amount of highly questionable transportation via air, road, rail and water by reasons of this fragmentation, changing labour and product markets, throwaway societies and consumerism, low transportation costs and desired profit. Environmental concerns play a secondary role at the most, as does labour exploitation and other negative aspects (Seeblind, 2016).

A clear definition, delimitation and differentiation of factory-related terms is not consistently given within factory- and factory planning-related literature (see appendix 2.1.1). The following terms and definitions are used in this thesis:

A 'factory' is the highest factory structure level, and involves all FOs/FSs and subordinated factory structure levels. The terms 'plant' and 'location' are used synonymously for the term 'factory', although the term 'factory' is primarily used. The term 'location' can also be used to indicate an area free of FOs/FSs. The designation 'plant' is mainly used to emphasise an automotive OEM plant which is a huge (multi-)factory with one location. The 'site'/'construction site' provides the basis for a factory, and this term can also be used synonymously where appropriate.

A 'production plant' refers to a linked system that consists mainly of machines. Production plants can be part of a production line, but the term is not used synonymously with the term 'factory'.

'Supply and disposal (s&d) plants' are large(r) FOs which are concerned with the supply, disposal and/or treatment of one or different types of energy and/or media. S&d plants can involve buildings, building structures and/or can be building-like structures.

The term 'facility' refers to an FO that belongs to a production flow, logistical/ material flow or s&d system. A building is never intended or incorporated when the designation 'facility' is used. 'Facility' is also not a synonym for 'factory'. Production, logistics and s&d facilities, for instance, are machines, conveyors and facilities which belong to technical building systems (e.g. air conditioning facilities). The designation 'process facility/ies' is used as an umbrella term for such objects. A production plant can also be covered when the designation 'process facilities' or 'facilities' is used. S&d plants are not designated as facilities. The definitions in this and the two previous paragraphs also apply to the respective singular or plural forms. Chapter 3 provides further information about factory-related definitions.

2.1.2 Factory Evolution and General Factory Requirements

All industrial revolutions have had the same general aims: to accelerate production and reduce costs. The same applies to 'Industry 4.0', the self-proclaimed Fourth Industrial Revolution, which is a self-organised and internet-technology-based concept that aims to combine the virtual and the real world, in which active parts and products carry information about 'how', 'where', 'when' and 'by whom/what' they should be processed. The organisation and control of processes is intelligent and decentralised, and enables smallest production lot sizes and high flexibility in a transparent environment (Dworschak and Zaiser, 2014; Bundesministerium für Bildung und Forschung, 2016). Industry 4.0 is in its identification stage. The same applies to 'smart factory'. Radziwon *et al.* (2014, p. 1186) suggest that the smart factory consists of a "...modular structure [and is] ... interconnected by a wireless network...". In addition, the smart factory is "transformable, agile and lean" (p. 1187). That "Industry 4.0 ... is a synonym for the transformation of today's factories into smart factories, which are intended to address and overcome the current challenges of shorter product lifecycles, highly customized products and stiff global competition", has been stated by Weyer *et al.* (2015, p. 579). All definitions of 'Industry 4.0' and 'smart factory' have in common the assertion that the transformability of factories is highly relevant and will be required in the future.

While the production of goods was characterised by an almost complete or continuous value chain within Ford's production halls (Ford, 2009), it is currently spread throughout the world (Pawellek, 2014; Grundig, 2015) and fragmented, which leads to numerous transportations (Seeblind, 2016) and further types of waste (Sredic, 2011). These were first defined within the 'Toyota Production System' and the paradigm of 'lean production' (Womack, 1991; Ohno, 1993). The main objective of the Toyota Production System can be summarised as a zero-defect strategy with a maximum production output and quality, and a minimum of wasteful processes (Womack, 1991; Ohno, 1993; Dichtl, 2013).

The need for lean production within factories has been increased by the Third Industrial Revolution, which has been driven by the improved information and communication technologies which accelerated globalisation (Schmidt, 2013). To enable lean production is a requirement of modern supply chains (Lamming, 1993), factories and production systems, which should be flow-oriented (Dorota Rymaszewska, 2014; García-Alcaraz, Maldonado-Macías and Cortes-Robles, 2014). Both the mass production of customer-individual products ('mass customisation') which emerged with globalisation and changes in buyer behaviour (Piller, 1998; Kull, 2015) play a significant role. Enabling a production system to handle the ongoing increase of product models, types and variants (Westkämper, Balve and Wiendahl, 1998; Rinza and Boppert, 2007; Müller, 2008), which means enabling mass customisation, and keeping the factory continuously 'lean', is therefore an overarching aim of process and factory planners.

Hildebrand *et al.* (2004) claim that factory planning should lead to a factory's total optimum. In addition, transformations should be performed without disturbing the ongoing factory operation, while investments should already be made within the initial planning in a way that enables future developments. Decisions (especially decisions with a long-term character) are a problem in the light of unforeseeable and volatile market requirements, and can lead to factory transformations (Bergholz, 2005, p. 1). This means that decisions, once taken, lead to FOs/FSs and can have unknown and irrevocable long-term effects. A process of continuous transformation is the consequence. Therefore, a stable status can be reached at best temporarily, which disables the optimisation of today's factories, as they are always between a state of production ramp-up and phase-out. High investment risks, huge transformation efforts and insufficient process efficiencies are the consequences. Too much transformability and a lack of stability can even be risky, as these can lead to a loss of efficiency and competencies in today's factories (pp. 1–2). Transformations can destabilise production systems and factories, which is a problem in times of a continuous shortage of product lifecycles (Wagner *et al.*, 2012). Thus, to keep a factory continuously lean, factory structures must be both highly transformable and able to reach stable statuses, which are central requirements of factories and/or production systems (Hernández, 2002; Bergholz, 2005; Sredic, 2011; Rauch, 2013; Radziwon *et al.* 2014). They must also have the ability to utilise synergies (Sredic, 2011; Schenk, Wirth and Müller, 2014) and absorb environmental requirements that lead towards a 'green factory' (Bergmann, 2010; Sredic, 2011; Mueller *et al.*, 2013; Rauch, 2013).

The general production industry has evolved over recent centuries. Factories housed craft production, mass production and mass customisation (Stearns, 2013), while a lean, green and transformable factory/production system has never been more required than today (Sredic, 2011; Kampker *et al.*, 2012; Rauch, 2013; Schenk, Wirth and Müller, 2014). Transformability is therefore the major factory characteristic, as it enables and preserves the efficient and green factory over time, which is flow-oriented/lean and synergetic (figure 2).

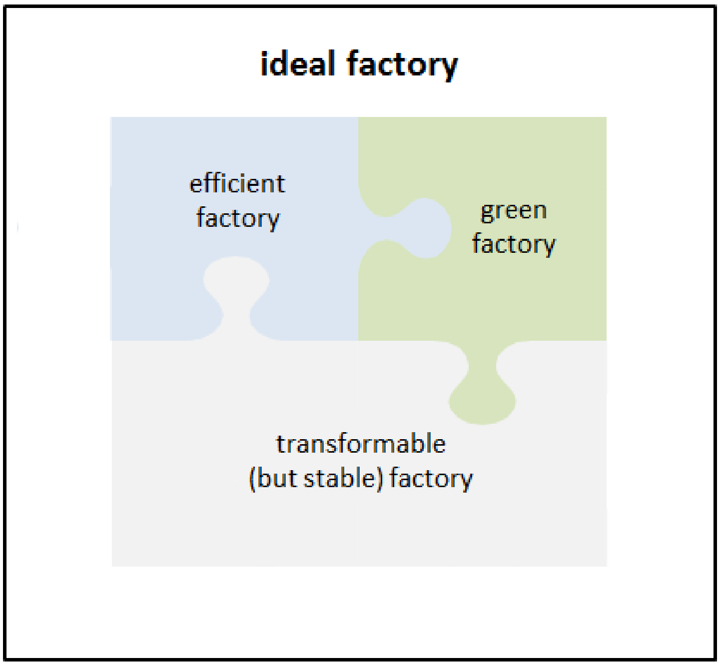


Figure 2: General factory requirements – three facets of the ideal factory

This is in line with Schenk and Wirth (2004, p. 468), who argue that the factory of the future is characterised by temporary transformable structures and the ability for fast reactions with respect to flexible product and resource changes. Wiendahl, Reichardt and Nyhuis (2015, pp. 114–117) present a “vision of the changeable [/transformable] factory” with the following characteristics and challenges: “factory setup time "zero"”; “plug & produce technology”; “material always flowing”; “pre-tested mobile production modules”; “zero emissions”; “attractive and healthy working environment”; “orientation to market”; “adequate changeability at all factory [structure] levels”; “external networking ability”; “sustainability from [an] economic, ecological and social view”; “mobile resources”; “platform-oriented segmentation”; “fast variant change”; “layout extendibility” etc. Ongoing globalisation leads to turbulent and merging markets that require transformable but stable structures. “A transformation from a flexible production to a changeable[/transformable] company occurs.” (Meier, Schröder and Kreggenfeld, 2013, p. 350). This has been recognised by various authors, whose concepts are presented in the following subsection.

2.1.3 Modern Factory and Production Concepts

Today, various factories and factory-like structures on land, water and above the ground are recognisable, e.g. rail- and water-mobile factories (Helbing, 2010). This research project focuses on factories on land and water. Relevant factory and production concepts which were developed from the 1960s onwards are described next.

Henn (1995, p. 183) argues that nature served as a model for the 'Fractal Factory'. The same applies to the two further concepts that are described in the following paragraph. They all have in common that lean process flows are considered.

'Holonic Manufacturing' is a nature-based concept. The term 'holon' was introduced and characterised by Koestler (1967). A holon is an organic and autonomous entity that can operate and cooperate with other entities. This entity is able to independently develop strategies, tactics and operative processes. In addition, a holon is able to change configurations and routes autonomously while it follows an overarching aim that restricts its autonomy. Holons can be combined together to create production lines and larger structures, but also play their part within single machines and production units. Consequently, transformable production systems can be created (Tharumarajah, Wells, and Nemes, 1996). 'Bionic(al) Manufacturing Systems' are comparable to cell structures such as those of diverse biological systems or organisms, with the difference that the structures within Bionic Manufacturing Systems can transform much more rapidly. The smallest units, 'modelons', are comparable to organic cells and can adopt different functions. Modelons are able to carry information and transform themselves when information changes. Numerous modelons in combination generate a highly transformable structure that can be complex but easily controllable (even self-controlled) and eco-compatible, and that follows an overarching objective (Okino, 1988). The 'Fractal Factory' is characterised through effectively interconnected (internal) organisational structures that enable sensible information and process flows. The whole factory is comparable to a living, learning and dynamic organism that follows a common aim, while relations with the factory environment are considered and processed through transformations. This capability is enabled through self-similar, self-acting and self-organised enterprise units: 'fractals'. Transparency is provided through different hierarchical factory structure levels (Warnecke, 1992, 1995; Dillerup, 1994; Zahn, Dillerup and Foschiani, 1997).

One could argue that the concepts in the previous paragraph have led to the development of transformable enterprises, associated structures and processes. Dynamic factory structures must be oriented towards processes and vice versa (Bissel, 1996). Transformable structures and direct processes influence indirect processes and vice versa (Westkämper, Balve and Wiendahl, 1998). Westkämper, Balve and Wiendahl (1998) emphasise the order management within transformable business structures. Further approaches to transformable enterprises are provided by Westkämper *et al*. (2000), Wiendahl and Hernández (2000; 2002), Wiendahl (2001; 2002) and Wiendahl, Reichardt and Hernández (2001). Westkämper *et al*. (2000) recognise that operational adaptability and strategic flexibility are key success factors of today's enterprises. They have developed a framework for the definition of transformability and described where transformable structures are required and how these can be developed.

Initial approaches to transformable factory structures were recognisable in the 1960s (Rockstroh, 1966), while the 'Modular or Segmented Factory' provides improvements towards transparency and is broken down into different self-controlled segments. Again, an overall aim is brought into focus by the segments, which should operate as autonomously as possible (Wildemann, 1998). Ideas about transformable and temporarily interconnected production systems are provided by Nyhuis, Reinhart and Abele (2008). Other ideas emphasise the mobility of modular factory structures (Eversheim, Lange-Stalinski and Redelstab, 2002; Zäh *et al.*, 2003). The planning of modular and mobile factories is discussed by Wiendahl *et al.* (2013), while further transformable factory concepts are described in Hildebrand (2005) and Rauch (2013). They all have in common that modularity is a key function which enables the transformability of factories.

Module and platform strategies lead to decreased investments, reduced planning efforts and increased quality (Schenk and Wirth, 2004, p. 137). The idea of building-related platform concepts with mobile foundations, building structures and contents is not new in factory planning (p. 161). Schenk, Wirth and Müller (2014, p. 205) argue that such platform concepts enable multiple utilisations and re-utilisations of building structures. Wirth, Erfurt and Olschewski (2003) have conceptualised technical platforms in order to meet different requirements of production facilities, technical infrastructures and buildings in the case of a factory transformation (e.g. machine dimensions and machine interfaces to the s&d infrastructure). To increase the flexibility and transformability of factories has been the aim of those authors who have perceived the significance of the mobility of FOs/FSs.

Hildebrand (2005) has developed theories for factories that are based on pluggable modules, and has analysed the theoretical capabilities and limitations of such modules. Hildebrand describes in this regard two factory structure types: the "PLUG+PRODUCE [factory structure type] I" and the "PLUG+PRODUCE [factory structure type] II" (pp. 60–61). Type I is concerned with 'inner mobility', which enables inner transformations within one location. Resouces and technical units can thus be integrated or exchanged. Type II enables 'outer mobility' and therefore efficient relocations of factories. Fox (2015) discusses different forms of movable factories and their combinations. He claims that "...moveable factories should be included in debate about best-shoring." (p. 56). Fox's aim is to change parts of the current factory planning theory. Road widths are limiting the scope of factory transformations (e.g. the movement of FOs) to a maximum of container sizes that can be transported by road (Hildebrand, 2005; Fox, 2015). Hildebrand's (2005) theory consequently has the same problem as Fox's (2015): the mobility-size of FOs/FSs is limited.

The authors of the concepts described in this subsection to this point have attempted to increase and preserve the operational effectivity and efficiency of factories and production systems in order to overcome the increasing challenges of globalisation. These concepts have one thing in common – none of them consider area systems. Therefore, areas and substructures of these concepts are the same as those of today's factories and factories from the first industrial revolution. Further concepts which are based on different types of area systems will be presented next.

Lui's (2004) factory design concept focuses on the application of the maritime area system 'Self-Elevating Platform' (a portable maritime structure) under consideration of further area systems (e.g. 'Ukitecture') in order to enable off-site (pre-)production of building components with minimum transport and implementation times and costs. The modular and movable concept increases the transformability of the layout. Huge areas can be formed (p. 1) and changing products produced (p. 7). "The overall strategy of the design is to provide flexible production layout and changeable supporting facilities for variable production activities to occur." (p. 8). Lui argues that "...there is no permanent construction or installation. The objective is to allow the greatest flexibility for easy construction, future expansion, and adaptability to changing needs." (p. 10). A "poor infrastructure" can be bypassed with the concept by using waterways (p. 7). Lui recognises the potential to convert and use renewable energy from the sun, wind and water. Various floating structures (modules and module combinations) with different superstructures can be plugged and unplugged as required (pp. 6–11). A "form follows flow"-principle is consequently possible, while various process flows can be applied. Thus, lean production flows can be enabled. A rectangular shape of a factory can, for instance, be transformed into an organic structure (p. 11). Modules that can serve as a warehouse and living quarters complement the idea, while single modules can be moved by ships (Lui, 2004).

The transformability of Lui's (2004) concept is limited and its transformation velocity low in comparison to other concepts, as the used area system must be fixed to the marine ground before an operation and unfixed before movements can occur. In addition, the transformability of technical infrastructure is limited. Impacts of the design concept on factory planning have not been analysed deeply, despite the fact that Lui indicates improved basic transformability as well as diverse advantages with regard to construction sites and logistics processes, and also that floating factories can meet the requirements of our "ever-changing world" (Lui, 2004, p. 1).

Several of Lui's arguments were described by Scanlan (1974), who is one of the first to have described a 'plug-and-produce'-principle. Scanlan's (1974) area system and related descriptions therefore provide a basis for the 'form follows flow'-principle of Henn (1995), Lui's (2004) concept and all other works that involve a 'plug-and-produce'-principle (e.g. Hildebrand, 2005). Furthermore, Scanlan's (1974) invention involves several basic considerations of the nature-based ideas discussed earlier in this subsection and was one basis for the development of Sredic's works.

Sredic's (2011) practice report 'Bluefield Plug & Produce' is mainly based on the practical experiences of the author with regard to production networks and factories, and on the area system patent registration of Sredic (2012b). The limitations of Lui's (2004) design concept and of different inventions (of which the relevant ones are discussed in subsection 2.3.5) have been reduced by Sredic (2012b) in order to improve the transformability of factories by means of the 'Bluefield®' area system, which involves different modular functional layers and an integrated modular technical infrastructure. Sredic's (2012b) reusable area system is universally applicable and can be used as a basis for factories, along with other possible uses and their combinations, while Sredic (2011) focuses on the disadvantages of today's factories and production networks.

Fragmented production networks imply high optimisation potential with regard to lean production, synergies and sustainability, as argued by Sredic (2011). Further aspects with regard to factories within production networks are also discussed (e.g. diverse forms of egotism). Sredic argues that factories grow out of themselves as years go by. Furthermore, they are solidly constructed within limited areas. In addition, the mobility of large structures is disabled, and as a consequence, the transformability of factories can also be improved (Sredic, 2011).

The direct use of wind, water and sun energy without long distance transportation of energy is only one example of possible synergies. Further synergies are enabled through huge area sizes (e.g. greater than 1 km^2). Through the merger of different enterprises, overhead costs can be reduced and the focus can be placed on lean production flows that can cross company borders. Production networks can be combined in one location and consequently not spread around the world. Thus, a one-piece-flow can be enabled throughout a production network, as different factories can be locally and regionally joined. Wastes such as packing, transportation, unpacking and double-handling can thus be almost completely eliminated, while environmental impacts are simultaneously reduced. Furthermore, area system modules can be pre-produced and pre-tested (Sredic, 2011). Figure 3 depicts the concept in which an OEM(s) is linked with its suppliers.

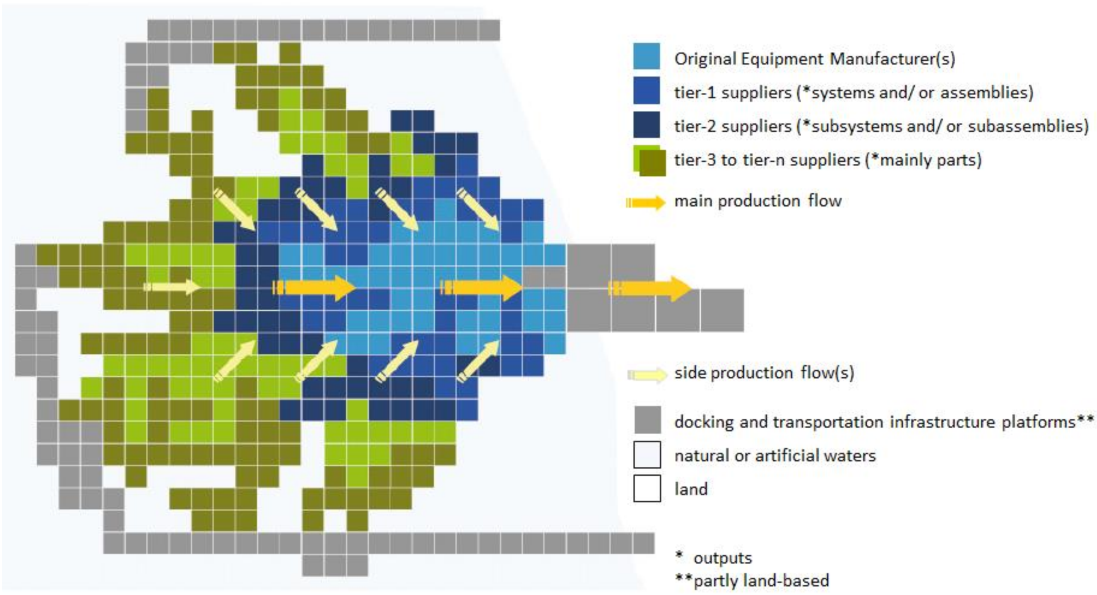


Figure 3: Bird's-eye view of Bluefield Plug & Produce (Sredic, 2011)

Sredic (2011) claims that such factories are highly transformable due to modular and mobile areas, and can be designed almost without restrictions (especially regarding their size and shape). Thus, huge areas allow the integration of whole production networks into one large plant. Consequently, lean, synergetic, energy-efficient and environmentally friendly production is enabled. These characteristics help to reduce overcapacities. Furthermore, a coupling and decoupling of suppliers and rapid integration of pre-producible and pre-testable production lines are enabled. In addition, intercontinental relocations of factories and production networks are possible. The impacts of area systems on factory planning have not been analysed deeply by Sredic (2011).

Some advantages of area system-based concepts have been recognised by factory planners and OEMs. Factories that are based on modules that can be integrated and disintegrated at different positions of assembly lines are described in Dashchenko (2006b), while Audi AG provides a vision of a smart factory in which movable modules are described (Audi, 2015). Besides maritime bases, terrestrial technical bases that can enable such visions are also available (Sredic, 2012d; 2015) (see subsection 2.3.4). The basic ideas of Sredic's work (2011; 2012b; 2012c; 2012d) towards efficient, green and transformable factory concepts are comparable with the basic ideas of Rauch (2013, p. 140), who confirms their meaningfulness. The use of standardised and reusable base modules with standardised interfaces which are compatible across the borders of factory locations (Sredic, 2011; 2012b; 2012c; 2012d) is also considered by Rauch (2013, p. 155). This applies likewise to the scalability, pluggability and linking ability of these base modules to sub- and superstructures which enable lean production systems (Sredic, 2011; 2012b; 2012c; 2012d; Rauch, 2013, p. 156). The requirement for effortless moves of large production facilities (Sredic, 2011) has also been confirmed by Rauch (2013, p. 118). Rauch, however, is dependent on scenarios (pp. 198–204). He focuses on technical, organisational and strategic issues (pp. 33–34), while the technical issues with regard to transformability mainly involve buildings and production facilities (pp. 155–156) and not area systems, the same as most of the modern concepts in this subsection. The active transformability of areas has consequently not been considered by this author. Furthermore, no technical details with regards to areas/factory substructures are described by Rauch (2013).

2.1.4 Summary

The impacts of area systems on factory planning theory have not been deeply analysed in the literature. Transformability has been identified as an important factory requirement, characteristic and capability. The transformability of factories is discussed in the following sections.

2.2 The Current Status of Factory Planning Theories

Factory planning is a permanent task (Hennersdorf, 2011) and comprises theories for the planning, implementation and transformation of factories, and the monitoring and controlling of required processes until the 'start of production' (SOP) (Eversheim and Schuh, 1999). Numerous models, approaches, methods, principles etc. are available. This section provides information about the theories that are relevant to this thesis.

2.2.1 Basic Factory Planning Cases

Current basic factory planning cases (BFPCs) are roughly defined types of factory planning projects and encompass one Greenfield and a number of Brownfield project variants (Helbing, 2010; VDI 5200, 2011; Grundig, 2015).

According to Grundig (2015), factory planning projects can be structured into five BFPCs. Some of the four Brownfield cases involve Greenfield characteristics (e.g. area-related works), while all cases require the analysis of the existing location. Grundig (2015) identifies the following cases:

- 'BFPC-A (Greenfield)' refers to a new factory planning and implementation on a 'green' field. It is an ideal case with no restrictions through existing structures. Greenfields require a definition of the production programme and are time-consuming. Sensible site selection and a good connection to the technical infrastructure are crucial.
- 'BFPC-B (re-engineering)' refers to the redesign and reconstruction of an existing factory. This case dominates factory lifecycles, as it is a permanent task that involves continuous adaptations of FOs/FSs, and continuous/rolling factory planning. Changing production programmes, technological innovations or required modernisations can initiate this case.
- 'BFPC-C (extension)': This case leads to the increase and/or intensification of area use. It is not necessarily associated with an extension of the area size. BFPC-C can require new site selection and factory relocations.

- 'BFPC-D (reduction)': This case involves the dismantling of factories (e.g. in the case of an economic downturn).
- 'BFPC-E (revitalisation)' refers to the re-use or new use of a location. Super- and substructures are remediated, decommissioned or demolished.

Helbing (2010, pp. 88–90) describes ten BFPCs. Helbing's cases one to six are covered by Grundig's cases (see appendix 2.2.1). 'BFPC-9' and 'BFPC-10' are basically comparable with Grundig's (2015) BFPC-E, while Helbing differentiates between a re-use or new use (BFPC-10) and BFPC-9 which represents a closure, demolition and recycling of a factory. Helbing (2010, p. 90) argues that compared to other Greenfield and Brownfield cases, the share of BFPC-9 is relatively low but increasing. He recognises that this increase is supported by factory ageing and unfavourable locations, and that in the current climate of globalisation the relocation of FOs/FSs is in vogue. As a consequence, Helbing claims further that the enhancement of BFPCs that follow their own rules is required, and that this is reinforced by the increasing possibility of having mobile factories which enable location changes.

Helbing's 'BFPC-7' and 'BFPC-8' are hardly comparable with Grundig's BFPCs, as they represent or combine subitems of the latter. According to Helbing (2010, p. 90), these Brownfield cases are similar to BFPC-2 (BFPC-A with an area limitation through narrowing, although this narrowing is not specified), but preserve the substance of a factory. These cases are associated with extensive construction measures and re-equipment, and are triggered by desired modernisation or a change of ownership (p. 90). BFPC-7 is a reconstruction and remediation project in which the production programme and cooperations are not changed, while BFPC-8 leads additionally to a change of the latter two. Site investigations, changes of technologies and transformations of the s&d infrastructure can, besides numerous further tasks, be required in each of Helbing's cases (2010, pp. 123–124). Helbing (p. 12) claims that Brownfields appear much more often than Greenfields.

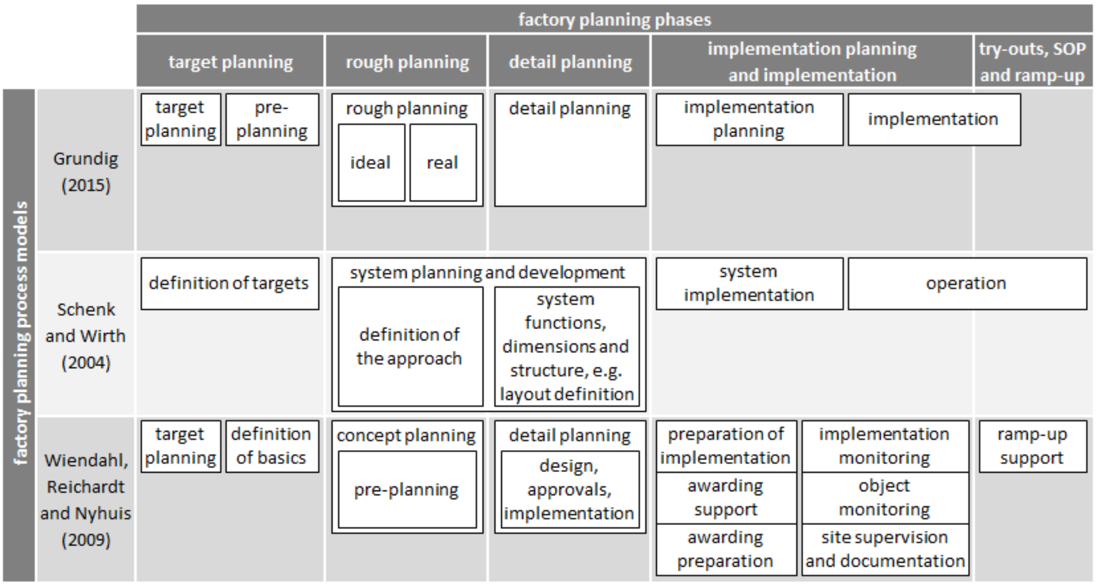
One problem with current BFPCs is that area-, building- and further FO-/FS-related project scopes and characteristics have not been differentiated. Current BFPCs do not encompass all relevant real-world factory project cases and do not indicate which of these cases are most important for factory planning and why. Furthermore, current BFPCs do not have much to do with the characteristics and extents of real-world factory project cases, which can be complex and have different impacts on a factory depending on the achieved factory development stage (which has not been indicated so far). The meaning of these impacts for factories remains unknown. Nevertheless, Grundig's (2015) definitions of BFPCs are used in this thesis, while Helbing's (2010) BFPC-7 and BFPC-8 are taken into account where appropriate. The importance and significance of Brownfield projects are in any case underestimated.

2.2.2 Factory Planning Process Models

FPP models are used for the planning, implementation and transformation of factories (Grundig, 2015). The first-mentioned involve numerous planning and construction, and are characterised by decision-making processes. A systematic and iterative procedure is required to complete these processes (Aggteleky, 1987). This is attempted in diverse factory planning approaches, while FPP models provide a basic structure which allows the structuring of a project. Factory and production planning contents are considered, while both meet primarily in factory buildings. Logistics and other process-related contents are also considered (Grundig, 2015; Wiendahl, Reichardt and Nyhuis, 2015).

FPP models are segmented into factory planning phases. Each phase involves specific FPPs (Grundig, 2015). FPP models are discussed in the context of subprojects in which different relationships and overlaps are considered. A factory planning project can involve several subprojects. These subprojects can last over several factory planning phases (Bergholz, 2005).

Various models of different scholars involve comparable contents and can therefore be subdivided into similar phases (Bergholz, 2005) (figure 4).



the overall process flow goes from left to right (arrows between phases and process steps are not depicted for reasons of clarity), this must be understood as an overview which aims to depict differences of factory planning process models on a high level, not all processes and details are depicted, and sizes do not indicate the duration or importance of a phase or process step

Figure 4: Factory panning process models of Grundig (2015), Schenk and Wirth (2004) and Wiendahl, Reichardt and Nyhuis (2009) (modified) (based on Bergholz, 2005, p. 71; Schuh *et al.*, 2007 and the original sources)

The contributions of the above authors have been aggregated and assigned to the following phases. The work of Bergholz (2005) has been reflected, but the contents of the original sources have been used and summarised for this thesis. The same applies to the contents provided by Schuh *et al*. (2007). Further relevant sources are named in addition:

- 'Target planning' involves planning premises which are anticipated factors that are required as a basis for factory planning (e.g. product models, quantities, possible markets and locations). The general structure can be considered (VDI 5200, 2011, 2016).
- First layout drafts are developed within the 'rough planning' (e.g. required FO dimensions and arrangements, technical infrastructures, interfaces, main inflows, outflows, personnel, material and production flows). Furthermore, resource requirements, shift models and capacities can be defined (Kettner, Schmidt and Greim, 1984; Aggteleky, 1990; VDI 5200, 2011, 2016). Ideal planning can be replaced by real planning (Kettner, Schmidt and Greim, 1984; Schenk, Wirth and Müller, 2014).

- Rough planning provides the framework for 'detail(ed) planning', in which the layout (with all FOs/FSs), approval, construction and further processes are planned in detail. Area-related, spatial, technical and functional aspects, transport concepts and all flows are planned in such a way that the functionality of the factory is given and available areas are effectively used (under numerous considerations such as escape routes and fire protection aspects) (Aggteleky, 1990; Helbing, 2010).
- 'Implementation planning' and 'implementation' have been combined into one phase in this thesis, as diverse planning- and implementation-related FPPs overlap and can hardly be kept apart. This phase involves purchasing and awarding processes, earthworks and construction processes (which can begin and be partly finalised in earlier phases). Furthermore, different FOs/FSs must be installed, which are often fixed after their implementation. Consequently, they require a thoughtful placement (Helbing, 2010).
- The last phase involves 'try-outs', the 'SOP' and 'ramp-up'. When the try-outs and required audits are completed, the SOP can take place.

Factory planning becomes more obligatory/binding with the completion of the single phases. The analyses of potential locations and sites leads to site selection, approval processes to approvals, negotiations to contracts, and a factory specification book to a bill of quantities, functional specification documents and finally to factory implementation (or transformation). In sum, planning turns into reality, while decisions and planning mistakes can have serious consequences within the logical structure of FPP models, which involve numerous processes which are related to one another.

The following FPPs in particular are relevant for this thesis:

- site preparation, earthworks and substructure works
- construction processes (e.g. technical infrastructure, foundation and building construction works) and assembly processes (e.g. for TBSs)
- building-, production-, logistics- and other process-related installations

- all processes that belong to the ‘try-outs, SOP and ramp-up’ phase

The main focus lies on physical processes (e.g. earthworks and construction works). Non-material FPPs (e.g. approval, awarding and purchasing processes) are considered where appropriate. In addition, site selection plays a main role.

The analyses of different locations and sites are important, as they have profound and long-term effects on factories. The selection of a site takes place against the backdrop of basic premises/assumptions that are often changed in a later step and lead to additional requirements (Hansmann, 1974, pp. 15–16). Customer and labour market proximity and a good connection to technical infrastructure networks are, amongst other factors, crucial requirements for a site. After site selection, site development takes place; this can begin in one of the planning phases. This means that besides further works, the site must be prepared and connected to external technical infrastructure networks (Helbing, 2010; Grundig, 2015; Wiendahl, Reichardt and Nyhuis, 2015).

Aggteleky (1990) highlights a ‘point of no return’ before a project is released for implementation, which is the end of the detail planning. Grundig (2015) sees the ‘point of no return’ as being between the rough and detail planning. Changes after this point can lead to delays and huge efforts.

Such changes can require transformation planning process models. The transformability of factories is important not only for factory transformations but also for factory implementations and related planning activities, as future factory developments and transformations must be considered and (pre-)planned. The initial factory configuration strongly determines future transformation possibilities. Factory planners develop different factory layouts with different development possibilities, and select the presumably most appropriate one (Friese, 2008; Grundig, 2015). To oversize today’s factory structures from the start is sensible. In the case of OEMs, the upfront acquisition of large areas (e.g. doubling areas) in order to enable future factory duplications is common practice. This empowers factories to meet increasing production capacities (Jordahl GmbH, 2012). Such (extension) areas increase the transformability of today’s factories.

The transformability of FOs/FSs and the point in time when transformations must take place are crucial (Hernández, 2002). The assessment and planning of transformability and of transformations were defined by this author, who has described a transformation planning process model that can be used in addition to FPP models (figure 5).

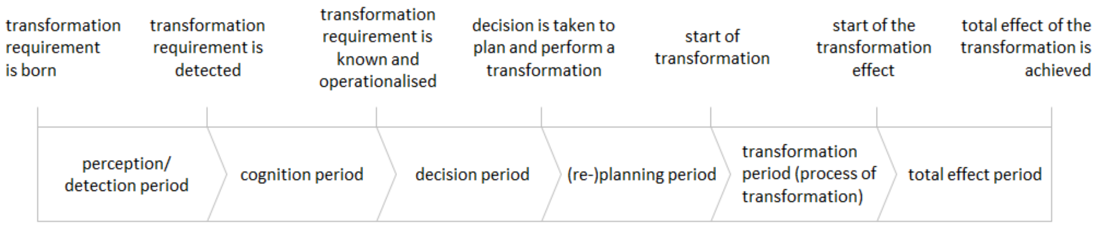


Figure 5: Transformation planning process model (modified) (based on Hernández, 2002, p. 49)

First, a transformation requirement must be detected and operationalised. Next, it must be decided whether a transformation will be planned and performed. Finally, a period of time is required until the total effect of the transformation is achieved (Hernández, 2002, pp. 48–49).

Factory and transformation planning process models can guide factory planners, but relations between data are only superficially considered and the level of detail is rough. Phase-oriented planning models are incapable of adequately meeting factory planning challenges. Reasons for this are a shortage of planning durations, uncertain forecast data and increasing information requirements; the planning is consequently challenging (Kampker *et al.*, 2010; Burggräf, 2012), and efforts are made to handle these limitations using factory planning approaches.

2.2.3 Factory Planning Approaches

Various planning approaches have been developed to handle the complexity of factory planning in order to create preferably ideal factories.

Planning that considers a theoretically ideal factory as the basis for the development of a best possible factory against the backdrop of numerous restrictions is essential (Grundig, 2015). Schenk, Wirth and Müller (2014) describe an ideal layout as being flow-oriented, and with a spatially ideal arrangement of

FOs(/FSs) where restrictions are blanked out. Flows are ideal when crossings of flows, transportation distances and process times are minimised. A functional arrangement of FOs/FSs can lead to a block layout, which provides a basis for the real planning (Kettner, Schmidt and Greim, 1984). The block layout is confronted with economic, technical and area-related/spatial restrictions (e.g. area size, area shape, soil quality and available funding) during the planning phases (Schenk, Wirth and Müller, 2014). Grundig (2015, p. 169) argues that ideal site characteristics (e.g. area size and geometry) are rather unlikely to be found. As a consequence, a change of arrangement of FOs/FSs, and of sizes and geometries of areas may be required.

To develop and perform a factory project under consideration of required FPPs can be challenging. "A planning project can be developed systematically [e.g. algorithm based] and/or situation-driven..." (Schenk, Wirth and Müller, 2010, p. 18). Situation-driven planning is driven by operational decisions in order to change processes and FOs/FSs. Systematic planning is driven by an ordered project definition, development and implementation against the backdrop of the requirements of the different factory structure levels involved (pp. 17–21). Bergholz (2005) provides an approach that is based on software engineering methods as well as lean aspects and concepts that have been transferred to factory planning (and design). His approach provides advantages for transformable superstructures against the backdrop of a dynamic factory environment, as it makes requirements towards transformations transparent. Bergholz (2005, p. 54) recognises the interconnection of different factory projects and the increasing complexity in factory planning, and claims that these circumstances require synchronisation of these projects. Thus, subprojects must be delimited with regard to time characteristics (e.g. due dates) or different types of planning objects. The planning approach must be developed in a manner that considers these subprojects, which can consequently be delimited and synchronised. Further factory planning approaches can be found in the literature, and two of these are explained in more detail below.

The '0 + 5 + X Planning Model' of Schenk, Wirth and Müller (2010) is based on three steps. First, the project must be defined by means of selection criteria/ specifications such as BFPCs, factory planning phases and FPPs. Second, design steps such as the dimensioning and definition of factory sections are taken to develop the project. Finally, specifications for the implementation of the project are defined (e.g. technical specifications). These three steps are mainly based on checklists and questionnaires which can be reworked “in a loop or spiral process” (p. 30). Dependencies between single elements are considered by means of a PDCA-cycle. This planning model helps factory planners to define and specify their project and to choose or assess their project activities (Schenk, Wirth and Müller, 2010, pp. 29–30).

Schenk, Wirth and Müller (2010) use current BFPCs to specify these activities. Nevertheless, not all relevant events are taken into account (e.g. displacements), even if collisions are considered. This planning approach is a compilation of possible required elements, tasks and processes for different BFPCs. Tasks etc. and their sequence can be specified based on an information pool which provides rough selection criteria and wide room for interpretations. This is conceded by the authors, who state that “the planning model is only a rough guideline” (p. 30). Factory planners can be led astray by complexity, despite the usefulness of such models. This is in line with Rauch (2013, p. 235), who argues that system designers receive guidelines but are left alone with several methods.

Rauch (2013) defines a concept of a transformable, decentralised and replicable production system for franchise models with pre-definable extension steps and a related factory planning approach which supports this concept. The most important functional requirements of the production system are transformability and the ability to enable a step-wise extension of production units. An easy and fast replication of pre-definable extension steps of the production system (or decentralised franchise units) is possible (p. 138). These steps can be adjusted quickly and simply (p. 236) while influencing factors that are relevant for the planning and the interdependencies between these factors are considered and can be better handled with the developed approach than with other approaches (pp. 232–235). The approach involves recurring reviews between planning and reality in a regular feedback process (pp. 196–197). Rauch reflects on developments of the factory environment towards normative extension steps (or design levels) and adapts the latter, the same as related planning procedures within definable time intervals (pp. 194–197). This back-coupling enables the identification of whether a (inner) transformation is sufficient or whether a subsequent extension step is required. Rauch (p. 235) argues that the planner of a complex (e.g. production) system hardly has a chance to overlook all interdependencies between system elements (or related FPPs). Rauch's approach therefore considers a breakdown and decoupling of functional requirements and single system elements (or design parameters), while the latter can be derived based on these requirements. Complexity is thus reduced (Rauch, 2013).

The planning, implementation and transformation of pre-defined production system structures within franchise models (and beyond these) can be accelerated through Rauch's approach, but the problem remains that one planning mistake or a later change in the factory environment can lead to a substantial failure and inability of the production system. Rauch's approach relies on anticipation. This problem has been recognised by Rauch (2013, pp. 236–237), who argues that it can be handled if the design parameters are defined by interdisciplinary teams. This is highly doubtful, as incorrect parameter characteristics and relations between parameters are hardly tangible (p. 235) and even less foreseeable. Rauch's (concept and) approach consequently meets the same fundamental problems as other approaches. Furthermore, franchise models are often based on simple products which can make Rauch's ideas basically work, but have less to do with complex products (such as automobiles) which disable the functionality of his ideas, even if Rauch claims that his approach for the derivation of production system requirements is generally valid and universally usable (p. 236). The fundamental problems mentioned above remain.

The complexity in factory planning is perceptible in all factory planning approaches. Whether these approaches are capable of handling this complexity against the backdrop of changes of the factory environment and some unconsidered characteristics and developments of today's factories with regard to their transformability is highly questionable, and this is reflected in subsections 2.2.7 and 2.2.9. The complexity in factory planning is discussed next.

2.2.4 Complexity in Factory Planning

Production system requirements change continuously. When the transformability of a production system is insufficient, it leads to a time-related complexity. The initial planning and what is and/or needs to be implemented drifts more and more apart. Finally, this can lead to a system collapse if the production system does not fit the requirements of the environment (Rauch, 2013, pp. 194–195).

Wemhöner (2005, p. 125) recognises the increasing complexity of technologies, products and FPPs, and claims that a reasonable handling of this complexity is a challenge. Product complexity leads to a complexity of factories (Graf, 2006). An automobile body consists of several hundred different sheet metal parts, while a body shop can involve a degree of automation of over 90% and more than 900 robots (Audi, 2015). The complexity of FOs/FSs and (e.g. multiple coupled) factory-related flows is recognisable in Helbing (2010). Grundig (2015) describes several guiding principles that must be considered for sensible general structure planning. Numerous parties are involved in factory planning (Grundig, 2015), while the complexity of information systems is already recognisable in the case of SMEs (Rezaeian and Wynn, 2016). In addition, lifecycles of products and FOs/FSs decrease more and more and have a significant impact on factories (Burggräf, 2012).

Klemke (2014) provides catalogues and tables which refer to diverse FOs/FSs, processes, laws and regulations. Numerous construction processes, objects and structures are perceptible when analysing StLB(-Bau), StLK (S-B) (Richter and Heindel, 2011), and DIN 276(-1 and -4) (Siemon, 2012). There are a multitude of DIN-standards/-norms (DIN, 2017). Different foundations and restrictions that are caused by water-related laws and regulations are identified in Fritsch *et al.* (2014); further laws and regulations are described in numerous other documents.

Burggräf (2012, p. 2) designates factory planning as a “Black-Box”, which is an open system with interdependencies and mutual influences between system elements. He describes the limitations of the use of algorithms in factory planning, and argues that mathematical models cannot consider framework conditions that are relevant for practice (pp. 31–32). This is in line with Syska and Lièvre (2016, p. 69), who recognise factories as chaotic and social systems that cannot be controlled through algorithms. Nevertheless, factory planning lacks a systematic description of complexity.

In order to handle the complexity in factory planning that is characterised by continuous data changes, two main supporting options exist: digital factory- and scenario-based planning. Digital factory-based planning is important (Bracht, Geckler and Wenzel, 2011) but has clear limitations, as physical limits cannot be ignored. To master the virtual world does not suffice, as the real world is decisive (Schenk, Wirth and Müller, 2014, p. 96). The advantages of digital factory are not questioned by the author. As (today's) factory planning is often based on highly questionable results of scenario planning, the following subsection is concerned with scenarios.

2.2.5 Scenarios in Factory Planning

Hernández (2002) and Wiendahl, Reichardt and Nyhuis (2015, pp. 377–381) differentiate "non-steerable and steerable key [(influencing)] factors". (The English designations are used by Wiendahl, Reichardt and Nyhuis (2015).) These key factors are comparable with 'change drivers', with the difference being that key factors "...are particularly significant for the object of consideration". This designation is used in scenario planning (p. 379). "Non-steerable key factors" are determined by the factory environment, while steerable ones can be determined by scenario and factory planners (p. 380). A scenario portrays a possible future development of all key influencing factors over time, while this development can occur with a probability 'p' (Wemhöner, 2005, p. 115). Scenarios mainly involve anticipations (Friese, 2008).

Scenarios are used to anticipate a factory status(es)/configuration(s) that presumably will be required in future (Friese, 2008). Hernández (2002), Witte and Vielhaber (2004), Wemhöner (2005), Rauch (2013) and other authors depend on knowledge about future requirements and use scenarios without serious consideration of aspects which are relevant for their use. Some statements with regard to scenarios are curious (see appendix 2.2.5 for details).

The complexity of the reality and the dynamic of its developments are partly recognisable by reviewing the previous subsections. Syska and Lièvre (2016, p. 72) claim that the more dynamic a factory is, the less possible it is to make forecasts.

Nevertheless, relevant impacts of these circumstances on factory planning have not been described to the required extent. There has been no explanation in the factory planning literature as to why it is hardly possible to make reliable forecasts for complex factories. Moreover, the limited transformability of terrestrial areas (and substructures) that furthermore decreases over time has not been appropriately considered. Even if it were possible to forecast future factory requirements, this would not lead to significant advantages, as the different factory configurations that are required over time exclude one another. This is only one pattern that demonstrates that no considerable benefits could be gained even if scenario techniques would work. Scenarios are a stopgap solution, but there is no other obvious way to anticipate the future.

2.2.6 Lifecycles in Factory Planning

Transformation process-related timeframes (Hildebrand, 2005, p. 46) underpin the short-term thinking in factory planning which is required against the backdrop of numerous fast changes of the factory environment. The dismantling and decommissioning of today's factories at the end of their lifecycle substantiate this short-term thinking (from a sustainability perspective). Numerous FOs/FSs cannot be reused and are scrapped, while others are demolished. Thus, today's factories are not sustainable. Sustainable solutions are either reusable and/or recyclable.

Products impact on processes and processes on FOs/FSs, and finally on factories (Schenk and Wirth, 2004). Different FOs/FSs are associated with different lifecycles (Wirth, Enderlein and Peterman, 2000). Hartkopf (2013, p. 41) talks about a capacitive factory lifecycle, and shows that lifecycles and capacities of FOs/FSs are aggregated through the entire factory lifecycle, which is characterised by continuous transformations. Hartkopf shows that transformations have an impact on the lifecycles of FOs/FSs, which is not considered by numerous other authors.

Although some impacts of factory transformations on factory lifecycles have been discussed, the frequency of occurrence of transformation requirements (i.e. transformation cycles) and the extent of their impacts (i.e. impact-types and outreach) remain unknown.

2.2.7 Transformability of Factories

Hernández (2002, p. 52) defines transformability as the proactive (e.g. reserved extension areas) or reactive potential of a factory to create a new configuration or reconfiguration of transformation objects with little effort in order to retain or to increase the efficiency of a factory. The transformability of factories is a system-characteristic/capability (Hernández, 2002). The higher the transformability of FOs/FSs, the better they can be transformed (sufficient area(s)/space(s) must be available).

Wiendahl, Reichardt and Nyhuis (2015, pp. 106–109) differentiate between “agility”, “transformability”, “reconfigurability”, “change-over ability” and “flexibility”, while “changeability” is used as superordinate term. These “classes of changeability” (p. 107) refer to long-term (or strategic), medium-term (or tactic) and short-term (or operative) transformation capabilities of FOs/FSs. Agility considers the factory environment and is strategically oriented. Whenever a factory requires physical transformations, transformability is involved. Physical transformation can happen quite rapidly compared with what is often a rather long (re-)planning time. “Flexibility refers to the operative ability of a manufacturing or assembly system to be able to reactively adjust itself ... by inserting or removing individual functional elements quickly and with minimal costs in regards to hard/software.”

The definitions of transformability and flexibility within the previous paragraph are relevant to this thesis and are further differentiated in the following paragraph. Changeability considers an organisational part. Therefore, the term changeability is not used in this thesis, as is the designation “change enabler” (Wiendahl, Reichardt and Nyhuis, 2015) for which ‘transformation enabler’ is used instead.

Reconfigurability can be assigned to transformability while it depends on the specific case if the change-over ability (which is comparable with retooling) that can not only happen reactively, as claimed by Wiendahl, Reichardt and Nyhuis (p. 108), but can in parts be prepared, is rather assigned to transformability or flexibility.

One difference between transformability and flexibility is the time required to perform a change. Transformability involves production system structures, while flexibility refers to a complementary characteristic of the transformability through which a production system can be adapted without a structural transformation (VDI 5201, 2017). Furthermore, transformability is more precisely defined by means of transformation enablers, objects and units, the transformation velocity, and the types of transformability which are described next.

Transformability can be separated into spatial, technical and organisational types (Hernández, 2002, p. 57). The organisational type is not considered in this thesis. Figure 6 indicates the types of transformability and the time character that can be allocated to different FOs/FSs.

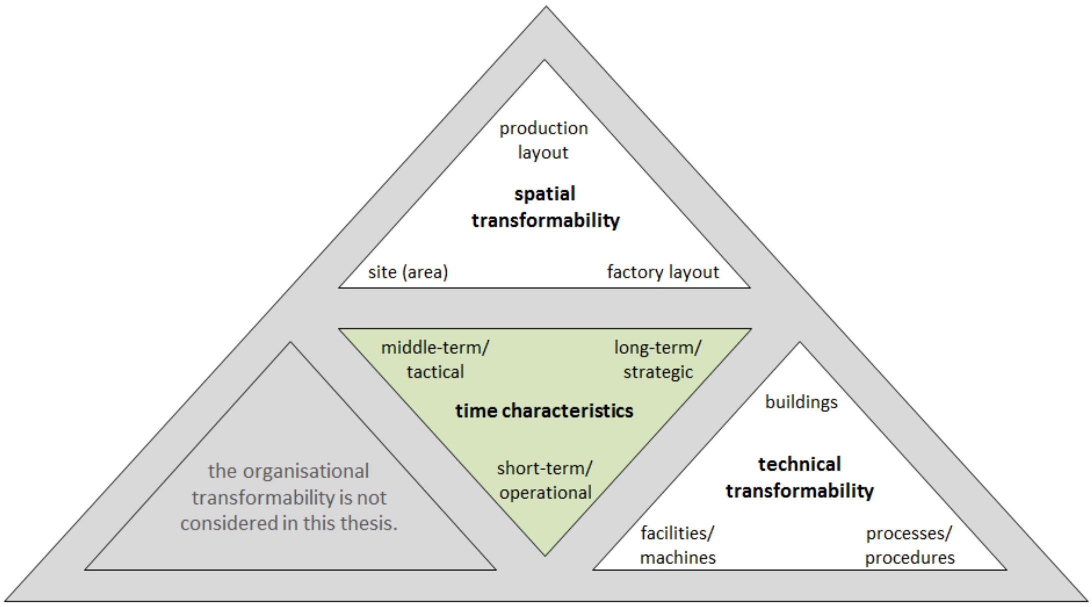


Figure 6: Types and time characteristics of transformability (modified) (based on Hernández, 2002, p. 57 and Wiendahl and Hernández, 2002)

Spatial transformability involves the scalability of today's factories, which is mainly determined by the 'breathability' of the site, factory and production layout. All technical systems, buildings, production facilities and processes are assigned to technical transformability. An area or building extension is strategic, a production layout or process change is tactical and a process facility adaptation is operational (Hernández, 2002, p. 58).

Transformation velocity is the speed within which individual FOs can be transformed to new customer requirements (Schenk, Wirth and Müller, 2014). This characteristic can be defined as the quotient of the transformation scope and transformation period (VDI 5201, 2017).

A 'transformation enabler' is a characteristic of an FO(/FS) that determines its transformability. Transformation enablers influence the transformability of FOs either negatively or positively, depending on their availability, as well as peculiarities and features within an object that must be transformed. Transformation enablers are consequently required to simplify and accelerate a transformation task (Hernández, 2002, pp. 54–56). The transformability of each object influences the transformability of a factory, which means that all transformation-related characteristics (or capabilities and limitations) of all FOs within a factory determine the transformability of the latter (Hernández, 2002). Hernández (2002) considers the transformation enablers "modularity", "mobility", "disintegration and integration ability", "expandability and reducibility", "function and utilization neutrality" and "linking ability" (Wiendahl, Reichardt and Nyhuis, 2015, pp. 96–102). Wiendahl, Reichardt and Nyhuis (2015, pp. 96–102) provide the English terms and definitions for these enablers, while the definitions of Hernández (2002, pp. 54–56) are mainly relevant for this thesis:

- Standardisable and pre-testable units/elements are basic ideas of "modularity". Modules are highly compatible units/elements which can be easily exchanged.
- "Mobility" enables the relocation of objects.
- "Disintegration and integration ability" enables the integration and disintegration of objects, products, parts and the like into given structures and processes (e.g. production lines).

- Spatial breathing of all types of areas is enabled through '(expandability/) extensibility and reducibility'. The latter allows an extension and/or reduction of different FOs(/FSs) to the X-, Y- and Z-axes.
- Numerous requirements, purposes/functions and tasks can be met/fulfilled by means of 'function and utilisation neutrality'.
- "Linking ability" enables different relationships, flows and statuses inside and outside of factories.

The use of brief designations is advantageous (Heger, 2006, p. 77). 'Extensibility and reducibility' have been renamed into "scalability", and 'function and utilisation neutrality' into "universality" in accordance with Heger (pp. 74–83) and Wiendahl, Reichardt and Nyhuis (2015, pp. 96–102), while their original meaning in Hernández' (2002) sense is valid for this thesis. 'Disintegration and integration ability' has been renamed 'pluggability', which compared to 'linking ability' is rather a technical linking ability. 'Linking ability' is rather flow-oriented and enables a networking capacity with regard to the general structure. Compatibility enables pluggability, as it allows the trouble-free combination and/or interaction of objects, while pluggability enables – together with the other transformation enablers – the linking ability of the general structure.

Transformation enablers can be allocated to 'dynamics', 'complexity' and 'connectivity' (or rather combinability) in accordance with Hernández (2002) and Wiendahl, Reichardt and Nyhuis (2015) (figure 7).

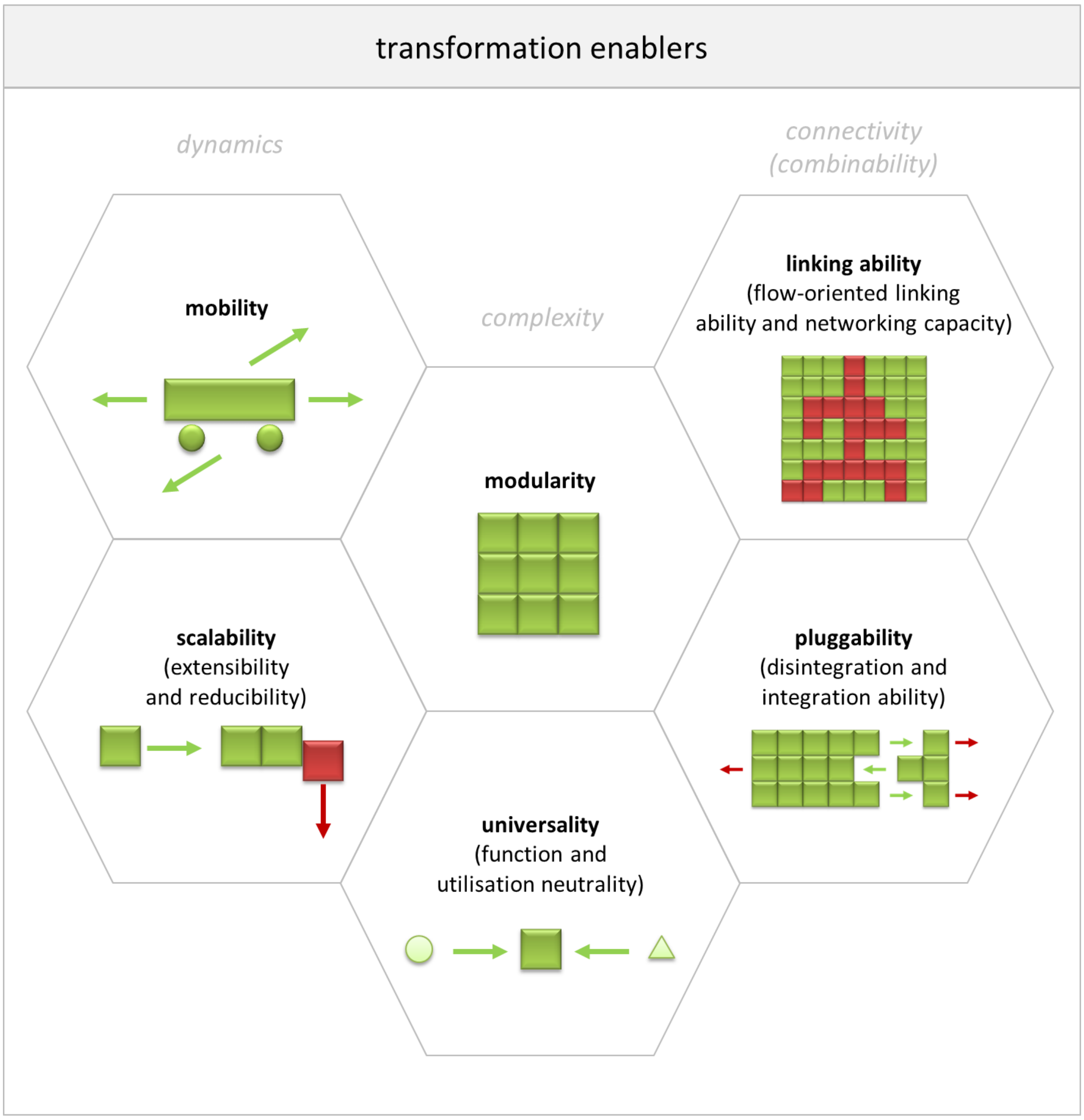


Figure 7: Transformation enablers (modified) (based on Hernández, 2002; Heger, 2006 and Wiendahl, Reichardt and Nyhuis, 2015)

Heger (2006, pp. 74–83) splits 'function and utilisation neutrality' into 'universality' and 'neutrality', while neutrality enables an object to have no negative influence on the capabilities of other objects.

When a transformation object can be combined with a transformation enabler, a transformation unit is created (Hernández, 2002, pp. 53–56). A transformation object, for instance, can be a workstation or a production line. Table 1 depicts disabled transformation units.

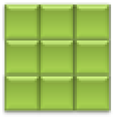
		transformation enabler
		modularity 
transformation objects	site (area)	**disabled transformation unit**
	general structure	**disabled transformation unit**

Table 1: Disabled transformation units (modified) (based on Hernández, 2002, p. 79)

Further limitations of transformability are considered in subsection 2.2.8.

Heger (2006), Velkova (2013) and Klemke (2014) consider inhibitors. Velkova (2013, p. 68) argues that inhibitors make the implementation of measures more difficult. Technical structures and buildings can be such inhibitors. Heger (2006, p. 70) identifies that for each FO a transformation potential must be objectively defined. This potential is based on the characteristics of a transformation object and its future transformation requirements. Heger (p. 97) discusses characteristics with regard to the area besides those of numerous further sub- and superstructures; obstacles and soil conditions, for instance, can be inhibitors. Klemke (2014) also acknowledges the importance of the transformability of factory sub- and superstructures. He has developed a method for their assessment which allows the definition of the status quo of single FOs/FSs, their transformability and actions required to perform their transformation. Klemke's method is partly based on catalogues that are used for the assessment of these objects and structures. Special attention is given to the area, since it has been subdivided into fixed and unfixed areas, the s&d infrastructure, and the transportation infrastructure. Interfaces of the external technical infrastructure are considered, the same as mutual influences between FOs/FSs.

The functionality of methods for the assessment and planning of transformability and of transformations is partly open to question, especially in the light of today's real-world factories, and their complexities and developments. To use such methods is not practical and is cumbersome.

A homogenous and consistent definition of transformability-related theories is not available at present. Methods for the assessment and planning of transformability and of transformations are hardly distinguishable and overlap in part with factory planning approaches. Even though these methods involve more details regarding how the transformability of factories can be assessed, the following aspects must be considered: It is necessary to define the delta between an 'as is'-status (current status) and a 'to be'-status (target status) of a factory (or all impacted FOs/FSs) that must be implemented (and/)or transformed. This delta enables factory planners to define actions/FPPs that must be performed in order to reach the desired 'to be'-status. Both the desired 'to be'-status of a factory that must be implemented (and/)or transformed and the corresponding status of the transformability of this factory must be anticipated, assessed and planned. This means that besides the 'as is'-transformability, the 'to be'-transformability must be assessed and planned in addition to the corresponding factory statuses. Not necessarily only one but optionally several 'to be'-statuses (at different points in time) which should turn into future 'as is'-statuses must be anticipated, assessed and planned. These statuses impact on one another, which is particularly valid and problematic for today's factories. Besides other factors such as decisions, the number and characteristics of considered (but often unlikely) future statuses determine how the first (and further) 'as is'-status(es) is transformed, while the transformability of the latter significantly influences the possibilities and consequently the planning. When the lifecycle of one factory of one company is reflected, only the first 'as is'-status (e.g. of the site) that is to be transformed does not need no be anticipated, as it is given. Nevertheless, the site (and given FOs/FSs) must be investigated in order to define its characteristics. In sum, the (number and types of) deltas between considered statuses determine the required FPPs that must be performed in order to reach the desired 'to be'-statuses (in this case, the word 'considered' implies decisions etc.).

A problem with today's factories is that a transformation can negatively impact on their transformability (Hernández, 2002; Heger, 2006; Klemke, 2014; Grundig, 2015). That the 'to be'-status(es) must be anticipated is a further limitation. As a consequence, the abovementioned methods and approaches meet the same problems. To date, this has not been adequately considered.

Inner and outer mobility have been described by Wirth (2000) and Wirth, Enderlein and Peterman (2000). Inner mobility refers to the ability of a factory to relocate different FOs within one location. This mobility type is relevant for (inner) factory transformations, whereas outer mobility is concerned with the ability of FOs to relocate to new sites. Examples that enable outer mobility are containers and modular building structures (Schenk, Wirth and Müller, 2014). Outer mobility has a strong influence on transformability, since it enables relocations of process facilities and modular factories.

2.2.8 Requirements and Limitations of Transformability

This subsection provides an overview of important requirements and limitations of the transformability of factories that have been recognised.

Kraemer (2013, pp. 106–107) argues that the location and the site are elementary factory elements, as they involve essential basics for the transformability of a factory. The site determines the development and shaping of functional areas inside and outside buildings. Locations and sites should be chosen carefully. This has been considered by Heger (2006, p. 97), who assigns potential 'growth areas', 'growth directions' and 's&d infrastructures' to the area-scalability. That the amount/ number of these areas and directions must be considered, is shown in Hernández (2002, p. 89).

According to Helbing (2010, p. 342), each factory system should have an extension area of up to 20%. Extension areas are required not only for factory extensions but also for other transformations (e.g. system element replacements). Helbing (p. 243) recognises that FOs/FSs are mutually dependent, and claims (p. 90) that practical experience confirms that the replacement of one machine can lead to the requirement to move, rearrange and fix 20 others. Furthermore, Helbing (pp. 572–580) discusses displacements of FOs/FSs that require spaces/rooms. An area-related and spatial dimensioning of FOs is also considered (p. 199), the same as a process-dimensioning through the consideration of FOs/FSs, pits, floor loads and numerous other area-related characteristics (pp. 232–235). Types and characteristics of different process flows (e.g. multiple coupled flows) (pp. 200–208) in combination with the other information in this paragraph provide a hint of both 'changing transformation requirements' and transformability requirements of areas and factory substructures.

That requirement-conforming machine-installation, 'spatial-technical definitions' and standardisations are crucial for a proper functioning of factories was indicated by Kettner, Schmidt and Greim (1984). According to Göpfert (1998), standardisations of technical modules and their interfaces can help to handle complexity and meet transformation requirements. The importance of standardised plug-in slots, interfaces and a flexibility in this regard have been recognised by Heger (2006). Nofen, Klußmann and Löllmann (2013, p. 17) argue that through the standardisation of technical modules and their interfaces it can be ensured that modules are easily scalable and exchangeable. Standardisations are considered by Heger (2006) due to their frequency of occurrence, while customisations can be ignored (p. 78); this is not advisable, as they are both relevant.

Standardised area-modules increase the transformation potential (Heger, 2006, p. 99). These area-modules are not real modules, but are rather area parcels. This is in line with Hernández (2002, p. 79), who claims that the production layout is the only spatial transformation object to which the modularity can be allocated, and that the spatial arrangement of areas that involve a homogenous function can be understood as an area module.

Bergholz (2005, pp. 3–4) claims that the definition of an optimal transformability-degree is a challenge. He speaks about a trade-off between this degree and stability. Klemke (2014, p. 4) talks of an activation effort, while Westkämper and Zahn (2009, p. 14) argue that transformations should be performed quickly at the lowest possible cost. Factory structures should be independent (Heger, 2006, pp. 75–76). Hildebrand *et al.* (2004) argue that the modularity and mobility of factory structures are crucial requirements of factories. Nofen, Klußmann and Löllmann (2013, pp. 26–27) claim that modularity is the most important transformation enabler. Grundig (2015, p. 28) talks about a modularisation and standardisation of areas and elements within rooms that can be flexibly combined, the use of flexible industrial structures that are demountable and reusable, and a targeted oversizing of FOs/FSs. Schenk, Wirth and Müller (2010 p. 7) claim that the transformability of "production facilities ... is becoming a top priority for modern enterprises". Workstations within transformable factories must be structure- and location-flexible (Schenk and Wirth, 2004, p. 136). Furthermore, production processes should neither be disturbed nor interrupted during a transformation; required production stops should be minimised (Grundig, 2015).

Wiendahl, Reichardt and Nyhuis (2015, p. 115) talk about "breathability" and "utilization neutrality" with regard to "adaptive buildings". Pre-tested and movable building modules are a requirement of transformable factories. Sufficient building height, high loading capacity of the supporting structure and large column grid spacings are, in addition to transformable façades, requirements of buildings (Hernández, 2002, pp. 141–144). Furthermore, the area should not be partitioned/segmented by interfering contours/structures such as columns and walls. Other interfering contours/structures are s&d facilities and infrastructure elements inside buildings (e.g. building control systems, extraction systems, ventilation shafts, water pipes and other media routes). The usable building area is more flexible for future transformations with regard to personnel, material and production flows without such disturbing contours/structures (Wiendahl, Reichardt and Nyhuis, 2015).

Wirth, Erfurt and Olschewski (2003) have recognised the importance of the mobility of factories and buildings. Fink (2003) describes the need for flexible s&d infrastructure. In addition, the importance of mobile foundations has been indicated by Fink. Helbing (2010, p. 90) recognises that the relocation of FOs/FSs has become fashionable.

Wiendahl, Reichardt and Nyhuis (2014, p. 129), the VDI 5200 (2016) and Hernández (2002, pp. 71–74) claim that areas are immobile. Hernández (p. 79) claims furthermore that area-modularity is not possible. Wirth, Enderlein and Peterman (2000) do not consider the modularity and mobility of areas when discussing the inner and outer mobility of different FOs. The same applies to Enderlein *et al.* (2002, cited in Schenk, Wirth and Müller, 2014, pp. 216–217), Günther (2005) and numerous other authors. Transformations of sites/areas and substructures cannot happen by means of the active transformability of areas (to which access is denied) if terrestrial areas are used.

Hernández (2002) stresses repeatedly the importance of function- and utilisation neutrality, and argues that a preferably square-shaped area leads to utilisation neutrality. Furthermore, continuous area-neutrality (which means homogeneous soil condition and stability with no differences in level) is preferred. The arrangement of buildings and further FOs which can only be moved/relocated with huge effort should be done sensibly in order to preserve the transformability (p. 79). Heavy production facilities should be located at outer positions of the factory layout to create large utilisation-free (i.e. neutral) areas in the centre that are not restricted through fixed points. The importance of the linking ability – which reflects the main flow capabilities – has been partly identified, as Hernández recognises the requirement for a gapless supply network and system (pp. 143–144).

Nevertheless, Hernández (2002) concludes that the transformability of areas is not relevant in the light of required transformation scopes. The general structure and site(/area) are uncritical transformation objects, as both imply only minor transformation requirements (pp. 144–146). Hernández' scenarios led to a factory solution that involves a TBS (pp. 145–146), which is shown in subsection 2.3.1.

These statements were made based on a scenario-related application example that considers, compared to automotive OEM plants and similarly huge complex factories, a small simple factory. Furthermore, the number of key factors has been limited and a time horizon of seven years considered, which is a further simplification of the real complexity and related developments. Moreover, probability theory and the limited transformability of factories which decreases further over time have not been considered. Therefore, Hernández' (2002) results have little to do with huge complex factories – especially over long periods of time. Areas are not relevant to Hernández from a transformability perspective and this makes little sense if huge complex real-world factories such as numerous OEM plants and their developments are considered.

Wiendahl, Reichardt and Nyhuis (2009, p. 140) recognise that the transformability of the layout/general structure is required. Grundig (2015) emphasises that the area and general structure are important for the transformability of factories.

This subsection shows both that diverse statements are conflicting and that a 'traditional terrestrial area-related way of thinking' dominates factory planning. All area-transformability-related solutions have in common that potential future area-related transformation scopes must be predefined and reserved. Such reserves determine factory layouts. The importance and significance of the transformability of areas and factory substructures (and of the general structure) are far too underestimated, which directs factory planning. That terrestrial areas are taken for granted is probably one reason for this, and is why their transformability is not questioned appropriately.

2.2.9 Summary

Available factory planning theories provide important information and, to some extent, a good basis for further development.

That a transformation can negatively impact the transformability of today's factories has been recognised. This is a problem if transformation requirements change during a project or afterwards. On the one hand, factory (implementations and) transformations should be planned accurately and in enough detail, while the 'as is'- and 'to be'-statuses of all FOs/FSs involved must be appropriately considered. On the other hand, transformations should start as early as possible, as the transformation velocity is low if terrestrial areas and/or rigid structures are significantly impacted. If a transformation, for instance, is performed with a line of least resistance attitude in which rigid objects and structures are the outcomes, changing transformation requirements (during a project or after its completion) cannot be processed and absorbed as required. The limited and furthermore decreasing transformability of today's factories and permanent changes of the factory environment are consequently not sufficiently considered, and it is highly questionable whether these factors and their consequences can be handled appropriately with today's factories. This is not sufficiently considered in the factory planning literature. Furthermore, the assessment and planning of 'as is'- and 'to be'-statuses of FOs/FSs, and of their 'as is'- and 'to be'-transformability is not sufficiently thought out, as it can neither be completely delimited nor completely combined – at least not within today's factories where transformations significantly impact the transformability, or rather rigidity and inhibition.

Scenarios are used to define the 'to be'-status(es) of a factory, which is hardly possible for huge complex factories. The 'to be'-status(es) is required for all factory planning approaches and methods for the assessment and planning of transformability and of (implementations/)transformations, which leads to their poor operation. Furthermore, even if these scenarios, approaches and methods were to work, no considerable advantages could be gained, as the practice of factory planning is not sufficiently considered (e.g. the limited and furthermore decreasing transformability of today's factories).

The question is how far the abovementioned approaches and methods can be improved at all when today's factories are involved. Notwithstanding this, terrestrial areas have not been considered in factory planning theory in a way that is capable of showing their importance. Transformation requirements for areas have also not been sufficiently described, as is the case with the limitations of today's factories and factory planning theories. These theories are relevant for practice, as they are used by factory planners. The new model may lead to advantages for both theory and practice.

2.3 The Technical Status Quo of Factories, Areas and Area Systems

This section is concerned with factory superstructures, terrestrial areas, factory substructures, and area systems.

2.3.1 Factory Superstructures

Besides traditional FOs/FSs, there are also modern ones (which in this thesis means transformable). This subsection provides an overview of the technical status quo of factory superstructures.

Diverse definitions with regard to FOs/FSs can be found in the literature. It was reasonable to classify these FOs/FSs into buildings and building structures, building contents and further FOs/FSs that can be partly comprised by other FOs/FSs and/or located outdoors, before providing information about factory sections (which require section-/user-specific building characteristics and building contents) and further outdoor objects.

Helbing (2010, p. 362) defines a building as a foundation-based superstructure with floors, walls and a roof. A building provides a usable area and volume with openings and connections to the technical infrastructure. In addition, internal and external influencing factors or variables (e.g. climatic influences and roof loads) are indicated by Helbing, who provides information about different building, building structure and building system types (pp. 753–777). A building is a central entity for the coupling of the s&d infrastructure with different kinds of building contents since it provides the room for required interfaces and a protective shell against environmental influences such as mechanical and thermal loads. Furthermore, buildings provide interfaces to suppliers and room for required inputs and outputs (Hildebrand, Mäding and Günther, 2005, pp. 113–116). Thus, a building serves as a protected place for the production of industrial goods (Schenk, Wirth and Müller, 2010, p. 9).

Based on Hildebrand, Mäding and Günther (2005) and Wiehndahl, Reichardt and Nyhuis (2015), the following wording and definition are used in this thesis: A building is a foundation-based FO with a supporting structure, shell, s&d facilities and infrastructure, and an interior construction. The building type used for this thesis relates to industrial hall constructions (multi-storey buildings are, in the main, not considered, but discussed in appendix 6.2.1_01).

Today, modular building structures enable lean construction performances but are hardly transformable, as their building elements often cannot be separated non-destructively (Günther, 2015). Solutions for modular production halls and structures are also available (Jordahl GmbH, 2012). Such structures can be partly separated and reused, but this does not apply to complete buildings.

Matt, Rauch and Franzellin (2013) outline the technical status quo of pre-producible solutions for transformable building structures and their manufacture. Künzel and Kott (2003a) present options of modular building elements which can be dismantled and reused. Hildebrand, Mäding and Günther (2005, pp. 117–121) discuss a reversible steel skeleton building. Such structures lead to lifecycle advantages (Künzel and Kott, 2003b). Unfortunately, transformable solutions are not extensively implemented in practice (Kraemer, 2013, p. 103; Reichardt, 2016). Nevertheless, transformation requirements have led to transformable building structures by which buildings can be transformed. Transformable buildings which are based on a modular construction are available (Wiendahl, Reichardt and Nyhuis, 2015). These buildings can be more easily transformed than brick buildings and those that are only based on building modules but are not transformable. Heger (2013, pp. 134–135) discusses a transformable assembly hall with a modular supporting structure, shell and (building-related) s&d infrastructure which can be extended with little effort and has been implemented in practice. Figure 8 depicts such a transformable building which is based on a modular and lightweight steel-construction, elements of which can be relocated. It involves characteristics that are sufficient to cover the transformation requirements of the considered scenarios (in Hernández' thesis), as claimed by Hernández (2002, pp. 145–146).

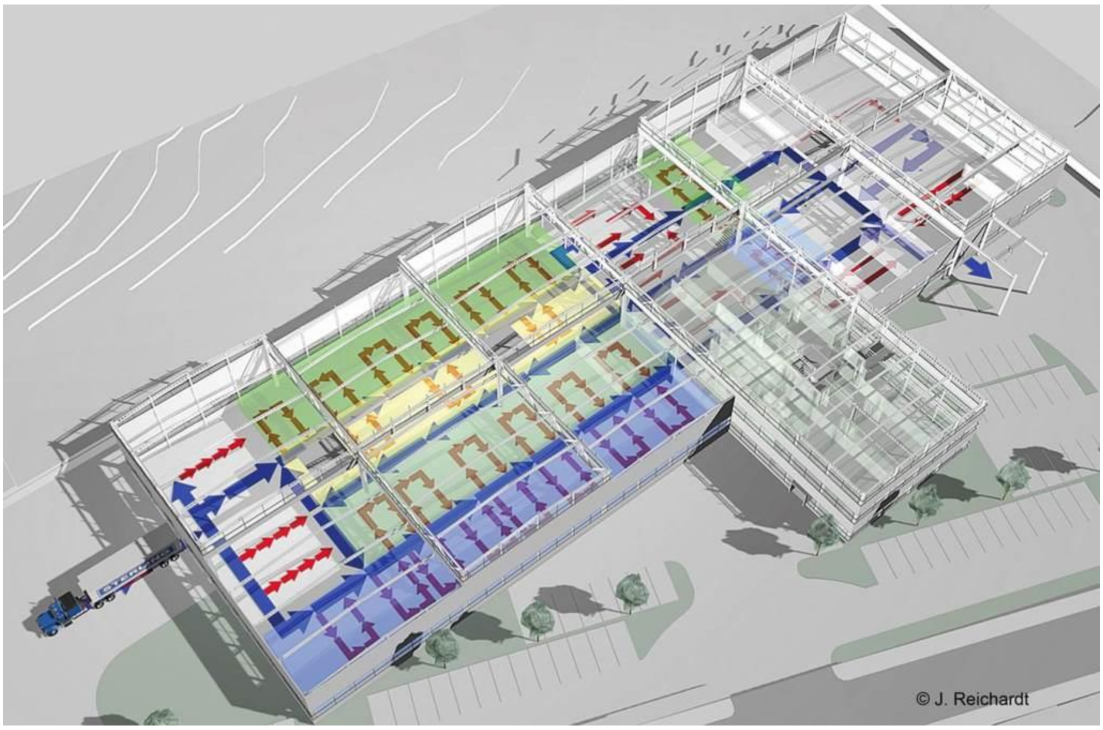


Figure 8: Example of a rough 3D layout (IFA 15.512 E_B) (used by permission of the originator: Jürgen Reichardt)

Heger (2013, pp. 136–137) states that initial investments for transformable solutions are higher compared to rigid ones, while from a long-term perspective transformable solutions are often more beneficial, as future transformation costs are lower, which in sum lead to lower total costs of ownership. The greater the number of transformable solutions that are desired, the more their costs will decrease.

Real-world examples of transformable building structures can be seen in Reichardt and Wiendahl (2009, p. 399) and Hildebrand, Mäding and Günther (2005, p. 120). Goldbeck (2016) presents solutions for factory halls that are transformable with regard to their basic shape. In addition, column grid arrays and spacings are transformable, the same as façade elements. Further buildings consist of containers (Kleusberg GmbH & Co. KG, 2013a; Kleusberg, 2016a; Kleusberg, 2016b), while other examples of transformable buildings are available (Kleusberg GmbH & Co. KG, 2013b). Additional transformable superstructures and related construction technologies are compiled in Llinares-Millán *et al.* (2014). Naboni and Paoletti

(2015) provide an overview of different solutions with regard to building designs, architecture and construction. These solutions focus on customisation, while related production facilities and processes are also considered. Besides transformable factory building designs, modular and movable assembly lines and production facilities are presented in Dashchenko (2006a) and ElMaraghy (2009). A selection of modern FOs/FSs is presented next.

Production systems comprise diverse FOs/FSs such as production lines, cells, machines, conveyors, racks and operating equipment. Positions of process facilities change (Helbing, 2010). Fixed process facilities are therefore a problem. Such intransformable facilities were the starting point for the development of modular production cells (Klug, 2010, p. 411–414). According to Schenk, Wirth and Müller (2010, p. 119), process facilities should be flexible and foundation-free.

‘Competence cell’-based production facilities are mobile and foundation-free (Näser and Ackermann, 2003). Schenk, Wirth and Müller (2014, p. 540) recommend a transformable over-roof s&d infrastructure for the combination with such facilities. The ‘MobiCell’, for instance, is an autonomous, modular and movable production unit that is used in body shops. A basic steel frame, in which welding and/or handling robots, different modular devices, and control cabinets can be integrated, is the basis for this cell. The inner and outer mobility of these cells is enabled, while trucks, forklifts and/or cranes are required for their relocation. Reusability leads to advantageous total costs of ownership (Meichsner, 2007; Breitenbach, 2013), similarly to the advantage that parts of MobiCells can remain untouched when a transformation is performed. Such cells have increased the availability and flexibility of production systems, and can be demounted, relocated and integrated much faster than traditional solutions (e.g. fixed robots) while solitary and/or more flexible lines can be created and changed again later depending on the latest requirement (Meichsner, 2007). Meichsner (2007, p. 79) mentions different requirements such as pre-testability, simple extensibility, and type-independent subsystems. In addition, appropriate substructure-requirements must be given. Meichsner (2007) uses MobiCells for the creation of flexible production layouts and recognises that displacement efforts can be reduced by increased mobility. Similar solutions are provided by Kiel (2013), and Wemhöner (2005) provides theories that support such solutions. Nevertheless, material flow systems such as conveyor systems are required (Klug, 2010, p. 414).

Conveyors amalgamate production and logistics within factory sections. Today, conveyor-based assembly lines are often rigid systems. Slat, skillet and monorail conveyors, for instance, are often hardly reducible or extensible; some conveyor systems involve turning, lifting, rotating and/or tilting functions which can also inhibit their transformation. Despite such rigid systems, flexible assembly and production lines are available (Mößmer, Schedlbauer and Günthner, 2007). Such lines can be based on automated guided vehicle systems (Audi, 2015). These systems were first viewed as too expensive or uneconomic. Their development forecast was not promising due to the economic situation and the technological status quo at the end of the 1980s (Ullrich, 2015, pp. 8–17). New developments in vehicle, navigation and other technologies finally laid the foundation for their comprehensive implementation (Ullrich, 2015, p. 10). Thus, high initial investments in new technologies are not necessarily decisive for their future development. Snowman (1997, pp. 214–216) presents an example with regard to different lyophilisation processes in which automated solutions led to advantages in terms of productivity and consequently to the possibility to decrease costs. This validates the concept that new solutions can lead to advantages in niches first and can finally influence other areas positively. Further modular and transformable structures are provided by Heinecker (2006, p. 121), Complete Logistics Systems international GmbH (2016) and many others. Next, s&d facilities and infrastructures are outlined.

Grundig (2015) recognises the requirement of a flexible s&d infrastructure that can be changed with regard to its position. S&d infrastructure networks and elements can be under, in and above floors/the ground inside and outside buildings (pp. 212–214). The importance of the roof and floor load capacity has been recognised in this context (Felkai and Beiderwieden, 2015, p. 91). That relocatable non-load bearing walls, floors, false ceilings and break-throughs are relevant for the laying of s&d infrastructures has been indicated by Schenk, Wirth and Müller (2014, p. 198).

Fischer (1997) and Waurig (2013) provide solutions for modular s&d systems/ facilities. The USPTO, EPO, GPTO and other patent and trademark offices provide numerous additional solutions in this regard. Furthermore, modular infrastructures such as ventilation shafts are available. Geberit Vertriebs GmbH (2017a; 2017b) provides modular and pluggable pipe-systems. Heger (2013) discusses cablings; cable bundles with numerous cables can either be connected separately to a control cabinet or preassembled in a plug. The variant with the plug is initially more time-consuming and expensive but leads to advantages when transformations must be processed (p. 138). Information about factory sections and outdoor FOs/FSs is presented below.

Different factory sections involve different requirements. A paint shop with diverse facilities and basins differs from a press shop which involves deep-drawing presses. That these and further factory sections and their FOs/FSs differ is shown in Klug (2010), although this author emphasises logistics-related objects rather than factory substructures. Area requirements are partly described, but Klug (2010) does not focus on them. Conveyor systems are overarching systems which can be located within different user-specific buildings, involve different area and substructure requirements, and cross building borders (Klug, 2010). The same applies to technical infrastructures. Different FOs/FSs are furthermore located outside buildings (e.g. s&d plants), and in the area (Helbing, 2010). However, factory substructures are often ignored or put in second place in factory planning and factory-related literature.

Several of the modern solutions in this subsection are partly specific to factory sections (e.g. MobiCells for body shops). Nevertheless, specific requirements often cannot be met by available approaches of transformable factory. This is inherent in the system, as changes are performed within given system boundaries, which lead to demolitions, reconstructions and new constructions. Furthermore, the timeframe in which changes can be performed cost-effectively and without significant delays during the planning and implementation of factories is short (Sredic, 2011).

Transformable factory superstructures are available. The presented solutions have so far not been combined into concepts. This is done in this paragraph so that they can be used in this thesis. Available transformable building solutions were combined into 'transformable building systems' (TBSs) and available production, logistics and s&d facilities, and s&d infrastructures into 'transformable factory objects/structures' (TFOs/TFSs). The designation 'transformable building contents' (TBCs) is used where appropriate to discuss TFOs and/or TFSs inside buildings. TBSs are modular, mobile (or movable/transportable), scalable and pluggable, while TFOs/TFSs are at least modular and mobile/movable. A TBS can also take the designation TFO.

'Rigid factory objects/structures' (RFOs/RFSs) are fixed and cannot be relocated without earthworks and/or demolitions. Furthermore, due to their characteristics (e.g. size, weight and/or fixing), RFOs/RFSs are either hardly or not at all movable. 'Rigid building contents' (RBCs) summarise RFOs and/or RFSs within buildings or refer to these. The following subsection is concerned with terrestrial areas and factory substructures.

2.3.2 Terrestrial Areas and Factory Substructures

According to Felix (1998, p. 32), besides energy, information and others, area is one factor that must be converted in order to fabricate products. Kuhn (1995; 1997) recognises area as a limited logistical resource. Scanlan (1974, p. 7) argued that "...the problems of locating the factory near rail and highway transportation limit the available sites for such factories ... Accordingly, the area that can economically be served by permanent factories is definitely limited."

Different typologies of areas exist. Koether *et al.* (2001, pp. 53–54) differentiates between open and closed developments. A closed development is characterised by buildings that are not separated by roads, while an open development involves roads between buildings. Wiendahl, Reichardt and Nyhuis (2009, pp. 368–373) consider footprints of single buildings, while centralising and decentralising factors determine their development. Buildings with a high fire risk, for instance, should be decentralised, while areas and buildings that belong together functionally should be centralised to enable efficient processes. Further information about the classification of areas can be found in DIN 277. Helbing (2010) differentiates between free, supply, disposal, maintenance, logistics, assembly, production and other areas. Areas for different types of movements are also differentiated.

Substructures (e.g. foundations) are not always large individually cast units, but can also be modular. Transportation infrastructure modules are available (Kluth and Jäger, 2013). Furthermore, pre-produced foundations and related elements are available (Vroom Foundation Technology N.V., 2017; Voorbij Funderingstechniek B.V., 2017). Modular substructures which include combinable modules can also be used as water reservoir(s) (Finger Baustoffe GmbH, 2017). Concrete modules are also used along infrastructure canals (Max Bögl Bauservice GmbH und Co. KG, 2015) and tunnels (Friese *et al.,* 2005). Such objects can only be moved/relocated by means of cranes etc. Furthermore, building structures and contents of factory sections of OEM plants have special requirements for their substructures which limits the possible use of such objects.

Such requirements can be seen in Wiendahl, Reichardt and Nyhuis (2015, pp. 267–270). The importance of interfaces between FOs, areas and the s&d infrastructure is crucial for the proper functioning of factories (Hernández, 2002, p. 71). Process facilities require different types and designs of foundations for vibration insulation (Schenk, Wirth and Müller, 2010, pp. 162–167).

Foundations must be designed properly in order to prevent the transmission of mechanical vibrations from the area to a part and vice versa (Kettner, Schmidt and Greim, 1984; Braun *et al.*, 1996; Heinzler *et al.,* 1997). Hydrogeology combines geology and hydrology and is important for civil engineering and factory planning. Groundwater is significantly important for civil and construction engineers (Thurner, 1967; Henningsen, 1982; Hölting and Coldewey, 2013). It can impact soils, objects and structures and vice versa, which can have negative impacts on construction processes, costs, timelines and the environment. Water law-related aspects must be considered besides (further) environmental aspects. A surface foundation, for instance, requires different approval processes than a deep foundation. Such differences are relevant for sections and involved FOs/FSs (Majstorović, 2017). Asbestos, other contamination and archeological aspects are also relevant for earthworks and substructure construction works (Helbing, 2010).

A homogeneous soil condition and stability with no differences in level are desired, as these reduce area-related works (Hernández, 2002, p. 79). Terrestrial areas can involve homogenous and inhomogenous conditions, and comprise different layers. Relevant backgrounds which show that the desired conditions are rather unlikely to be found for huge sites (e.g. OEM-sites) are described in Redlich, v. Terzaghi and Kampe (1929), Bendel (1944; 1948), Prinz and Strauß (2011), Genske (2014) and Ameratunga, Sivakugan and Das (2016). The following paragraphs provide information about area- and substructure-related works and processes.

The acquisition and development of land requires time. Litigation land, for instance, is often a problem when landowners do not want to sell their properties or proceed tactically in order to receive more money. Further restrictions can be identified during the site investigation. These restrictions might lead to consequences in terms of floor load allowance, water law and many other matters. Unexploded ordnance and contaminations are often a problem (Huber, 2017). After the land acquisition and required approval processes, the ground investigation can take place. Ground investigation can also occur before the acquisition of land (Majstorović, 2017). Ground surveys and soil investigations are required when site conditions are unclear. Soil samples etc. provide information about relevant area characteristics (Ameratunga, Sivakugan and Das, 2016), but site conditions remain partly unclear since the complete site often cannot be investigated (Majstorović, 2017). Approvals are also required for area-related and building construction works (Helbing, 2010; Schenk, Wirth and Müller, 2014; Grundig, 2015). First, land levelling and excavation works are undertaken. Foundation works can then proceed while infrastructure works often begin in parallel with area-related works (existing infrastructures must be appropriately considered, for example connections to the external infrastructure). Superstructures can then be erected.

In sum, factory projects require approvals, area-related preparation and earthworks (e.g. excavations of pits) prior to the construction of sub- and superstructures (Max Bögl Bauservice GmbH und Co. KG, 2015; 2017; Huber, 2017; Majstorović, 2017). Land levelling requires geomaterials to be brought to the construction site if the available on-site materials do not suffice. Minimisation of the amount of these materials, for instance, is possible through the definition of an optimal ground surface or base level (Zhang, 2008; Nassar and Hosny, 2012; Parente, Cortez and Correia, 2015). The number and types of available machines and equipment determine the duration of earthworks and construction works, the same as the volume of geomaterials (m^3) and the maximally possible load volume rate (m^3/h) (Parente, Cortez and Correia, 2015). According to these authors (p. 6674), "earthworks are [often] the most costly and time-consuming component of infrastructure constructions...". Earthworks should also not be underestimated in factory projects. Excavated (geo)materials must be relocated and transported to soil depots (Majstorović, 2017). Excavators, trucks, compactors and many other machines and equipment (e.g. for energy generation and water supply) are required and are also relocated (e.g. to free construction site areas) (Huang and Wong, 2015; Parente, Cortez and Correia, 2015). Besides excavations, filling, compaction, and transportation, wetting to reduce dust and dirt takes place. Large amounts of energy, fuel and other resources are often consumed (Günther, 2015; Parente, Cortez and Correia, 2015). In the context of construction sites, "noise", "construction wastes" and the removal of forests are described (Lui, 2004, pp. 4–7).

Labour-intensive site development and construction processes can still dominate construction sites. Human activities, behaviours and failures have an influence on these processes. Furthermore, mixing ratios and chemical properties have an impact on numerous processes such as the hardening of foundations which requires scheduled waiting periods. These physical and chemical processes can hardly be ignored. Advanced construction processes and stronger machinery use cannot change this circumstance (Günther, 2015; Majstorović, 2017). Safety at construction sites is a further important aspect (Saurin, 2016).

2.3.3 Recapitulation of the Previous Sections

Today's factories are based on immobile and rigid terrestrial areas and substructures. Therefore, the technical status quo of areas and substructures of factories has not changed since the first industrial revolution. Despite the optimisation potential of construction site-related processes by means of methods for the optimisation of earthworks and construction processes (Zhang, 2008; Nassar and Hosny, 2012; Parente, Cortez and Correia, 2015) and site facility arrangements and relocations (Huang and Wong, 2015), terrestrial areas do not fit with modern sub- and superstructure solutions. The active transformability of terrestrial areas and substructures is disabled, which makes the latter two more resistant to transformations than TFOs/TFSs, and limits the implementation and transformation capabilities of today's factories. Area-related construction processes are inefficient and far away from those that are enabled through modern solutions such as TBSs. Nevertheless, such transformable solutions also require foundations which are embedded in terrestrial areas.

It can be recognised in Grundig (2015) that the transformability of the general structure is limited through terrestrial areas. This is in line with Friese (2008, p. 2), who argues that the potential to increase the capacity of a single factory is limited to numerous structural adjustments. Sredic (2011) emphasises the importance of area size and shape, which limit the transformability of today's factories. Kraemer (2013, pp. 104–105) talks about "Vereinigte Hüttenwerke", which can be translated as 'united huts plants' (UHPs), and states that all transformations in sum lead to this factory status. He argues that the more transformations take place, the more difficult it becomes to define the right point in time to relocate a factory to another site that involves an optimal new factory environment. A UHP is a conglomerate of numerous different FOs/FSs that can overlap and be intertwined. Such factories are unstructured, disordered, non-transparent and neither efficient nor otherwise advantageous in relation to other factory requirements.

Area systems are capable of increasing the transformability of factories and production networks (Sredic, 2011) and could be capable of preventing factories becoming UHPs. Area systems are discussed in the following two subsections.

2.3.4 Terrestrial Area Systems

This subsection is concerned with terrestrial area systems, while maritime ones are presented in subsection 2.3.5. All area systems are composed of modular units (area system elements) that can be plugged and linked together. (‘Combinability’/‘combine(d)’ can be used to indicate or to refer either to both ‘pluggability’ and ‘linking ability’ or to only one of these. The terms ‘plugg(ed)’ and ‘couple(d)’ are used synonymously in this thesis. ‘Link(ed)’ is rather used to refer to the ‘linking ability’. ‘Dock(ed)’ can also be used for the ‘pluggability’, ‘linking ability’ or both transformation enablers.) Terrestrial area systems require a substructure for area system elements, while most maritime area system elements do not require a substructure due to being located on water.

One could argue that movable racks are a mix of simple area systems and factory superstructures. Simple area systems (e.g. Ukitecture, see subsection 2.3.5) determine area characteristics, while in the case of movable racks the area determines the characteristics and capabilities of the latter. Movable library racks, rocket launching sites with movable structures, musical/concert platforms that can be prepared before a show (while another show is performed on another platform on the stage) and afterwards rotated or moved to the stage, and CNC machines with rotating or shuttle tables are further examples for which the last statement is valid. These examples are superstructures and involve mainly no fundamental area functions. Rubio-Bellido, León-Muñoz and Pulido-Arcas (2014) discuss transformable basement structures which can be seen as light versions of area systems, because they can build the basis for superstructures but are incapable of carrying high loads, besides other aspects that are involved by the area systems that will be presented next.

Sredic describes two terrestrial area systems: ‘Hydrofield’ (2012d) and ‘Railfield’ (2015). Both involve similar movable area system elements, although their substructure differs. These elements are comparable with those of the maritime area system 'Bluefield' (Sredic, 2012b; 2012c), but are simpler because fluid tank-systems are not required.

Railfield is based on rails that can be optionally combined with conveyors and/or drives, while conveyors can also completely replace rails (further options exist). This enables a movement of the elements (figure 9).

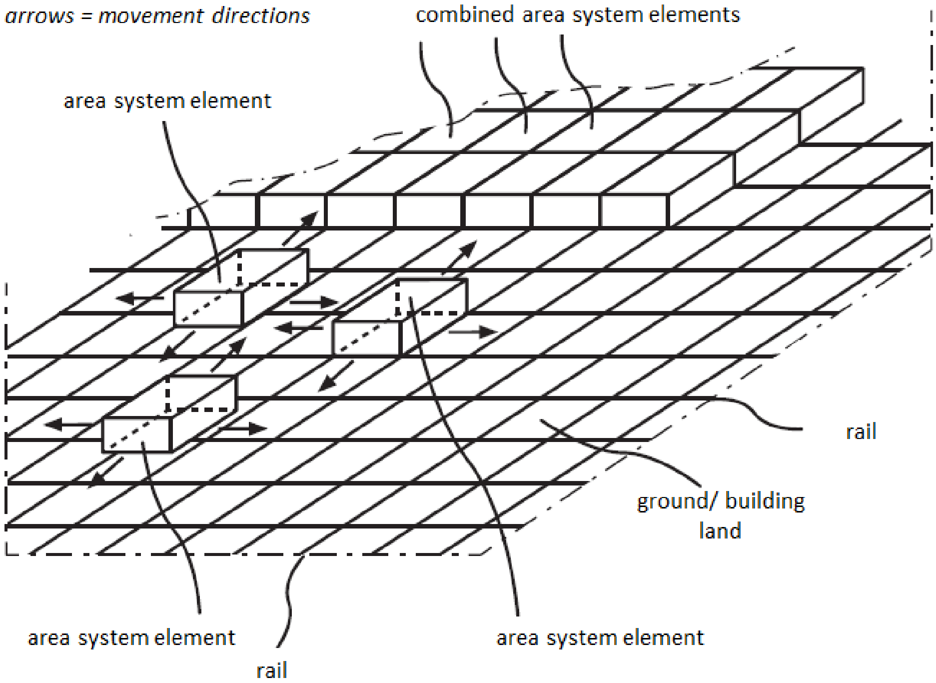


Figure 9: Separated and combined Railfield elements (Sredic, 2015)

The single elements can be plugged together and combined into different shapes. Railfield can involve an internal structure while a modular s&d infrastructure can be integrated into the elements. Process facilities and buildings can be mounted on top of the elements and connected to the technical infrastructure as required. Furthermore, Railfield enables container shifts and interactions with floating structures.

Hydrofield (figure 10) (Sredic, 2012d) entails the main capabilities of Railfield. In addition, Hydrofield elements can be lifted through a force effect that can, for instance, be applied by means of hydraulic systems and/or other means.

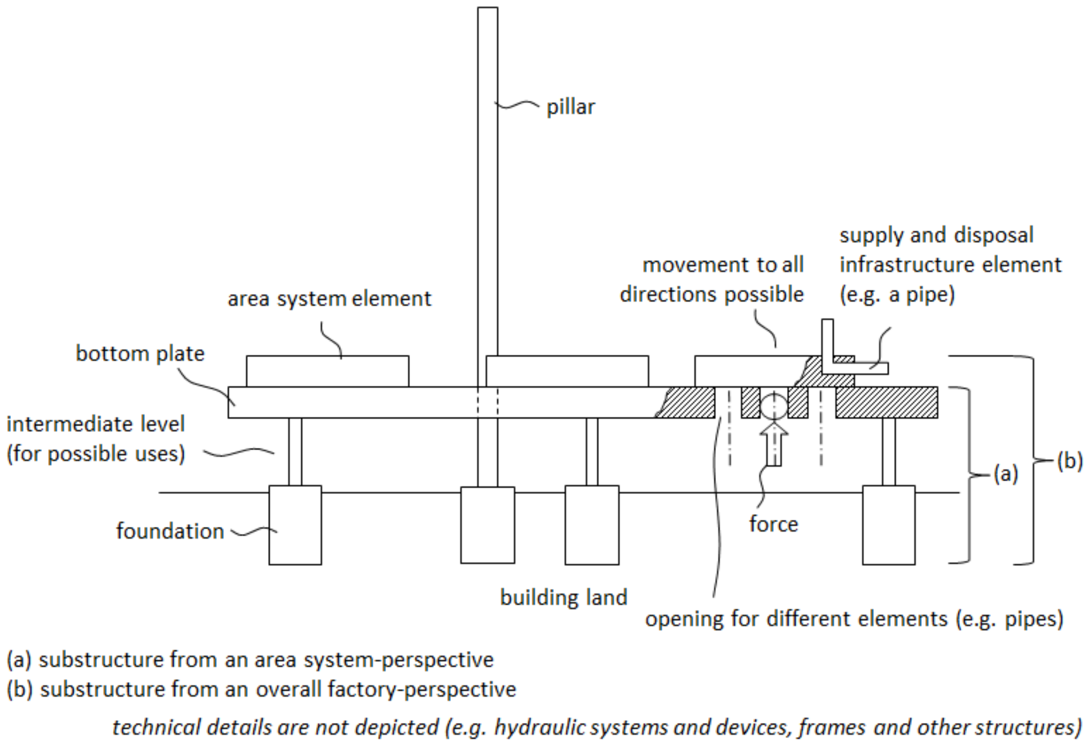


Figure 10: Hydrofield (Sredic, 2012d)

Thus, the elements are freely movable in all directions and not restricted by rails etc., as in the case of Railfield. Openings in the bottom plate can also be used for the s&d infrastructure.

Railfield and Hydrofield are basically comparable with Bluefield®, but are primarily restricted in terms of the area size and outer mobility, as they are constructed on terrestrial areas. Maritime area systems are capable of overcoming this restriction.

2.3.5 Maritime Area Systems

This subsection provides information about maritime technologies and developments. Maritime area systems are then presented.

> "The need to accommodate this expanding population through new spaces for habitation, work, infrastructure, recreation, storage, and food production; and the necessities of exploiting land-locked resources have increased pressure on governments to release and rezone near-city land-parcels for urban expansion" (Wang and Wang, 2015a, p. v).

The 'National Masterplan Maritime Technologies' (Bundesministerium für Wirtschaft und Technologie, 2011) shows that maritime technologies open numerous future markets and offer possibilities to solve the aforementioned needs. That floating structures are an important future market is recognisable in this document, as well as in Böttcher (2013), Wang and Wang (2015a) and numerous other publications. Therefore, maritime developments, their synergies, and synergies with available and further developments in various fields of knowledge must be considered in addition to numerous future markets, before one can make statements about the economic efficiency of maritime area systems.

There are still doubts about the technical capabilities of maritime area systems (Rauch, 2013, p. 90). However, those who are doubtful about the feasibility of such systems can rest assured: The basic feasibility is beyond any doubt, which is already understandable when a base knowledge has been acquired which is recognisable in basic and more sophisticated sources (Sverdrup, Johnson and Fleming, 1942; Currie, 1974; Hapel, 1990; Faltinsen, 1993, 2000; Faltinsen, Kvålsvold and Aarsnes, 1997; Faltinsen, Landrini and Greco, 2004; Krause, 2005; Skejic and Faltinsen, 2008; Spurk and Aksel, 2008; Truesdell and Rajogopal, 2009; Alkhalidi, Neelamani and Al Haj Assad, 2015; Jung *et al.*, 2015).

Diverse universities, institutes and/or groups work and/or have worked in collaborative projects on the development of 'multi-use offshore platforms' (e.g. Tropos, 2015; Mermaid, 2016) and have considered (e.g. technical and/or environmental) feasibility and further aspects. Whether the following area systems were considered in these projects remains unknown. Factory planning- and transformability-related aspects as well as general thoughts about the human-globe system have not been sufficiently considered. These thoughts are relevant, as there are environmental and other risks if maritime area systems and/or multi-use offshore platforms (which have similarities with some maritime area systems) are implemented without sufficient critical reflection and consideration of the human-globe system. The direct environmental impacts of these platforms have been analysed, but this does not suffice. It is furthermore open to question whether it has been realised that the establishment of new disciplines is required in order to comprehensively implement maritime area systems. That this is probably the case is recognisable throughout this document. The human-globe system is briefly discussed in subsection 6.3.7.

Floating concepts are occasionally rediscovered. Mankind has used floating structures for many centuries (Wang and Wang, 2015b). That the transformability of basic floating structures and ships is limited was recognised by Scanlan (1974). The invention of Correll (1911) relates to a floating pontoon-based derrick which can be stabilised by changing liquid ballast in tanks; this is a principle that is followed by many maritime area systems. This and many other inventions built the basis for maritime area systems. Area system characteristics that are relevant for this thesis are described within this document. Technical details can be reviewed in Corell (1911), Mosdell (1966), Clingenpeel (1975), Gräf (2001), Voskamp (2008), the abovementioned and the sources in the following paragraphs. One relevant aspect regarding area systems is that several of their advantageous characteristics can generally be combined with one another, and area systems with modern solutions. Area system elements can be combined in the X- and Y-directions, while some can be stacked.

‘Portable maritime structures’ (Pointer, 1957; De Long and Suderow, 1959) have been further developed and are currently in use (Deme Group, 2017; Jack-Up Barge, 2017). The legs of such structures can be fixed into the marine ground and are extendible. This enables vertical movement, and the structure can be jacked above the water surface level in order to reach a stable position away from wave forces. The legs must be decoupled and retracted before relocation is enabled. Thus, the mobility of such structures is possible, but with larger effort than with solutions that are not fixed to the ground.

The ‘Ukitecture System’ is a floating design concept (Howe, 1996). Howe and Parsons (1996, p. 2) argue that “The Ukitecture System is ... a multi-purpose, floating ... foundation“. This system is an assembled structure and consists of floating pontoons, nodes, trusses and braces (p.2). Thus, it is rather simple. Other similar systems have been implemented. The upper structure of this area system can be used as a basis for floor plates. The lower structure enables its floatability. Pumps, generators and other machines/technical devices can be combined with the system to stabilise it. Objects can be positioned on top of floor plates, but pluggable interfaces to TFOs/TFSs are not provided.

Bluefield® (Sredic, 2012b; 2012c) is a universally applicable area system which is based on elements with an integrated modular structure that consist of different layers with various functions (figure 11).

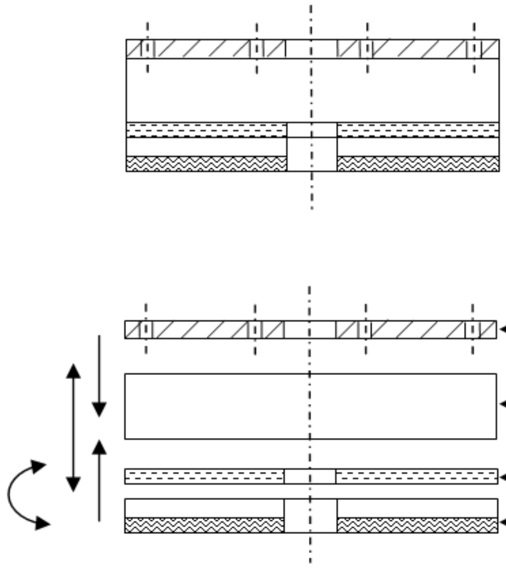


Figure 11: Bluefield element (Sredic, 2012c)

The 'floor layer' provides holes and openings that are required for different purposes such as the coupling of building structures and machines. S&d infrastructure networks can be flexibly integrated and assembled within the 'supply and disposal infrastructure layer'. The latter can provide room for diverse FOs/FSs, emergency escape and other routes. An 'energy conversion/vibration damping layer' can be optionally subjoined, while the 'base layer' involves a tank-system that enables floatability. Holes/openings within the layers enable a fast coupling of the s&d infrastructure with FOs/FSs. FOs/FSs can be coupled and non-destructively separated. In addition, columns/pillars and other supporting structures can be flexibly integrated by means of these holes/openings that can be provided throughout all layers (figure 12).

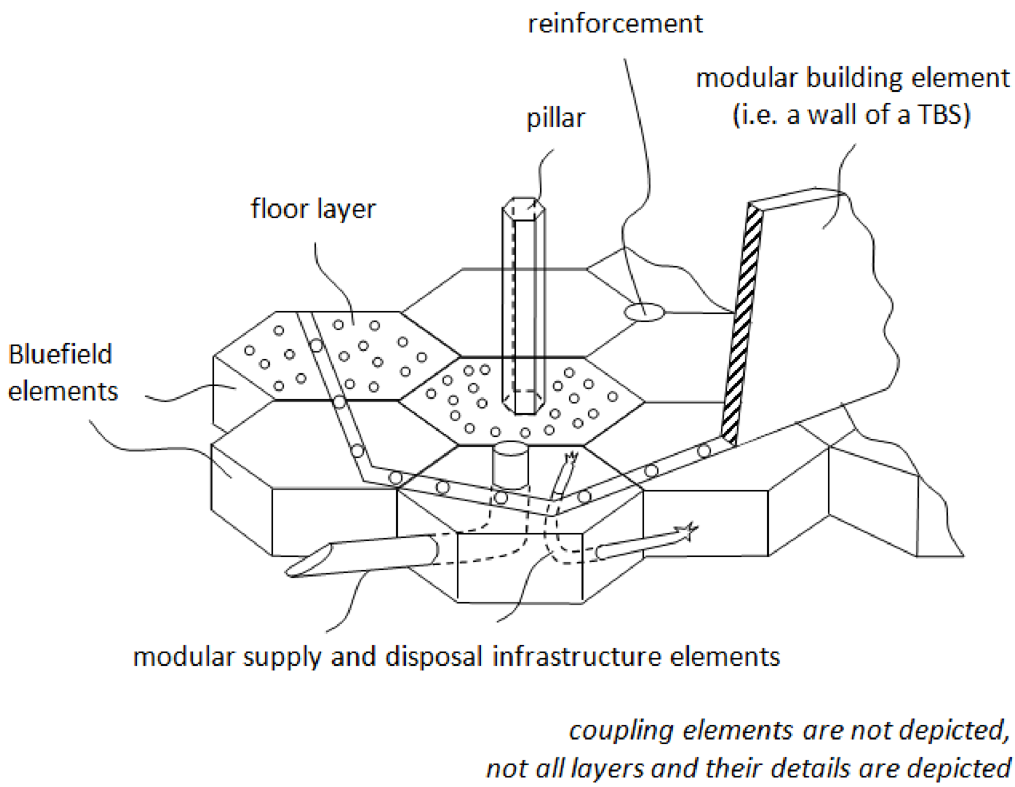


Figure 12: Bluefield (Sredic, 2012c)

All layers and internal structures (e.g. partition walls) are both standardisable and customisable. This means that types, dimensions and spacings of these structures and holes/openings can be designed based on standards on the one hand and are on the other hand at the same time transformable, as the layers and internal structures can be based on a modular construction which allows an exchange of elements (e.g. walls, floors, parts of walls and floors etc.). Bluefield elements can be combined to the X-, Y- and Z-axes. The same applies to their layers. Large superstructures (e.g. TBSs) can be mounted upon this area system, which can be docked to the shore and furthermore fixed to the marine ground; this is not necessarily required. Moreover, Bluefield elements can serve as transportation infrastructure. This area system involves different types of elements. Elements with integrated or docked drives can be connected to the Bluefield. Such drives enable autonomous movement of this system, but can also be used for hydropower conversion and vibration damping. In addition, the columns can be combined with wind turbines and the roofs with solar systems. The direct feed-in of renewable energy from the sun, wind and water enables a green factory and decreases distances to consumers. Bluefield provides a flexible basis for such power conversions, and can consequently be independent of terrestrial s&d infrastructures, despite the fact that this system can be connected to the latter. Furthermore, different types of breakwaters are considered. The elements can either be fixed (and/)or kept afloat, and are operational in both statuses. Docking and undocking processes can be performed quickly (Sredic, 2012c). Bluefield is a system that enables inner and outer mobility as well as high transformability, as it provides pluggable interfaces to TFOs/TFSs. Couplings between different factory sections are also feasible. Nevertheless, the system is complex.

Stranzinger's (1992) area system is relatively simple and can be produced at "low cost" (p. 5). Through appropriate standardisations and mass production, more complex area systems can also be cost-effectively produced. However, the initial investment in these systems is higher compared to the purchase of building land, which is sometimes provided by countries/regions/locations at no cost. To compare only the initial investment would be wrong. The whole factory lifecycle and numerous aspects which play a role during this lifecycle must be considered (e.g. the actual number and extent of transformations of diverse factories). Olsen, Weider and Myhr (2015, p. 161) describe that maritime structures can involve long lifecycles and be sustainable.

The 'Barge Factory' (O'Kon and Magness, 1976) is based on pontoons which are comparable with floating cargo barges. This invention is a further development of the 'Floating Factory for the Manufacture of Building Components' of Scanlan (1974). The invention "enable[s] the overall factory to be dismantled and the individual barges to be moved conveniently to various sites". The pontoons can "[be] arranged geometrically in a manner appropriately to fit into the available water site." (p. 7). The coupled floating barges provide a continuous and stable work area at the same horizontal level. Position changes of people and objects are possible without disturbing the functionality of the structure (O'Kon and Magness, 1976, p. 7). The barge factory integrates a functional control system and is transformable, but an s&d infrastructure network in or under the floor can hardly be combined with the system. “The primary advantages of the invention, however, are the capability of a large, efficient production operation for the manufacture of building components combined with a ... temporary and movable facility” that can be shifted in parts or as a whole. Scanlan claims that “the factory may very often be set up immediately...” and that “...only minor refitting of the barges [is required] to set them up for the manufacture of appropriate elements for the new job...” while factory transformations are not required if the same products, as at the previous site, are going to be produced after a factory move. “In any instance, many of the essential facilities of the factory remain permanently installed on selected barges and require no refitting.” (Scanlan, 1974, p. 9).

The idea of pre-producibility and pre-testability with regard to factories is not new. Scanlan (1974, p. 9) argues that

> “. . . it is an equally important advantage . . . that refitting of individual barges for a new job may readily be accomplished. For example, new forms for the next job can be prebuilt at or near the next job site (or at the old site) and then put aboard the appropriate barges. Similarly, spare barges can be prefitted with equipment for a new job and brought to the new factory site for "plugging in" to the rest of the flotilla.”

Maritime area systems are functional, partly implemented in practice and can be further developed. Several advantageous characteristics of area systems can be combined with one another. Area size-limitations can be eliminated through maritime area systems which enable the production and transportation of large products. That such systems can lead to significant advantages is recognisable by contemplating the following statement:

> "Many Managers would quickly move any factory anywhere in the country or the world where they could get cheaper, more reliable, and more fungible materials, subassemblies, parts, laborers, and vendors, and where laws and governments are more congenial. Ideally, they'd prefer to float the factory – put it on a barge that they could move to wherever the mix of what they needed is optimal" (McDonald, 1986, p. 82).

This is in line with Brzozowski (1976, p. 217), who argues that "the growing need to locate large process plants in inhospitable areas also increases the financial risks involved. One answer is to install plants in sea-going vessels."

The capabilities of (particularly maritime) area systems can be relevant not only for factories but also for cities and other structures in which transformation requirements occur. Furthermore, they can be used for numerous other purposes that have little to do with transformability.

2.3.6 Summary

Modern sub- and superstructure solutions do not fit with terrestrial areas and rigid substructures, but do fit with area systems, which are not explored in the current factory planning literature.

2.4 Chapter Summary and Conclusion

This section summarises the findings of chapter 2. The identified gaps provide the basis for the ROs.

Available factory planning theories do not, in the main, consider area systems, and neither do current implemented factory solutions and several modern concepts. Scanlan (1974), Lui (2004), Sredic (2011; 2012b; 2012c; 2012d; 2015) and others have described area systems in combination with factories or factory-like structures, but their ideas did not lead to factory concepts that could have been analysed against the backdrop of factory planning theory and practice. Thus, the meaning of area systems for factory planning is only superficially known.

Furthermore, there are gaps with regard to the capabilities and limitations of factories that are currently implemented, as well as in factory planning theories, regardless of area systems. The transformability of today's factories is low and furthermore decreases over time (if demolitions are not performed) which makes the first-mentioned insufficient against the backdrop of real-world factory transformation requirements which has not been appropriately considered in factory planning. Terrestrial areas are the main reason for these circumstances. The transformability of today's factories is low because of the limitations of terrestrial areas and their characteristic of being rigid. This rigidity fixes FOs/FSs (especially substructures), whereas transformability decreases further through the creation of additional RFOs/RFSs. To transform areas and RFOs/RFSs requires time, as the transformability and consequently the transformation velocity of today's factories are low if terrestrial areas and/or RFOs/RFSs are impacted. The same applies to TFOs/TFSs if they are fixed or limited through fixed substructures for example, as the latter determine the possible transformation scope of TFOs/TFSs. In addition, different factory configurations/statuses exclude one another. In particular, the durations of Brownfield projects are assumed to be often longer than those of Greenfield projects (due to the low transformation velocity and further aspects), which is a problem. Therefore, even if factory planning theories were functional, no significant benefit could be gained due to the limitations of the transformability of today's factories which are unknown in factory planning. Furthermore, factory planning theories have also limitations. Scenarios which are used to anticipate the 'to be'-status(es) of factories, are inoperative, which makes 'factory planning approaches' and 'methods for the assessment and planning of transformability and of transformations' also inoperative (at least dysfunctional), as the latter two require the 'to be'-status(es) for their operability. Even if scenarios were to work, these approaches and methods would be inoperative for complex factories (such as automotive OEM plants) – in particular in late factory development stages when factories become all the more complex (i.e. huge and unstructured) which leads to long project durations, overlaps and numerous other negative circumstances. Transformability and thus transformation velocity are too low in these development stages, and this is not considered in factory planning. As a result, when today's factories have reached a certain status, even restructuring programmes cannot avoid their development into UHPs (which has not been identified). Thus, the limitations of today's factories (i.e. the 'gap in factory planning practice') are not considered in factory planning theory. Practice makes some approaches and methods inoperative while theory cannot solve the gaps in practice. Therefore, the capabilities and limitations of today's factories are primarily researched and assessed, and those of factory planning theories secondarily.

In brief, a reliable theoretical construct that describes the limitations of today's factories and factory planning theories, and incorporates TASs/TFCs in factory planning is currently not available. That said, there is considerable value in analysing the real capabilities and limitations of today's factories (and factory planning theories), before those of TFCs will be demonstrated.

To make the gaps clearer, further details are provided in the following subsections.

2.4.1 The Gap in Factory Planning Practice

The transformability of today's factories is limited, and furthermore decreases over time, which has not been appropriately considered in factory planning. The root of these problems is the insufficient transformability of terrestrial areas which is the main working assumption in this thesis. The required but non-existent capabilities of today's factories lead to numerous problems and disadvantages that cannot be passed over with these factory concepts. In consequence, the actual capabilities of today's factories differ from the required capabilities. Thus, impacts of the changing factory environment are underestimated in light of the real capabilities of today's factories.

Although diverse requirements and limitations of the transformability have been identified, factory planning scientists/authors currently take terrestrial areas for granted. Even if they partly recognise the requirements and limitations of today's factories, they are caught in their traditional thinking, which is based on terrestrial areas, the same as their outdated factories that cannot sufficiently meet current real-world transformation requirements (despite diverse approaches such as

Industry 4.0). The real problems and consequently the real requirements have not been identified (which is also a gap in theory).

Factory planning theory attempts to process long-term developments, while in practice the terrestrial areas and substructures that are used are only capable of meeting short-term requirements at the most if demolitions – which can recover the virginity of areas and of the general structure – are excluded (consider the development of all areas and substructures of a factory). In addition, the different configurations of a factory exclude one another over time, which is only one pattern that shows that no considerable benefits could be gained even if scenario techniques would work.

2.4.2 The Gap in Factory Planning Theory

The ever-changing factory environment is the driving force that influences factory requirements (i.e. required factory characteristics and capabilities) and their developments over time. The longer a factory lifecycle, the more uncertain the developments of the factory environment, and, in turn, the more uncertain the factory requirements become (these can completely, partly or not at all be covered by a factory's transformability). The factory environment is considered through scenario techniques – but only in the light of anticipations and vast simplifications. These techniques, even though they are based on highly questionable data, provide a considerable part of or in combination with different factory planning approaches and/or methods, lead to the basic data for factory planning.

The longer a project duration, the less tangible these data are, which anyway cannot deliver a complete picture of the factory environment due to a limited number of considered influencing factors, vast simplifications of the latter, hardly considerable interactions between them and insufficiently considered aspects with regard to probability theory. These points were not reflected critically enough in the factory planning literature, even if it is hardly deniable that ever-changing factory requirements cannot be derived sufficiently from the factory environment, and that these requirements are unforeseeable. This applies to forecasts of short-term, medium-term and especially long-term requirements. These can be first known after their occurrence or a short time before, but are anticipated and processed from the start in order to implement and prepare (and/)or transform today's factories for possible future demands. Thus, numerous unknown future transformation requirements must be considered upfront. This is attempted by means of scenario techniques, and leads to a considerable gap with regard to factory planning theories. These theories are (mainly) therefore partly overestimated and are not as functional as desired and possibly assumed by diverse factory planning scientists/authors.

2.4.3 Overarching View of Today's Factories

Large parts of the factory planning literature convey the impression that transformation requirements with regard to areas are only minor, and that these requirements can be sufficiently met by means of extension areas and through the use of transformable superstructures. Extension areas and TFOs/TFSs can increase the transformability of factories – but considerable long-term effects on the transformability of areas fail to appear. The problem is that the effectiveness of these measures has been overestimated by factory planning scientists/authors, while the complexity and possible developments/changes of the factory environment have been underestimated and partly not considered at all. These developments require transformable areas.

That the transformability of areas is important has been partly recognised. Despite this (re)cognition, different FPP models, scenario techniques, approaches, methods, and transformable solutions (i.e. TFOs/TFSs), factories turn into UHPs, while some theories lead to a wasted working capacity (figure 13).

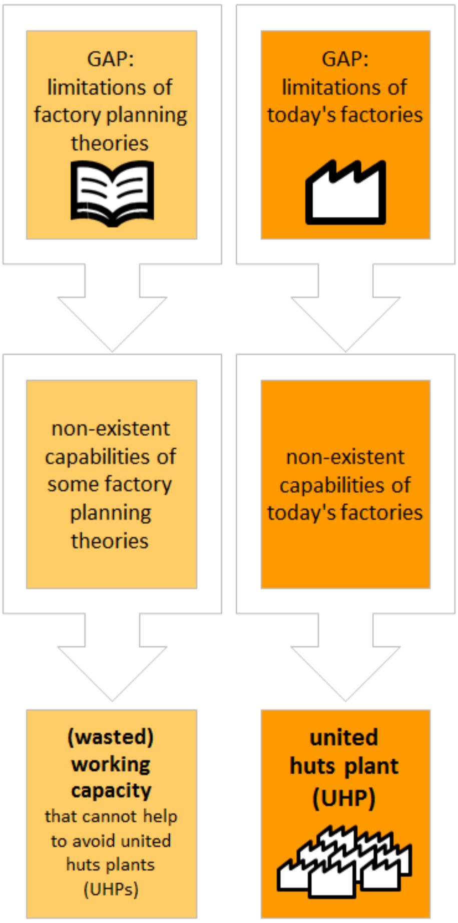


Figure 13: Wasted working capacity and united huts plant (regardless of area systems)

Working capacity is wasted, as it cannot avoid the development of factories into UHPs.

Theoretical solutions in factory planning are being developed and partly reinvented time and again. Numerous scientists/authors attempt to handle the problems in factory planning through the development of new theories without questioning whether this is at all possible. The usefulness of some theories is overestimated, while practical factory solutions more and more reach their limits because the right path (to enable transformable areas) has not been taken. Today's factory structures cannot handle the latest transformation requirements in an appropriate manner, especially in the light of long factory lifecycles (greater than 10 years).

This overarching problem has neither been recognised nor solved but can be understood if one takes a sober view from an adequate distance (figure 14).

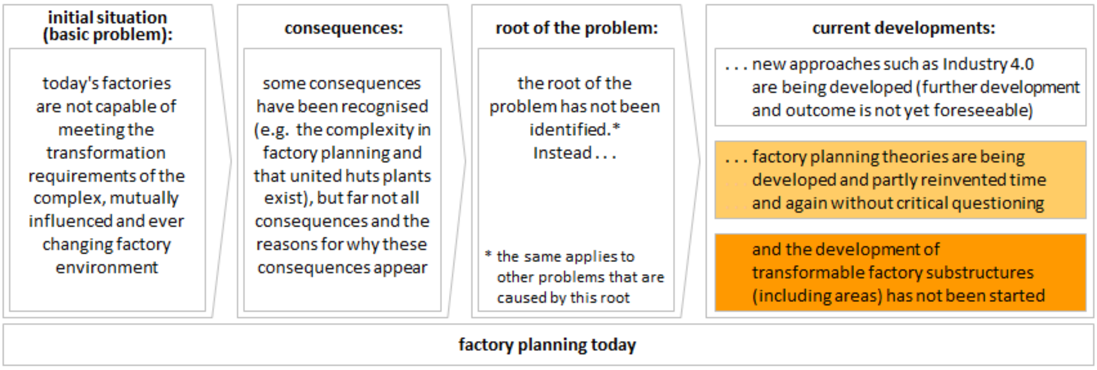


Figure 14: Factory planning today (regardless of area systems)

Factory planning lacks a holistic view and understanding. Not even the most important consequences (or symptoms) of the misery have been fully understood; how then should the root of the problem be identified and understood, not to mention resolved.

2.4.4 The Gap with regard to TFCs

It is assumed that practical factory solutions can be improved if areas are made transformable. Unfortunately, area systems are only superficially considered in factory planning. Consequently, the relevance and significance of the active transformability of areas for factory planning have not been identified. This circumstance was the starting point for the current study. Impacts of TFCs on technical and spatial transformability, transformation velocity, and on FPPs are unknown. This leads to a gap with regard to the capabilities and limitations of TFCs and a gap with regard to the capabilities of TFCs that cannot be reached by today's factories. These gaps have been neither identified nor described.

It is possible that TFCs can dissolve the limitations of today's factories, as these limitations build the basis for the development of the TAS-requirement profile. TASs build the basis for TFCs. TFCs could consequently meet the real-world transformation requirements that are required to be met by factories today. It is thinkable that the necessity for TFCs is not given in the light of some SMEs within a ten year-factory development which is considered in factory planning theory, but this eventuality does not change the fact that long-term factory developments (greater than 10 years) are not considered and exactly these developments might evoke the need for TFCs. SME factories can face the same problems with regard to transformability as larger factories, e.g. OEM factories. Such aspects are hardly considered in the factory planning literature. It is most likely that the dynamics of automotive OEM factories and long-term developments of SME factories require TFCs.

It is seldom questioned by factory planners whether the transformability of today's factories is sufficient or not. Factory planners do not open the door to a completely new layer of the transformability of factories. What is meant is the active transformability of areas. It is assumed that the transformability of factories can be increased with TASs and that TFCs are capable of meeting transformation requirements in order to always enable an ideal factory and consequently the future robustness of the latter. Whether Industry 4.0 is only a short-term trend or in fact the 'Fourth Industrial Revolution' is so far unclear. However this is unlikely if factories are still built upon terrestrial areas, as the transformability of today's factories is limited and decreases further over time. This has not been considered so far by (factory planning and) Industry 4.0 scientists/authors, nor have the limitations of scenarios etc. been considered. Furthermore, area systems have not been considered yet within Industry 4.0. It is probable that TASs and Industry 4.0-developments complement one another.

Technical possibilities of area systems are ahead of understanding and theory. A systematic description is not available. Consequently, in theory an integration of identifiable and achievable capabilities must occur.

2.4.5 The Gap with regard to the New Model

Today's factories pass through different development stages whilst diverse factory characteristics and capabilities develop negatively. This has not been analysed nor described. In addition, different configurations/statuses of today's factories exclude one another. Factories finally become UHPs, which can sometimes be changed with restructuring programmes but this leads to large demolitions, reconstructions and new constructions. The limited transformability of terrestrial areas is the main reason for this situation, which has not been identified.

To compensate for the 'gap in practice' (which has not even been identified by factory planning scientists/authors), diverse theories have been developed. Several of these theories are inoperative (especially in late factory development stages), while new ones which cannot compensate the 'gap in practice' are repeatedly developed. Furthermore, these theories are not capable of showing this incapability of today's factories, which leads to the requirement to develop a new model for factory planning.

The enabling of the active transformability of areas can generate considerable benefits (as it has a significant impact on the transformability of all FOs/FSs) which will be demonstrated and validated through the developed model.

Today's factories are only capable of meeting transformation requirements with large demolitions, reconstructions and new constructions, but are never as efficient and green as TFCs. Situations exist in which even demolitions etc. do not help, as transformations of today's factories can take so long that new transformation requirements occur before earlier initiated processes can be accomplished. The latter can still impact on factories, which disables the definition of the 'as is'-status of a factory (or impacted FOs/FSs). *(The 'as is'-status is, besides the 'to be'-status, necessary in order to define the required FPPs to perform an implementation or transformation.)* This has not been identified.

Tables 2 and 3 summarise the most important aspects of chapter 2 and put them in the context of this research. New aspects are described in the main body of text of the following chapters.

main aspect	**current status of factory planning (1.0)**	**meaning and significance for this research**
complexity in factory planning	The complexity in factory planning is recognisable, but the main reasons for this have not been recognised or systematically described.	required as a basis for a more systematic description of why factory planning is complex and why the use of algorithms in factory planning is limited
number and types of transformation requirements	**mainly unknown** (see BFPCs and difficulty factors below) (see also *)	required for the improvement of this picture; **it is necessary to identify that the transformability of areas is crucial, and why this is crucial**
requirements and limitations of transformability	The requirements and limitations of transformability/today's factories have been partly identified, **but this picture is incomplete.**	
important in this context (see also *)	Heterogeneity in factory planning is only superficially considered; its importance for transformations has not been identified.	required because heterogeneity is crucial for transformations
current basic factory planning cases (BFPCs)	BFPCs provide a basic structure and framework to differentiate factory projects, but do not show which factory project cases are the most relevant and why, do not have much to do with the characteristics, extents and impacts of real-world factory project cases, and are too superficial to enable their use within the new model.	required as a basis to enhance current BFPCs, which are relevant for the development of the new model in which the eBFPCs and BFPSs play an important role; research objective 1 (RO1)
important in this context (see also *)	**Difficulty factors are unknown** (except for displacements and some other impacts, which have not been deeply analysed).	**required in order to indicate the impacts of eBFPCs throughout the BFPSs, and thus the required transformability of current factories**
factory planning process models	provide a basic structure and framework to perform factory projects, and involve factory planning processes (FPPs), but do not make sense of them throughout a factory's lifecycle	required as a basis for all ROs
factory planning approaches (see also **)	attempts to handle complex, mutually influenced and ever changing data within real-world factory projects and to perform these projects appropriately, while it is highly questionable whether complex projects can be handled at all in late BFPSs of today's factories, in which these factories themselves often do involve a huge complexity	required as a basis to describe why these approaches and other theories are especially inoperative for complex factories such as automotive OEM plants (in particular in late BFPSs), the same as 'methods for the assessment and planning of the transformability and of transformations' (factory planning process models are often not able to deal with complex factory projects)
* methods for the assessment and planning of the transformability and transformations of factories (see also **)	provide basic methods/approaches and concepts that enable an assessment and planning of the transformability and transformations of factories, but these are incapable of showing the real transformation capabilities and limitations of today's factories (despite their inability to show the capabilities and limitations of TFCs), and the real transformation requirements of current factories	required as a basis for all research objectives; also as a basis to develop the new knowledge about the transformability of factories that is required for this research. This new knowledge can be used to further develop existing 'methods for the assessment and planning of the transformability and transformations of factories'
** scenarios/ scenario techniques (are required for almost all factory planning approaches and other theories)	attempts to anticipate the development of the factory environment and, in turn, factory requirements (i.e. the 'to be'-status(es) of a factory, including its future structure and transformability); the usefulness of scenarios in factory planning is overestimated, although some authors even claim that their use sets clear limits (nevertheless, without adequate evidence or demonstration)	required as a basis to analyse the limitations of scenarios in factory planning and to describe why they are especially inoperative for complex factories in complex environments

(continued)

Conclusion for chapter 2 (*these parts of the table aim to support the reader in keeping sight of the big picture*): Current factory planning ('Factory Planning 1.0') goes into depth without a holistic and comprehensive understanding of the main aspects that are relevant for factory planning. Therefore, Factory Planning 1.0 is actually too superficial. The development of the transformability and complexity of today's factories throughout a factory's lifecycle cannot be sufficiently demonstrated, the same as changing transformability requirements which increase throughout this lifecycle. This leads to more effortful and more time-consuming FPPs (and thus to more complex projects), and to decreasing possibilities to use Factory Planning 1.0 methods, models, approaches and other theories. Factory Planning 1.0 is particularly not always applicable for 'complex factory planning projects' in 'complex factories' such as automotive OEM plants (especially in late BFPSs). Furthermore, Factory Planning 1.0 cannot show what is required to be improved in practice, e.g. that areas must be transformable. Factory Planning 1.0 lacks concepts for this and its use in practice is often rather cumbersome, as Factory Planning 1.0 goes into depth without identifying and considering the main points. Factory Planning 1.0 is not holistic and comprehensive enough, and goes partly in depth only were it makes less sense to do so.
transition
The meaning of these aspects for this work: This research requires a model (and associated concepts) for factory planning that is capable of indicating the impacts of recurrent real-world factory project cases (i.e. eBFPCs) within different factory development stages (i.e. BFPSs) of different factory concepts. Such a model is currently not available. This model and its associated concepts are required in order to further develop factory planning theory (RO1). Only then it is possible to demonstrate the real-world transformation requirements and to make sense of them. These transformation requirements are used to improve the transformability of factories through TASs. The limitations of today's factories provide the data that is required in order to develop the TAS-requirement profile, and to develop TAS-based factory concepts (TFCs). Thus, RO1 is a basis to achieve RO2, RO3 and RO4. Difficulty factors lead to a certain complexity in this thesis, as they make the complexity in factory planning at least partly assessable, which is crucial for all ROs (especially for RO1, RO2 and RO4).
This work can only be a first move towards dynamic factory planning, i.e. 'Factory Planning 2.0'. Whether this thesis is, independently of TASs, (literally) a groundbreaking work, must be decided by the reader. This thesis can be difficult to understand, but this is necessary; otherwise the ROs cannot be achieved, as their achievement requires the improvement of factory planning (at least of some of its elements), which is not simple. This takes place mainly in chapter 5 and section 6.1. To leave contents out can lead to an improvement and to complexity reduction. The author has tried to do this against the backdrop of what is required to achieve the ROs. This research: 1. is a starter for dynamic factory planning 2. demonstrates the limitations of today’s factories 3. makes sense of these limitations, as these limitations are used to develop TASs 4. demonstrates the impacts of TFCs Complexity can lead to difficulties, but superficiality can lead to wrong activities.

Table 2: Current factory planning theory in the light of this research

Table 3 shows the differences between current factory planning and this research, which also explains the complexity of this thesis.

		current factory planning (1.0)	theory in this research*
main aspect/concept(s)	systematic description of the complexity in factory planning	◔	●
	real-world transformation requirements	◒	●
	heterogeneity in factory planning	as a crucial aspect not considered at all ◔	●
	requirements of transformability	◔	●
	limitations of today's factories, e.g. transformation inability	◔	●
	factory development throughout a factory lifecycle	◒	●
	reasons for this development	◔	●
	analyses of the functionality of scenario techniques	specialist literature about scenarios is excluded ◔	●
	analyses of the functionality of factory planning theory	approaches etc. are further developed; meant is current factory planning in general	●
	BFPSs (i.e. factory development stages)	◔ but not as a concept(s)	●
	eBFPCs and impacts of eBFPCs (which change with BFPSs)		●
	difficulty factors	◔ but not as a concept(s)	●
	accelerators and acceleration units	◒ but not as a concept(s)	●
	fundamental enablers	◔ but not as a concept(s)	●
	resulting factory planning processes (FPPs) (basics)	◔	●
	transformability-development throughout the BFPSs	and meaning of this development for FPPs ◔	●
	complexity-development throughout the BFPSs	◔	●
	meaning of these develop-ments for factory planning	◔	● e.g. unmanageable complexity
	TASs and TFCs; impacts of TASs and TFCs		●

● fully considered (against the backdrop of what is possible within the scope of this thesis)
◒ partly considered, but mainly not through analyses (which means that an effect occurs, but they know why and partly even not that it is an effect)
◔ hardly considered, but mainly not through analyses; an empty cell means not considered
*circles and parts of circles stand for 'analysed and described', 'developed and applied' or 'carried out and accomplished' (or a mix of these elements)

Table 3: Main differences between current factory planning and the developed theory

3 Conceptual Framework

The conceptual framework was developed based on available literature. It describes the surroundings and elements of a factory that are required to reflect and analyse the activities that take place in real-world factories. The contents of this chapter form a system model (Bossel, 1992, 2004) which, together with the concepts previously derived in subsection 2.3.1 (i.e. TBS, TFOs/TFSs, TBCs, RFOs/RFSs and RBCs), inhibitors (see section 2.2.7) and the new model for factory planning (chapter 5), provides the required sphere in which the developed factory concepts can be analysed. The general structure plays a key role for these analyses, which is recognisable in figure 15 (this figure is embedded in figure 16).

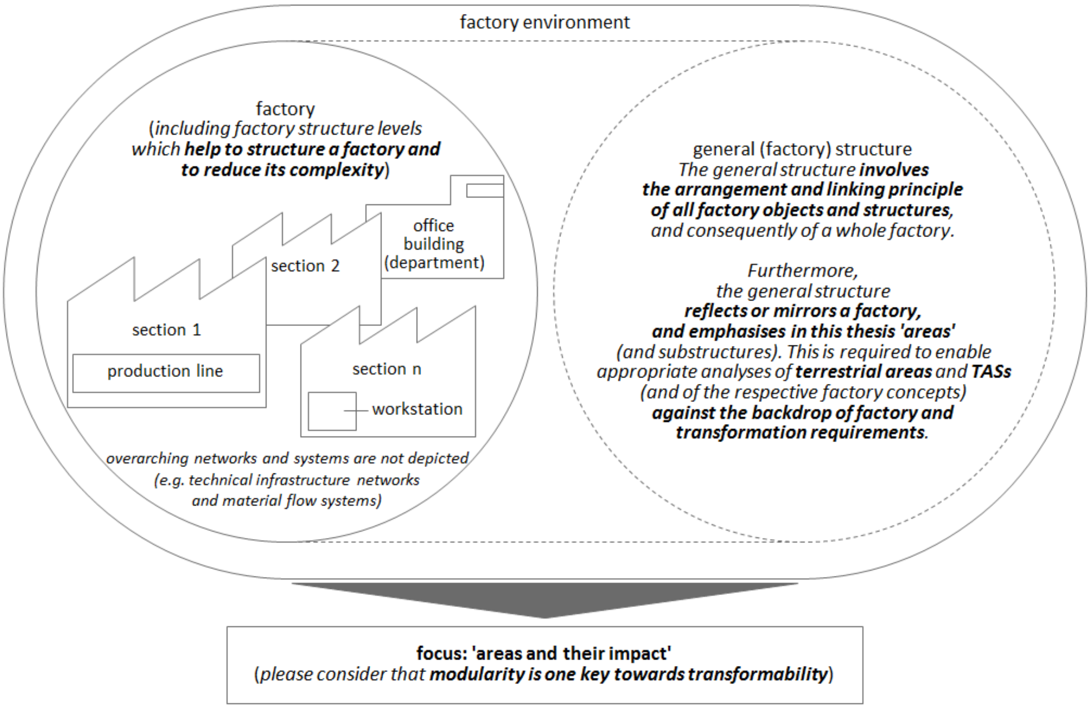


Figure 15: Importance of the general structure for this research

The abovementioned derived concepts and inhibitors play their role in the developed factory concepts – increasingly over time. Areas are crucial for these concepts, as areas (i.e. terrestrial areas or an area system(s)) dominate factory developments, which occur due to factory and transformation requirements. In this thesis, areas have a special role. This also applies to the role of areas within the definition of the general structure. Figure 16 depicts the conceptual framework.

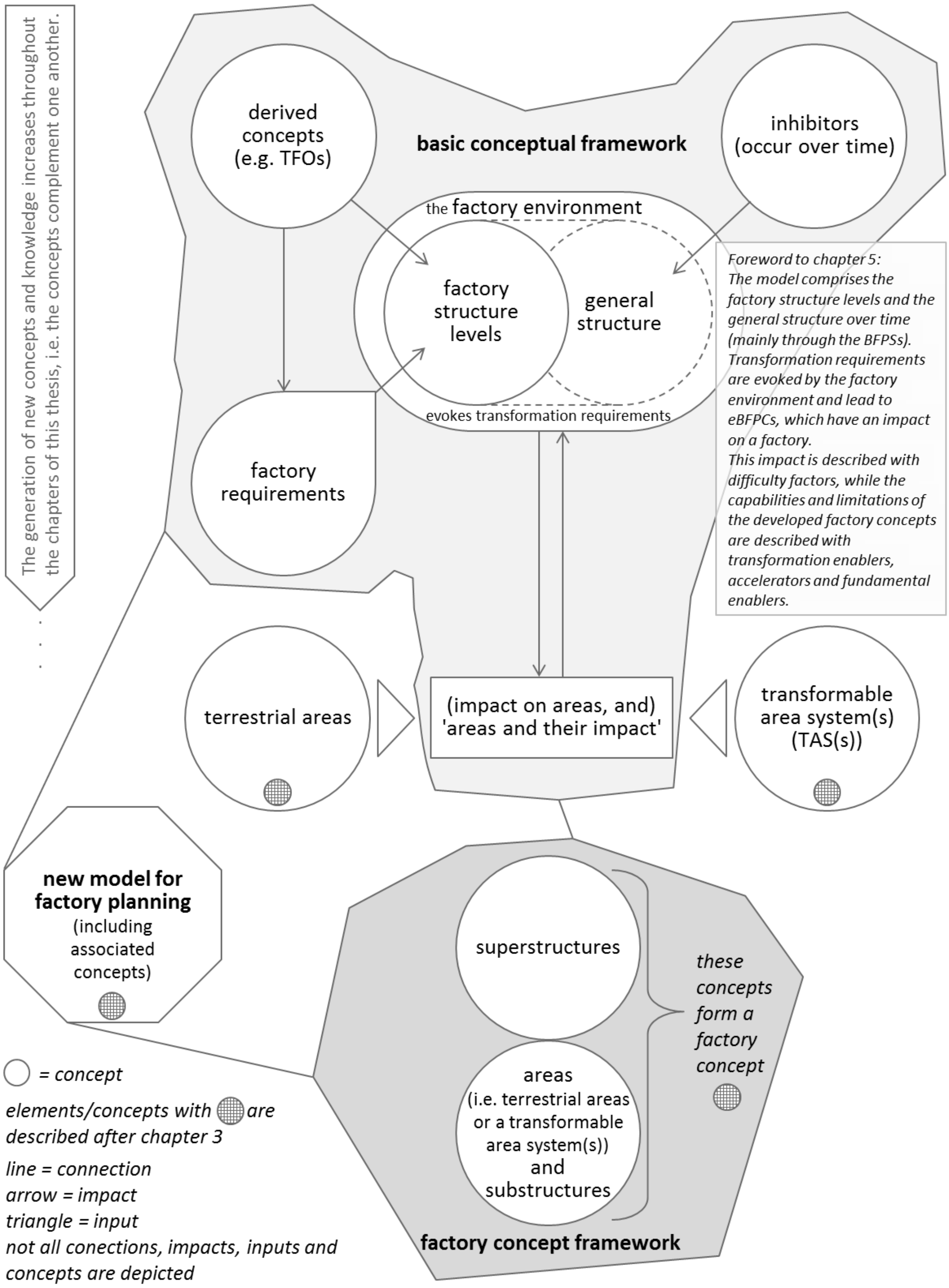


Figure 16: Conceptual framework

Areas are fundamental in this regard. The new model for factory planning and all relevant concepts that are not described in this chapter are described in subsequent chapters. Thus, chapter 3 provides a knowledge base which is complemented by the contents of the following chapters.

Section 3.1 describes the modularity in the context of systems. Section 3.2 describes the factory environment and factory structure levels. Section 3.3 provides information about generalised requirements and transformation requirements of FOs/FSs (including factory sections). The general structure is described in section 3.4, and the technical infrastructure in section 3.5. This chapter is summarised and concluded in section 3.6.

3.1 Modularity

Standardised units, of which the functionality and operative readiness can be pre-tested, are the bases that enable modular objects and structures, and consequently the modularity of factories. Modules are autonomous and highly compatible with one another and with their environment through appropriate interfaces. They can be easily exchanged with low expenditure of work, time and budget. An exchange of modules leads only to partial impacts on the involved objects and structures, and does not impact on the whole system (Koether *et al.*, 2001, p. 19; Hernández, 2002, p. 55).

Buildings and machines are systems (Koether *et al.*, 2001) which involve different complexities, while smaller units can also be systems. The physical size of a system does not define its complexity (Hansen, 1976). Subsystems of such systems are often designated as modules (Koether *et al.*, 2001, p. 19). Modularity increases the transparency of factories and the ability to create a clear arrangement of FOs, which leads to a structuring of a factory and a decrease in its complexity. Nofen, Klußmann and Löllmann (2013, pp. 26–27) describe 'factory structure forming' and 'element structure forming' characteristics of modularity. A structural formation with regard to a factory, its general structure and products is also recognisable (Schenk and Wirth, 2004). Planning periods and efforts can be reduced through structuring (Nofen *et al.*, 2003). Hildebrand (2005, pp. 140–142) and Heinecker (2006, pp. 94–96) provide further module descriptions that are in line with the explanations in this paragraph, while Hildebrand (2005, pp. 83–88) emphasises the autarky of modules and functional, physical/spatial, s&d-related and personnel independence, which are relative. Modules are also relatively independent of special conditions or events, emissions and other interferences. Thus, their function is not impaired by external disruptive factors such as noise, dust, temperature and oscillations. A relative dependency to such disruptive factors is given when technical resources are dependent on active or passive protective measures such as foundations, filter systems and noise barriers in order to fulfil their function (p. 88). Figure 17 depicts a module with its characteristics, interfaces, inputs and outputs.

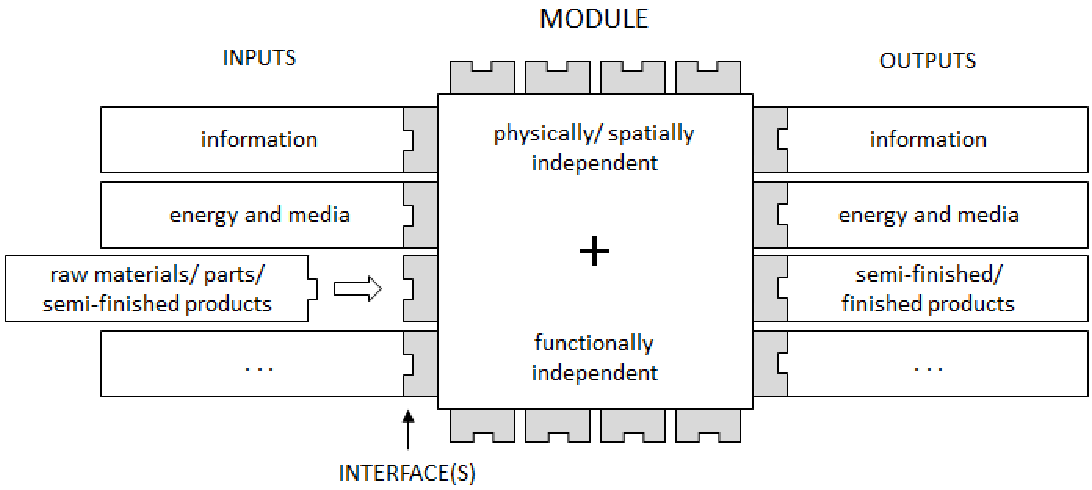


Figure 17: A module with its characteristics, interfaces, inputs and outputs

All flows that are required by a module to fulfil a specific task arrive at the latter through defined interfaces (Nofen, Klußmann and Löllmann, 2013, p. 21). Breitenbach (2013) classifies and differentiates geometrical, functional and production-technology-related interfaces, and claims that these allow a holistic description of interfaces within a factory. Connections to production, material, information, energy and media flows, required floor spaces/depths and floor loads are considered. Further flows are value, product, personnel and workflows (Schenk, Wirth and Müller, 2010).

Numerous definitions and subdivisions of modules exist in the literature. Nofen, Klußmann and Löllmann (2013) differentiate between factory modules and elements, while the latter are normally subordinated. Such a subdivision is used where appropriate in this thesis; the designations ‘factory object’ (FO) and ‘factory structure’ (FS) are mainly used. The terms ‘module’ and ‘element’ are only used where appropriate, and mainly synonymously. The designation FO relates to buildings, production lines, process facilities, workstations and s&d plants. FS is concerned with building structures and technical infrastructures, e.g. roof structure, pipe and road networks. Maritime area system elements (which are also designated as pontoons or platforms), for instance, are modules but also FOs, while infrastructure networks within area systems are designated as structures. Furthermore, a production cell can be a module, but appropriate framework conditions at a target location are required to enable its proper installation and setup, e.g. adequate area and floor load. A module in this thesis is a 3D-form (e.g. an object or a room) rather than a 2D-shape, e.g. an area parcel. The designation structure is also used to indicate an overarching structure, e.g. the structure of a factory.

Further information about flows, FOs/FSs, modules and how they are embedded in a factory are provided in the following sections.

3.2 Factory Environment and Factory Structure Levels

A factory is surrounded by its factory environment, which in this thesis involves a location, region, supraregion, and the globe, and accommodates different factory influencing factors (e.g. production networks, competitors and labour markets). Product markets in particular influence factory requirements. The factory environment provides the sphere in which factories play their part (Hernández, 2002; Wiendahl, 2002).

A factory can be structured into hierarchical levels – the factory structure levels. Thus, a subdivision of a factory into functional areas, buildings and subordinated FOs/FSs is possible. Factory sections have different user-specific requirements towards flows, buildings, building contents, technical infrastructures and areas. Unequal factory sections are therefore normally housed within individualised and separated buildings because of their heterogeneous structures. Thus, factory sections can be equated with factory buildings (Helbing, 2010; Müller *et al.*, 2013; Grundig, 2015).

Such a delimitation, structuring and classification of the factory environment and the factory itself leads to complexity reduction and allows an analysis of factories within their surroundings (Wiendahl and Hernández, 2000; Hernández, 2002).

The factory structure levels of this thesis are: ‘factory’, ‘section/department’, ‘production line/group’ and ‘single process facility/workstation’. The factory environment and the factory structure levels are depicted in figure 18.

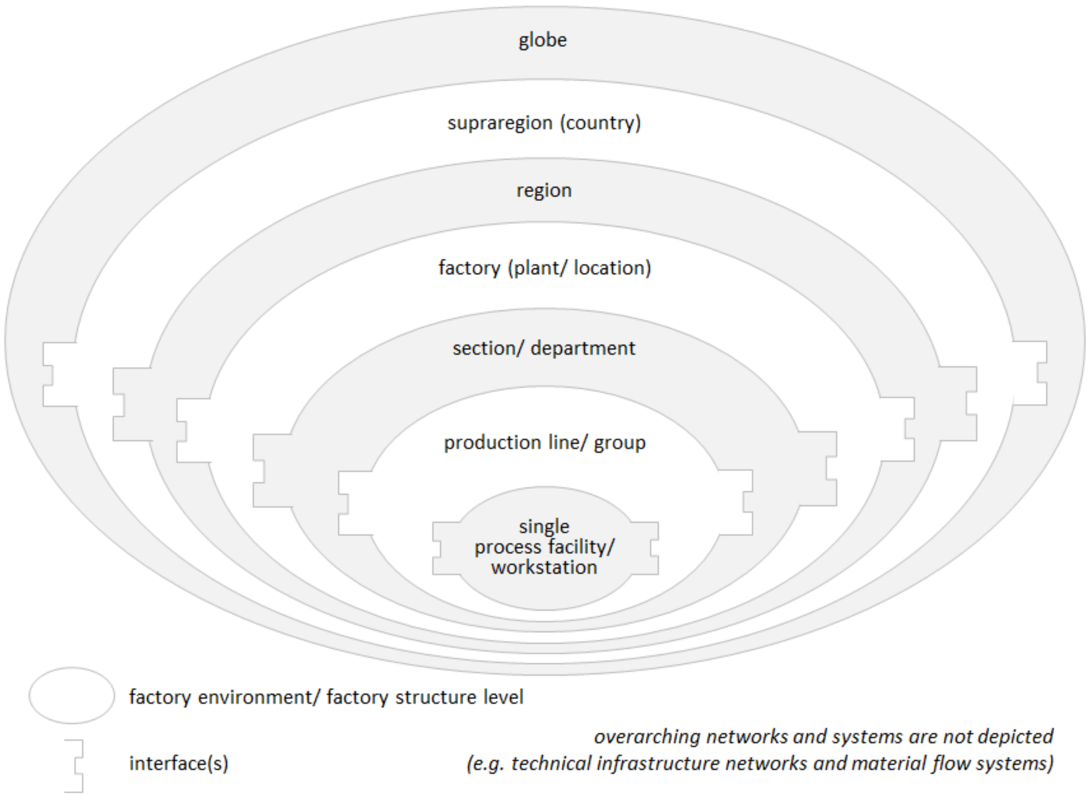


Figure 18: Factory environment and factory structure levels

A factory involves all factory sections and departments that are user-specific production and office buildings. Furthermore, other buildings or building-like structures such as canteens, s&d plants and filling stations are involved at the same hierarchical level as sections and departments. In addition, (internal) technical infrastructure networks with their systems, subsystems and elements are covered by a factory. The same applies to material flow systems such as conveyor systems (conveyors can also be used as interfaces between production buildings). Different further overarching systems and networks interpenetrate a factory and many of its subordinated FOs/FSs. This is in line with Nofen, Klußmann and Löllmann (2013, pp.

23–24), who argue that not all FOs/FSs can be clearly allocated to a factory structure level.

Sections of an automotive OEM plant are press shops, body shops, paint shops and assembly shops. Logistics, quality and maintenance perform tasks within factories and sections whereby their areas are segmented and spread all over a factory (Helbing, 2010; Klug, 2010). This is in line with Schenk, Wirth and Müller (2010), who present several area types (e.g. areas for transport and handling), while overlaps of areas are possible (e.g. production and logistics areas). Furthermore, workshops, tool and machine shops produce tools, jigs, fixtures and the like, and provide assistance to other sections.

A production line/group can comprise production plants, process facilities, single workstations and various tools and equipment. Furthermore, different types of logistics facilities, tools and equipment can be involved (Schenk, Wirth and Müller, 2010; Klug, 2010). Conveyor systems are often combined with production lines to ensure a clocked and continuous production flow (Klug, 2010).

Single process facilities/workstations represent the lowest factory structure level, while different smaller elements (e.g. pipes) complete this system model.

3.3 Generalised Factory and Transformation Requirements

Helbing (2010), Klug (2010) and other authors provide information about the requirements of factory sections, objects and/or structures. *(Factory sections/ buildings are FOs and are designated as such in this thesis. Nevertheless, factory sections/buildings involve numerous FOs/FSs, which sometimes makes it sensible to name them in addition to FOs/FSs.)* The following requirements for these have been summarised and generalised based on available sources.

An FO (e.g. a process facility) requires different inputs, outputs, spaces and appropriate substructure and superstructure characteristics (figure 19).

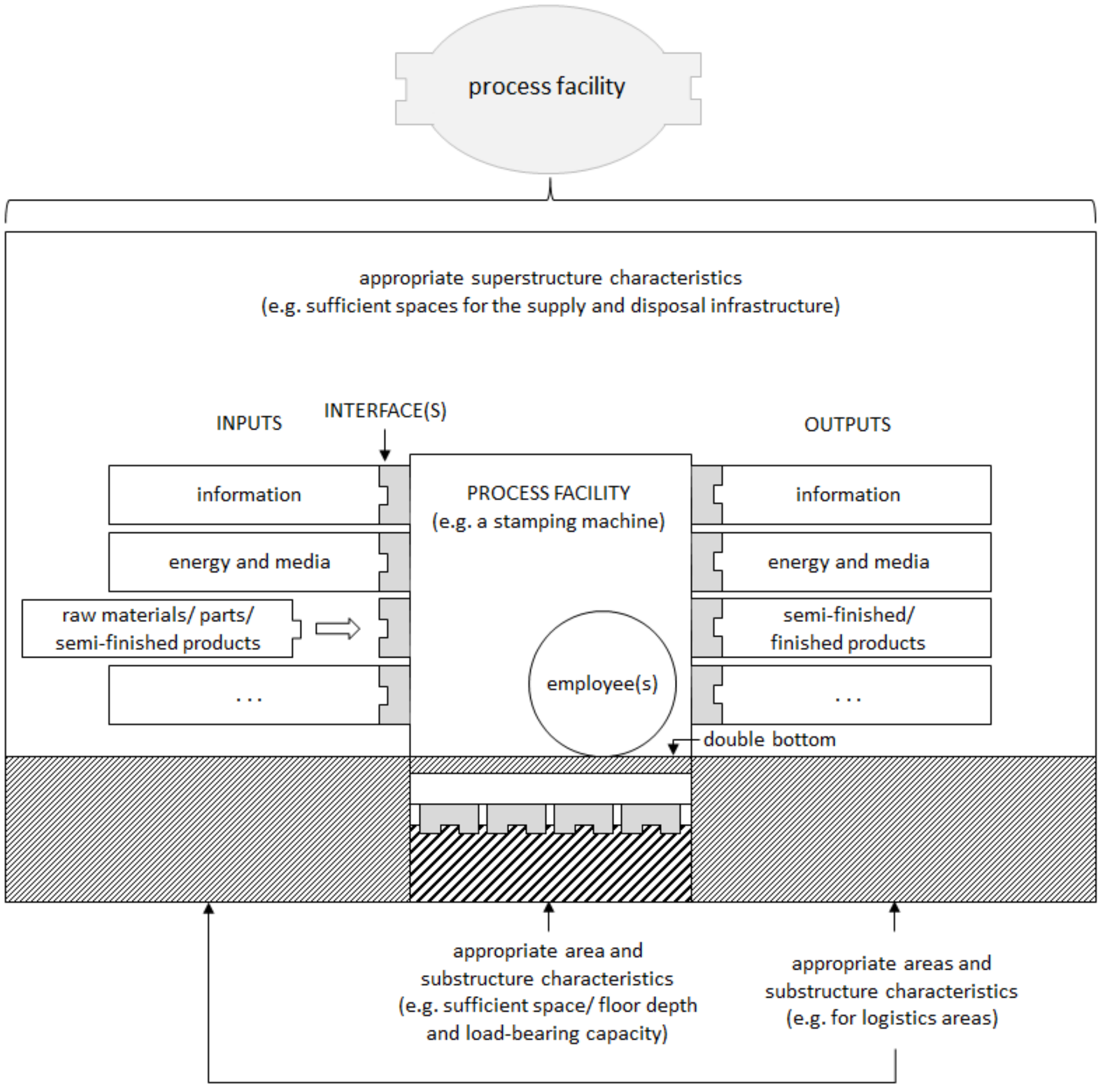


Figure 19: Process facility with its interfaces, inputs, outputs and requirements

Different approaches to defining required areas and spaces are available. They all have in common that an FO requires areas and spaces based on its own characteristics, adjacent and otherwise involved FOs/FSs and events that happen around it. Helbing (2010) and Schenk, Wirth and Müller (2010) emphasise area requirements, flows, related FOs/FSs and their requirements. Raw materials, parts, semi-finished and finished products are considered. It is not only the footprints of FOs that are decisive: people and process inputs and outputs also require areas and spaces. Load-bearing capacities of floors, roof structures and intermediate structures (e.g. intermediate steel constructions) must fit requirements. These and other requirements lead to heterogeneous factories. Heterogeneous FOs/FSs can be found throughout all factory structure levels. Transportation and s&d

infrastructure networks and other overarching networks and systems (e.g. conveyor systems) are also heterogeneous. Thus, all flows are heterogeneous when compared to one another, but also within themselves.

The heterogeneity in factory planning has been recognised by authors such as Helbing (2010) and Schenk, Wirth and Müller (2010), but has not been discussed as a core problem against the backdrop of current transformation requirements and the limited transformability of areas.

Figure 20 provides a simplified overview of (pre-)planned factory extension steps (Brownfields 1 to n) and involved FOs/FSs. Transformation requirements can lead to changes in all flows and can impact numerous FOs/FSs.

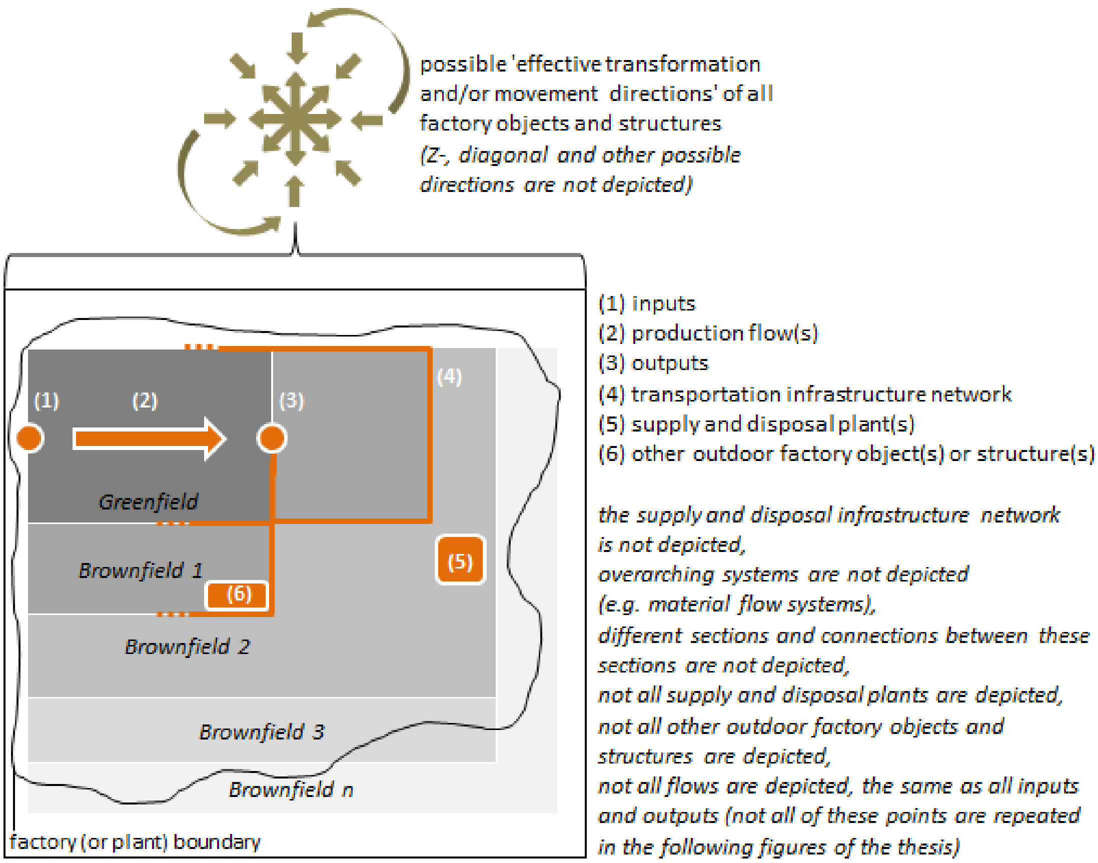


Figure 20: Extension steps of a factory

Required capacities, dimensions, shapes, positions (in X, Y and Z) and connections of these FOs/FSs can consequently change, which leads to different 'effective transformation and/or movement directions'. Overall, that which applies to a process facility with its interfaces, inputs, outputs and requirements (which can change), applies in a similar manner to all other factory structure levels, overarching networks, systems and related flows. This means that a transformation can impact all FOs/FSs (including areas/spaces) in a comparable manner. Changing/displaced areas/spaces are consequently assumed to be crucial for transformations. Movements/repositionings of numerous FOs/FSs are therefore important for factory planning and lead to the development of 'basic movement events' (BMEs) and further concepts, which are described in chapters 4 and 5 and section 6.1.

As changes of the general structure are decisive for movements/repositionings of FOs/FSs, and consequently for displaced areas/spaces, the general structure is described next.

3.4 General Structure

The dimensions, shapes, positions and connections of the main FOs/FSs (e.g. buildings, s&d plants and technical infrastructures) are comprised by the 'general structure', which is visible at the factory layout and involves the arrangement and linking principle of all FOs/FSs, which means the whole factory and its main flows. Inputs, outputs, systems and networks can be considered to be part of the general structure, and are from this point onwards only mentioned where necessary. The general structure determines particularly the layout and possible developments of (today's) factories, which means future factory transformations with regard to areas (Hernández, 2002, p. 67). Effective directions of transformations (in other words 'effective transformation and/or movement directions') and dimensional changes which occur in the case of area and building extensions are thus predefined by the general structure, since it involves the (available) area size, area shape and further area-related characteristics (e.g. soil conditions), as well as the forms and lengths of technical infrastructure networks. Overarching systems can also be involved in the same way as other FOs/FSs. Area-related transformations in particular can lead to changes in the general structure. Extension areas enable spatial breathing of a factory. (Today's) Factories and their potential developments therefore require strategic planning (Hernández, 2002, p. 78; Erlach, 2013, pp. 4–5), while "in practice, [(today's)] factories result from historically grown changes and adaptations applied in factory operations as well as planned interventions in factory planning." (Erlach, 2013, p. 4). The contents of this paragraph are in line with Grundig (2015) (and earlier editions of this book), who emphasises the importance of the area size and geometry for factory planning and the general structure.

Factory structure levels and the general structure have also been used by Hernández (2002) in order to analyse today's factories. According to Hernández (2002, pp. 66–67), the site(/area), general structure and buildings can be assigned to a factory. The site involves the area size, soil conditions and the transportation infrastructure. The assignments in this thesis are different: Although the general structure has its own definition, it is comparable to a factory, as all FOs/FSs are subordinated to them (also overarching systems and connections between buildings) (figure 21).

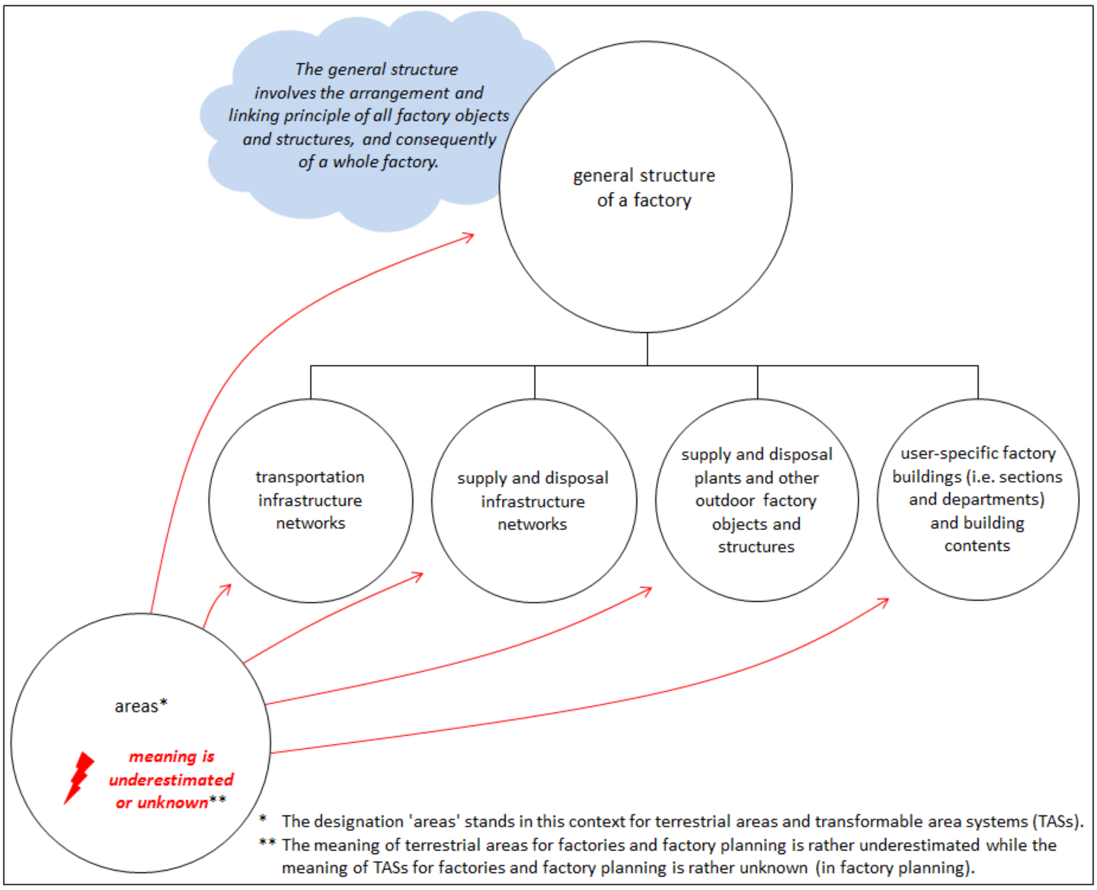


Figure 21: Rational view of a factory's general structure

Almost all FOs/FSs are either directly or indirectly bound to the area. Therefore, the area is an overarching transformation object and plays a major role in this thesis. Its importance and significance are disclosed in chapter 6.

Grundig (2015, p. 270) argues that the planning of the general structure should take place along with location planning, as the general structure provides specifications for location planning (e.g. the size of the site, building dimensions and building arrangements). That the general structure is decisive for Brownfield projects is also recognisable in Grundig (2015), but this has not been highlighted.

It is probable that changes in the arrangement and linking of numerous FOs/FSs are often required in order to keep a factory (and its flows) efficient and green.

3.5 Technical Infrastructure

This thesis is concerned with the ‘technical (or hard) infrastructure’, which involves the transportation and s&d infrastructure. These large physical networks are a prerequisite for the operation of factories (Helbing, 2010; Klodt, 2015).

Based on Koether *et al.* (2001), Helbing (2010) and Klodt (2015), the following definitions of technical infrastructures are relevant for this thesis:

The ‘transportation infrastructure’ involves all roads, railways, cycle lanes, pedestrian paths and waterways. This infrastructure type enables the movement of people, automobiles, trains, ships, and thus the transport of goods, materials and the like.

The ‘s&d infrastructure’ involves all pipes, canals, sewers, shafts/ducts, wires, cables, lines, conduits and related networks which are required for the supply and/or disposal of energy, media and information flows. Thus, electric power, gas, district heating, drinking water, fresh water, rainwater, cooling water, other industrial fluids, wastewater, pressurised air, materials/substances, wastes and data (besides others) are able to flow. In addition, the supply of sprinkler and other systems with corresponding media must be ensured by appropriate installations.

Sufficient media capacity is required to ensure adequate supply potential in the case of an accident.

Both the transportation and s&d infrastructure are differentiated into external and internal infrastructure. The factory boundary separates the external from the internal infrastructure (Hildebrand, 2005, pp. 108–110).

A region or location provides the external, whereas a factory owner provides the internal infrastructure. The s&d takes place by means of s&d networks, plants (e.g. power, cogeneration and wastewater treatment plants) and facilities (e.g. transformer stations), which transfer and/or process media and/or energy in different forms. Proper processing and/or disposal/recirculation of media such as wastewater and rainwater must be ensured. Used water, for instance, must be separated from rainwater and recirculated in a different way (HM Government, 2015). Further regulations exist.

3.6 Summary and Conclusion

The conceptual framework provides one basis for this research, as it describes the environment in which the new model for factory planning will play its part; to fulfil the ROs and to satisfy the research aim will thus be possible.

- The factory structure levels help to structure a factory and reduce its complexity (e.g. for analyses); this also applies to modularity. These levels and modularity are also required to classify diverse FOs/FSs and to understand transformability. Modularity enables transformability and is therefore crucial.
- The general structure comprises the positions and connections of the main FOs/FSs in particular.
- These FOs/FSs were described in this chapter, as were overarching systems and networks.

Furthermore, factory requirements and dynamics (which lead to transformation requirements) were briefly reflected against the backdrop of FOs/FSs and their characteristics. This has not previously been done in such a way in factory planning. Factory planning lacks a model by which these dynamics can be analysed.

The conceptual framework and the new model enable the analyses of the developed factory concepts. By means of the factory structure levels and the general structure, a static description of a factory is possible. The model – particularly the BFPSs – considers these levels, and the general structure as well as their development over time, while the number of FOs/FSs increases, which impacts transformations.

BFPSs are a key component of the new model. BFPSs are not considered in the factory planning literature, but are (besides other concepts which belong to the new model) required to analyse (dynamic) factory developments of the developed factory concepts. BFPSs enable a lifecycle perspective in which eBFPC and difficulty factors (e.g. displacements) play their part. The new model and associated concepts are described in chapter 5 and section 6.1, while chapter 4 involves further data which is required to understand how the model and associated concepts function and how these were developed.

4 Research Methodology

Chapter 4 explains and justifies the research methodology.

Section 4.1 outlines the research methodology and process. Section 4.2 describes the research paradigm and other methodological foundations. Section 4.3 describes the research process from several perspectives. Furthermore, relations of the ROs, approach and methods are explained in order to bring the research process to a higher level. In section 4.4, the ROs, approach and methods are matched with the sections of chapter 6. This explains why the research results are multiply and mutually validated. Coding is explained in section 4.5; this involves grounded theory-related coding procedures. Further elements of grounded theory are explained in section 4.6. Section 4.7 describes all relevant elements and matters of the interviews, which are the key method of this research. Section 4.8 is concerned with research ethics.

Thus, chapter 4 is concerned with the theory and model development (including concepts) while chapter 5 explains in more detail the model and associated concepts, and their interplay. The developed model is both a research result and part of the methodology that is required to reach the other ROs.

4.1 Overview of the Research Methodology and Process

"Triangulation refers to the use of different data collection techniques within one study in order to ensure that the data are telling you what you think they are telling you." (Saunders, Lewis and Thornhill, 2009, p. 146). Several independent data sources and methods of data collection and analyses applied in combination confirm findings (Guba and Lincoln, 1994; Bryman, 2006). Thus, triangulated data can lead to valid and reliable research results (Perry, Riege and Brown, 1999).

This research is based on empirical theory development and a triangulated multiple methods approach. It is not mixed-methods research, as no quantitative research was conducted. The theory development builds upon the systematic research and analysis of literature and technologies, and particularly on semi-structured interviews with factory planning experts against the backdrop of methods/elements of grounded theory (i.e. theoretical sampling, open, axial and selective coding, constant comparison, analytical/memo writing and theoretical saturation). The theory, model and concepts of this thesis were developed from, and are grounded in, existing theory and practice.

Existing theory can be used to develop theory (Layder, 1998) while literature and practice can enable focused research as a basis for semi-structured interviews (Corbin and Strauss, 2015). The interviews provided valuable insights into and about factories and their developments. Numerous Greenfield and Brownfield projects which have led to these factories and their development were disclosed and supported the theory and model development. The interview data comprises 'real-world factories, factory project cases, factory developments' and 'real-world factory-related, factory project-related, factory development-related and factory planning-related knowledge/know-how and experiences'.

Elements of grounded theory were used to develop the model (RO1), the results with regard to today's factories (RO2), the TAS-requirement profile and TFCs (RO3), and the impacts of TFCs on transformability etc. and on FPPs (RO4). The model confirms that the results are grounded, as this is required in order to achieve RO2, RO3 and RO4. Nevertheless, the empirical data necessary to achieve all ROs emerged from the interviews (figure 22).

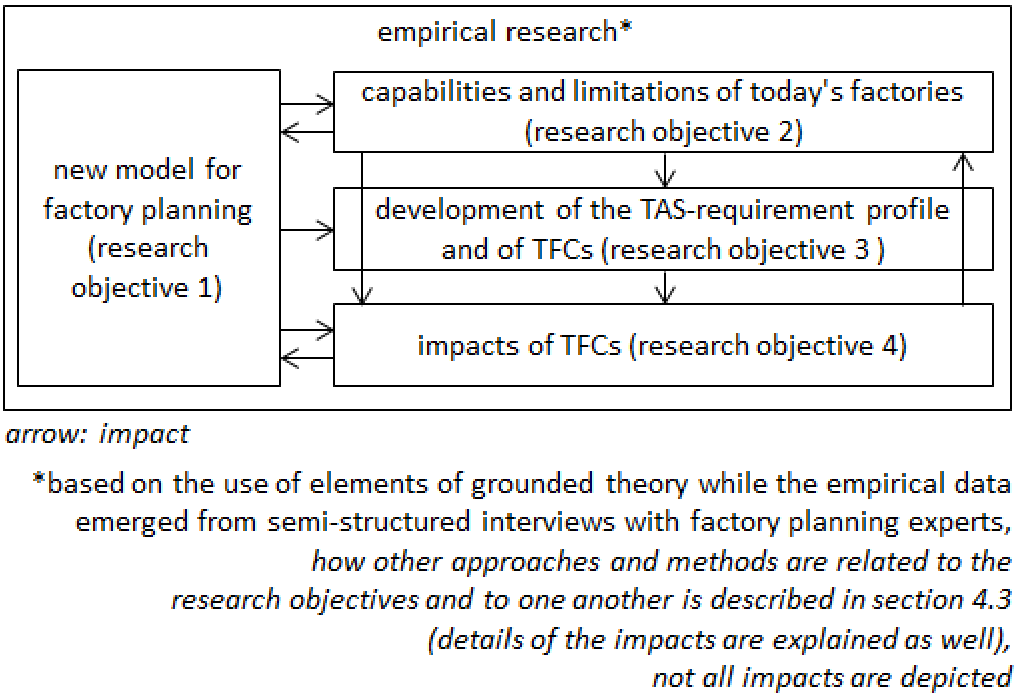


Figure 22: Empirical research as a basic approach to fulfil the ROs

The evolving results supported the author in understanding the interplay of all concepts, and thus also the interplay of the model and its associated concepts, while the majority of concepts as well as the model were developed during the research (due to the interaction of the ROs or, in other words, the model and all concepts). Even though the research results were not developed linearly, it can be claimed that the limitations of today's factories led to the TAS-requirement profile. Interview data led to these limitations and this profile, and provided a further basis for the identification of the impacts of TFCs.

The literature and technology review showed that TASs are not accommodated within existing factory planning theories. Area systems are not seriously considered in factory planning (terrestrial area systems not at all). Therefore, numerous options to conduct this research project exist.

The available theories, models, and concepts cannot be directed and combined in order to show the dynamics in factory planning and to indicate the changing factory characteristics, capabilities and problems that transformations and factory developments can lead to throughout a factory's lifecycle, nor can they identify which aspects are important in this context. Furthermore, the real transformability-, transformation velocity-, and FPP-requirements cannot be shown with available concepts and consequently remain unknown. In addition, a reader of literature must define her/his own picture of a current factory if there is no defined factory concept, while TFCs are unknown.

Thus, it is not currently possible to demonstrate the dynamics in factory planning and the real requirements which factories are confronted with today throughout their lifecycle, nor to define the capabilities and limitations of today's factories and (the impacts of) TFCs; this requires new concepts and a new model for factory planning which have been developed, tested and validated in this research. This model must be able to incorporate and be valid for both today's factories and TFCs. Furthermore, the new concepts must be valid and usable with these factory concepts.

Real-world factory planning, implementation and transformation requirements determine required factory capabilities. The limitations of today's factories are the 'difference range' between the required and the real capabilities of today's factories or, in other words, real-world factory requirements that cannot be met by today's factories. The objective is to use these limitations to develop the TAS-requirement profile.

Required real-world factory capabilities have not been completely identified. To identify these capabilities is the first step. Only then can the real-world factory requirements which cannot be met by today's factories be defined. To develop solutions that will solve the problems that are embedded in this gap is the second step. Such solutions are new factory concepts – the TFCs.

To close these gaps, a new model for factory planning and new associated concepts are required. This model must incorporate real-world factory development stages (the BFPSs) and must be capable of indicating the impacts of eBFPCs by means of BFPSs and difficulty factors for each of the developed factory concept. The factory concepts have also been developed, which shows that most of the contents of this thesis are grounded in new data/theory. Finally, the capabilities and limitations of all developed factory concepts will be known (figure 23).

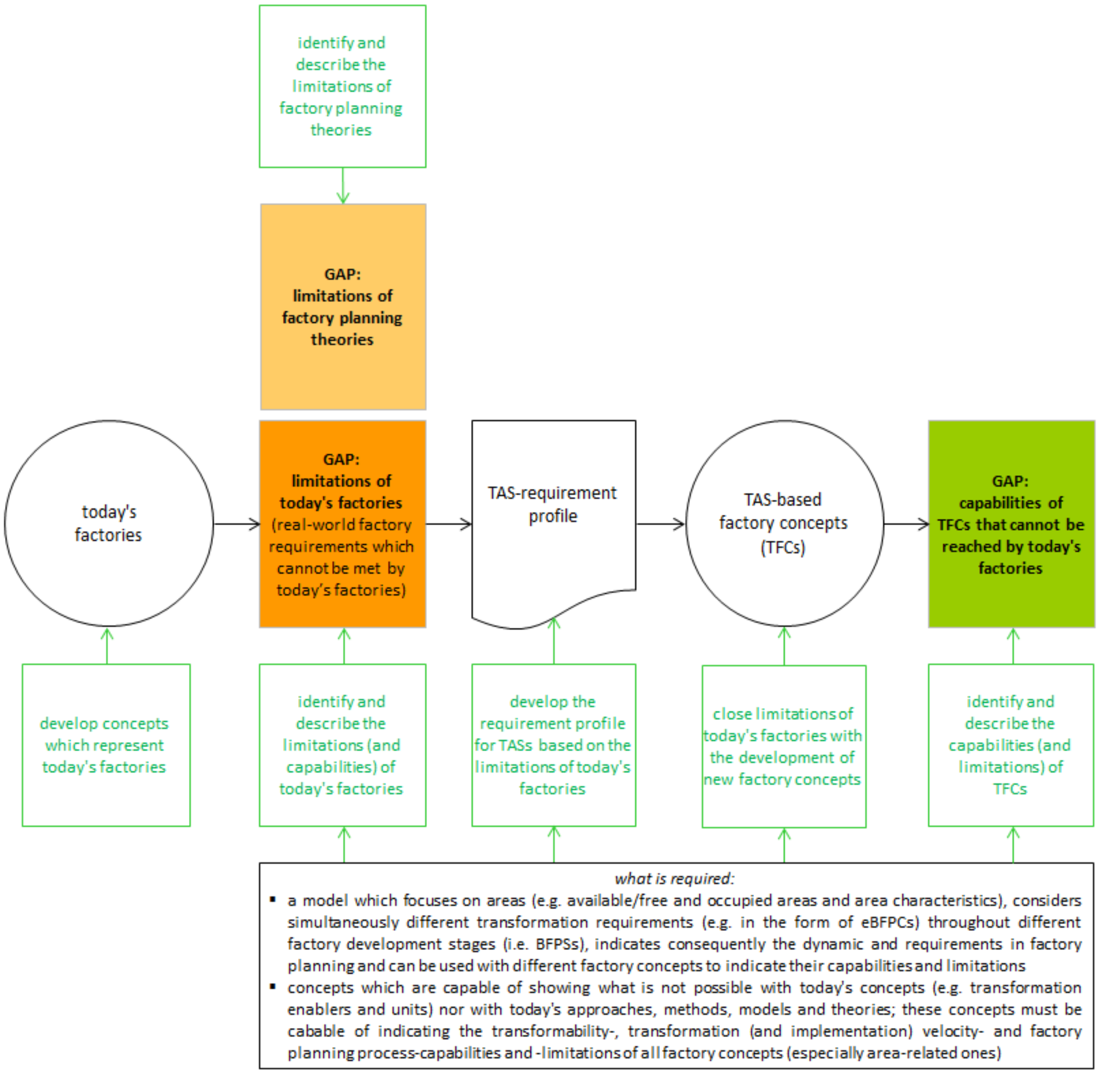


Figure 23: Required process steps

4.2 Research Foundations

4.2.1 Research Paradigm and Time Horizon

Realism was followed as a research paradigm (Saunders, Lewis and Thornhill, 2009), as realism was assumed to be the most appropriate paradigm to develop valid, reliable and realistic research results. The use of codes and categories makes this paradigm scientific (Leplin, 1984; King and Horrocks, 2010).

The time horizon of this research is cross-sectional (Saunders, Lewis and Thornhill, 2009), while some longitudinal aspects are also examined (Taris, 2000), e.g. long-term factory developments.

4.2.2 General Research Approach and Logic

The research is conducted qualitatively, as various complex fields of study and knowledge are examined (Creswell, 2009).

This project is mainly conducted inductively due to the model and concepts' development; however it also involves a deductive approach due to the permanent theory and model application/testing and reflection, which led to their further development. This combination of inductive and deductive approaches is in line with Easterby-Smith, Thorpe and Jackson (2008). The relations between the ROs also indicate this combination.

The limitations of today's factories and technical characteristics of area systems make RO3-results partly deductive. One example is that pipes in terrestrial areas are not transformable, but should be; those in TASs must be transformable. Directly usable interview statements were used to induce and deduce concepts and theory.

BFPSs were developed based on literature and concepts which come from reality (e.g. UHPs), and very clear assumptions are derived from these. The BFPSs were initially largely empty frameworks, and it was necessary to test their validity; this could be ensured through interview data, as these data could be clearly assigned to each BFPS. The use of BFPSs was top down and deductive, while numerous concepts emerged bottom-up from the interview data, and thus inductively. The BFPSs and these concepts could be combined into the model and theory.

What is (technically) feasible with TASs? What potential can be gained through their use? Which developments speak for TASs? How can the limitations of today's factories be converted to develop TAS-requirements? To answer these and further questions required furthermore abduction. The best explanations from a logical perspective were developed based on facts (Burks, 1946; Hanson, 1958). Abduction is crucial for all research results and particularly for the RO3- and RO4-results.

The dynamic in factory planning and real-world factory requirements which emerge through this dynamic emanated from the interviews, and are recognisable throughout sections 6.1 and 6.2. The same applies to the limitations of today's factories. A mix of induction, deduction and abduction led to the development of the TAS-requirement profile. Content and relational analyses were required to identify concepts and their relationships. Analyses of cause-and-effect relationships play an important role in this regard. These are explained next. Further details about abduction are provided in sections 4.3 and 5.4.

4.2.3 Systematic Research and Analysis

Systematic research is planned (Dixon-Woods *et al.*, 2006). A systematic research approach allows the interpretation of data and is reproducible (Tranfield, Denyer and Smart, 2003). New search terms were constantly identified and considered during the research project (see appendix 4.2.3 for search terms).

Clear aims are required to identify cause-and-effect relationships based on a systematic and analytic procedure. One aim of this study was to identify relevant objects and structures and relations among these objects and structures. A cause leads to an effect/impact, while the cause can be backtracked (Schlick, 1925). King and Horrocks (2010, p. 9) argue that "the world is made up of objects and structures that have identifiable cause[-]and[-]effect relationships." They (p. 14) argue further:

> "Demonstrating causality requires the researcher to show that an effect is due to a particular cause/variable. For example, we might undertake research to investigate a causal link . . . Causal explanations are usually in a linear form, stating cause[-]and[-]effect in a straight line – X causes Y."

Causal relationships are not only linearly interconnected. The complexity of factory projects disables the detailed definition of all cause-and-effect relationships. Dunleavy (2003, p. 69) argues that:

> "Systematic accounts disaggregate complex processes into their component parts . . . Causal analyses go further than simply handling different aspects under category headings. They seek to reconstruct complex multi-causation processes by grading and sifting how influences are patterned, weighting causes against each other . . ."

Thus, 'analytic plus descriptive' and 'analytic, argumentative plus descriptive' approaches were used (Dunleavy, 2003, pp. 72–75) to create memos. Analytic means that causal analyses were based on systematic accounts under category headings. Independent and dependent variables could be differentiated (Rath, 2008). Changes in factory environments impact on factories. Actions lead to consequences. The interviews provided numerous cause-and-effect relationships. These real-world data have ensured the validity and reliability of the research results. Confounding variables were not identified, but dilutive effects were (see subsections 4.6.1 and 4.7.4).

All research results were developed based on systematic research and analysis. This is particularly recognisable through the relation of RO2 and RO3 (and the other RO-relations). The model development and testing also took place systematically. Furthermore, the interviews followed a systematic approach (see section 4.7).

The functions of Citavi® (4) (Swiss Academic Software GmbH), Microsoft® Excel® and Word® were used for data analyses. Thus, the author could organise and analyse data systematically in order to identify relationships and patterns. The keywords and categories in Citavi® in particular assisted the author to perform causation-coding and coding and to develop the concepts, model and theory. Word® was used to sort data, the same as Excel®, which was furthermore used to create mind, concept and process maps. This was supported by hand-written memos. Thus, relations between research elements (i.e. categories and concepts) could be identified and defined (see axial coding and further coding procedures in section 4.5).

The interview transcripts were analysed line-by-line. Codes gave meaning to text segments (open coding). Words that were used by the interviewees were partly used as codes. BFPSs were labelled (deduction), as were new/emerging codes (induction). Codes were constantly compared (constant comparison) and their relationships defined (axial coding). This process was repeated as new codes emerged from the interviews. Thus, the author returned to already analysed/coded transcripts.

Codes were grouped, which led to concepts such as eBFPCs and difficulty factors. EBFPCs can be differentiated through the BFPSs and then be broken down and further differentiated with the difficulty factors. BFPSs were critically reflected and did not change. Based on the interview data and real-world factory layout developments, it could be concluded that BFPSs are sensible.

The concept of 'difficulty factor(s)' was developed from codes such as 'small displacement' and 'large displacement'. Initially, other codes were used, and these were changed during analyses. Some initial codes were 'area size', 'area shape', 'area characteristics and required processes' and 'substructures and required processes'. These were partly adapted and led finally to the concept of 'fundamental enabler(s)'. The final codes are recognisable throughout this document, as these are equivalent to the final categories and concepts.

BFPSs provided good support in analysing the large amount of interview and other data, as they provided a framework which helped to bring occurrences and research elements together and to identify their relationships. Finally, the concepts and relationships between the research elements could be identified and defined and the text developed (selective coding). This procedure is also comparable with the framework method or analysis (Ritchie and Spencer, 1994; Mason, Mirza and Webb, 2018; Gale *et al.*, 2013). The following sections provide further information and evidence for these and further process steps (see subsection 4.3.2 for details about the development of BFPSs, section 4.5 for coding-related sources and section 4.7 for interview analyses-related sources).

4.3 Research Process

4.3.1 Research Design, Phases and Process Steps

Figure 24 depicts the 'research design', which is characterised by a continuous theory and thesis development and (re-)writing process. This was based on a mix of a top-down and bottom-up approach (Dunleavy, 2003).

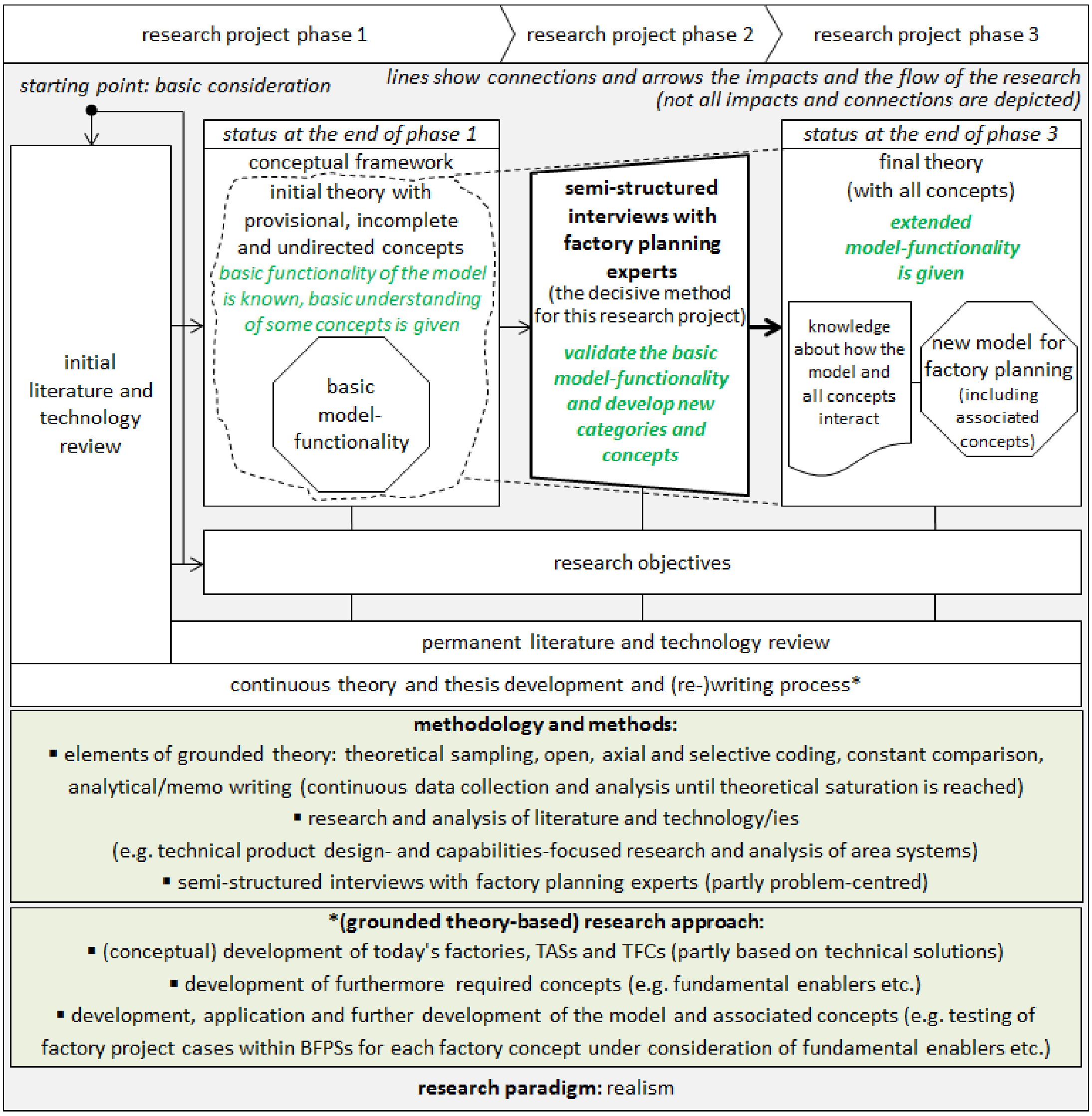


Figure 24: Research design

The author's basic consideration (appendix 4.3.1) initiated the initial literature and technology review. Factory-, factory planning- and area system-related sources were examined, which led to the identified gaps in factory planning theory and practice. Furthermore, the conceptual framework, ROs, initial research results and rough body of work were developed.

Three phases dominated the research project: In ‘phase 1’, the initial theory and model were developed. At the end of this phase, the basic model-functionality was known and a basic understanding of the known associated concepts given. This means that the BFPSs were known and that an eBFPC leads to different impacts within different BFPSs. Not all concepts and categories were known, and particularly not their complete interplay. The developed initial theory and model helped to create reasonable and focused interview questions (IQs), since relevant events and framework conditions with regard to factory planning were considered. In order to increase the chance to consider the most important aspects, one-to-one conversations with twenty-four factory planning experts were conducted prior to the interviews. The most important aspects of these communications were considered in each subsequent communication. With twenty-two of these experts, two or more communications took place. The development of the initial theory and IQs was supported by this approach, which involves advantages of the Delphi technique (Häder, 2014) and increased the validity and reliability of the research results (see theoretical sampling in subsection 4.6.1).

‘Phase 2’ was dominated by semi-structured interviews which were guided by the initial theory and model (Patton, 2002). The research elements were either validated or developed further, while new ones emerged from the interviews. No assumption was rejected or disproved. The interviews helped to explore and develop relevant issues. Real-world data from the interviewees led to the validation of the basic model-functionality, which could be further developed based on this data. Furthermore, the initial theory could be validated and extended to form the final theory. The transcribed interviews were, against the backdrop of the author’s ‘knowledge-to-date’, read and analysed several times during the research process. Data to develop the new concepts and to identify their importance emerged from the interviews (mainly through real-world factory project cases and their impacts, which were explored through numerous follow-up/probing/specifying questions). Several cause-and-effect relationships could thus be identified. The grounded theory-based approach and further analyses of cause-and-effect relationships (e.g.

during the analyses of the interview transcripts) supported this process. Thus, the concepts and the model could be developed and their interplay examined.

In 'phase 3', all research contents were finalised. An understanding of how all concepts interact with one another and the model (extended model-functionality) was acquired (mainly based on the interview data and the grounded theory-based approach; see subsection 4.3.2 and chapter 5). The relationships and importance of concepts changed partly and became more specific and clear-cut (Corbin and Strauss, 2015). The theory could be finalised.

Figure 25 provides an overview of the main process steps of the three phases with the main emphasis on the interviews.

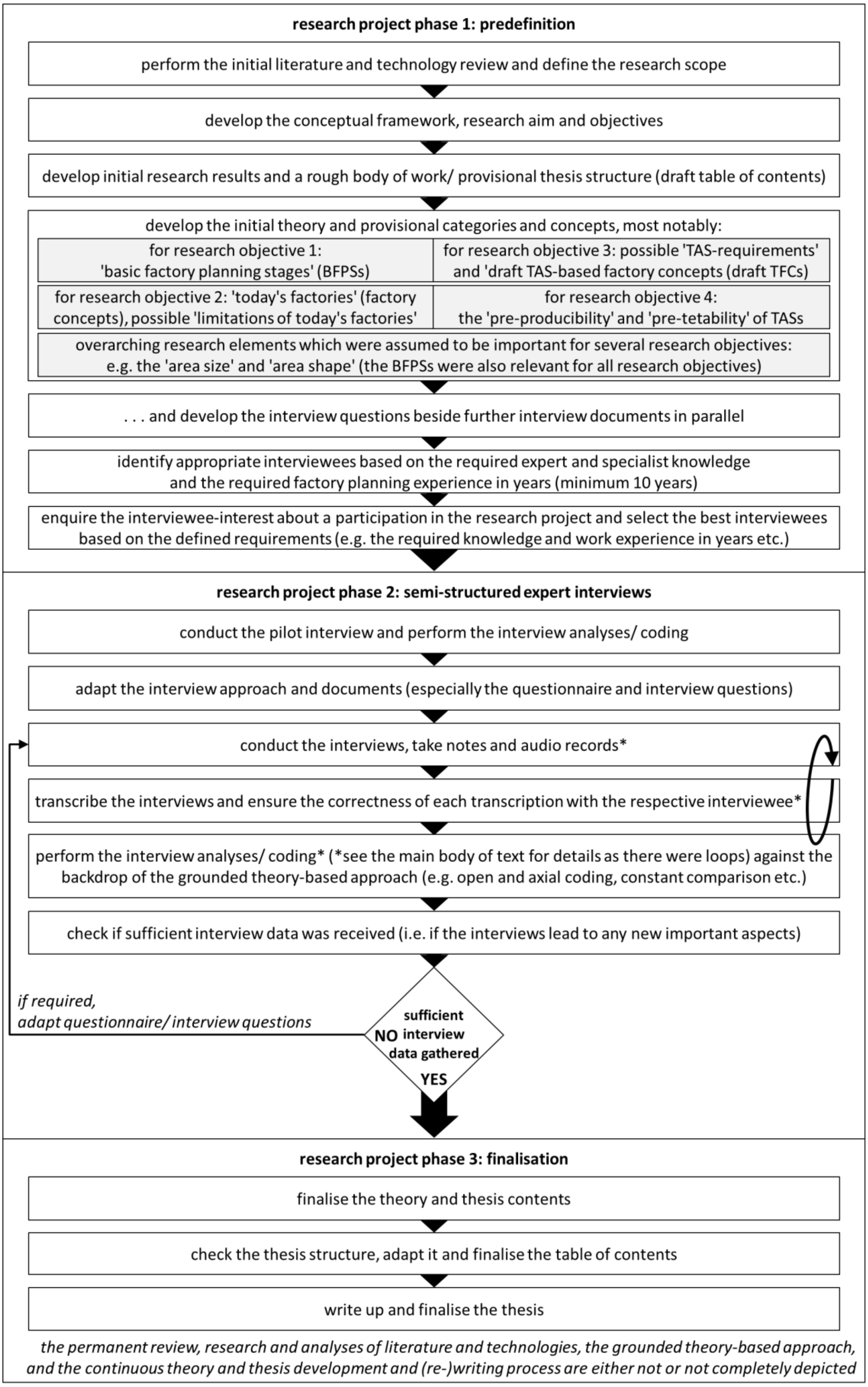


Figure 25: Process steps of the three research phases

Section 4.7 provides details about the development of the questionnaire and IQs and the criteria for the selection of interviewees (as well as further information). The pilot interview was conducted to check the readability and comprehensibility of the interview documents (Roberts, Wallace and Pfab, 2008). This interview was transcribed and analysed (Lamnek, 2005) in the same way as the first interview. To avoid the risk of focusing on less important topics (Schlegel, 2015) and to reduce the risk of getting lost in the data (Roberts, Wallace and Pfab, 2008), the subsequent interview analyses took place after several interviews had been completed (David and Sutton, 2011). Nevertheless, new topics/issues which came up during the interviews were considered in subsequent interviews (Lamnek, 2005).

The literature and technology review and the data collection and analyses took place continuously. Besides coding and grounded theory-related elements, 'concept maps' (Maxwell, 2013) were used to develop codes, categories, "concepts and the relationships among these". Furthermore, 'process maps' which depict the main operating steps and their outcomes were developed (p. 54). Thus, cause-and-effect relationships could also be analysed and stored.

The model (i.e. a BFPS and eBFPC in combination with a factory concept) indicates the required actions (mainly the 'what', the 'where' and the 'when'). The understanding of the other concepts (particularly fundamental enablers) and their interplay with the model is required to highlight the 'why'. This understanding came to the author throughout the phases 2 and 3. Thus, the basic functionality of the model was clear after phase 1, but it was not completely clear how the model and some concepts interact (because some concepts were provisional or incomplete, and also because new ones emerged from the interviews, interview analyses and the grounded theory-based approach). The interviews validated the basic model-functionality and led to new data by which the extended model-functionality could be examined and developed to its final status in phase 3, in the same way as the theory.

The research process was complex, as its elements are interlinked. For a proper understanding of the research process, model- and concept-related information must be provided within the following subsections, as the model and associated concepts were required to achieve the ROs.

4.3.2 Model-related Research Process

This subsection is relevant for all ROs. The following two paragraphs provide an overview and are followed by explanations about the model-related research process, while some concepts are briefly described.

The limitations of today's factories emerged mainly from the interviews. These and further interview data built the main basis for deeper analyses. For these analyses, a new model for factory planning was required. The model and associated concepts were developed and applied (RO1) in order to research and assess the capabilities and limitations of the developed factory concepts (RO2 and RO4). RO1- and RO2-results (i.e. the model and associated concepts, and the limitations of today's factories) are required to define the TAS-requirement profile (RO3).

The models' associated concepts (mainly BFPSs, eBFPCs and difficulty factors, which play their part in the interplay of eBFPCs and BFPSs) were developed and combined to show which transformation requirements occur in each BFPS. The area of each developed factory concept (i.e. a terrestrial area or TAS) is encompassed by the BFPSs, which allows the analysis of the importance of terrestrial areas and TASs for factory planning. This is possible if the capabilities of today's factories and TFCs are considered (i.e. their transformability and FPP-capabilities). Transformation enablers, accelerators and fundamental enablers were applied to assess the capabilities and limitations of the developed factory concepts within the different BFPSs.

The BFPSs build the framework of the model. Site selection is decisive for the location, as the location is determined in the case of today's factories. Required location changes and extensive transformation requirements can thus lead to problems. The fact that transformation requirements come up during Greenfield projects (Sredic, 2011) and that initial configurations of today's factories are crucial for their further developments (Hernández, 2002; Friese, 2008; Erlach, 2013) emerged from the literature. It was assumed that the availability of free undeveloped areas is crucial and that problems occur more when areas are occupied, as UHPs often do not have such areas (at least in their centre). This led to the assumption that built-up/overbuilt/covered areas are the starting point for UHPs, and that the limited transformability of terrestrial areas is the main reason for factories developing into UHPs. The model and concepts' development process and the analyses of different real-world factories and their developments began with these assumptions. These analyses were based on numerous factory layouts which show these factories at different points in time. Several OEM and SME factories were analysed. The analyses indicated the impacts of dynamic factory developments and the dynamics in factory planning. The author has realised that factories follow developmental stages, and that the impacts of transformation requirements differ for each development stage. Consequently, the BFPSs were developed, which built the main basis for the one-to-one conversations and interviews. The initial layout analyses provided a basis for further research and deeper analyses. Further layout analyses were performed in phases 2 and 3, and these analyses have revealed the same patterns. Thus, it could be validated that new and modern factories follow the same overarching developments as the initially analysed factories, which was furthermore validated through all interviews. The results of these analyses are summarised in appendix 4.3.2. Reading this appendix is recommended.

The eBFPCs lead to different transformation impacts/impacts on a factory, depending on the achieved BFPS (and the general structure). BFPSs therefore provided a framework for the interview analyses, where the interview data and results could be sorted. This was because the real-world factory projects and further real-world interview data could then be allocated to the appropriate BFPS. The interviewees described real-world factory project cases and their impacts on factories. Each case occurred in a specific BFPS, which enabled this allocation of data and the enhancement of BFPCs. Furthermore, data for the development of difficulty factors were provided by the interviewees and used to indicate and distinguish the different impacts of the real-world factory project cases for each BFPS. Thus, interview data enabled the conceptualisation of difficulty factors, which additionally enhanced the eBFPCs. This describes the extended model-functionality which emerged from the interviews and the grounded theory-based approach. The following circumstances also belong to this extended model-functionality: The model (and associated concepts) is able to indicate the meaning of the developed factory concepts for factory planning. Factory concepts have different impacts on inhibitors, as factory concepts have different impacts on transformability and FPP-capabilities.

The capabilities and limitations of the developed factory concepts were assessed using transformation enablers, accelerators and fundamental enablers. Their transformability can be assessed with transformation and fundamental enablers, and their FPP-capabilities can be assessed with accelerators and fundamental enablers, while transformability impacts on FPPs. Both this and the fact that fundamental enablers impact on both transformation enablers/units and accelerators/acceleration units indicate the importance of fundamental enablers for factory planning (and that the importance of transformation enablers has decreased throughout and because of this research project). The application of transformation enablers and accelerators leads to the formation of transformation and acceleration units, while fundamental enablers have an overarching status because they provide all-encompassing information about area and substructure characteristics and capabilities in a current factory status (e.g. an achieved BFPS) for each of the developed factory concepts. Thus, fundamental enablers are understood as variables which involve and describe a range of possibilities, and depending on their availability and characteristics/capabilities, impact on transformation enablers/units and accelerators/acceleration units. Fundamental enablers (except for the fundamental enabler 'movable area size' (MAS)) are generally not formed into fundamental units, as this is often not possible and/or reasonable. The designation fundamental unit(s) is not used. The extent to which it is possible and reasonable to form fundamental units crosses a philosophical border and is not analysed further. Acceleration and transformation units are only formed to the required extent. The MAS has a special role and importance in this context: The MAS of today's factories is zero. MASs of TFCs depend on the TFC-type and can involve ranges from e.g. 16 m^2 to entire building footprints and larger structures. The MAS(s) significantly impacts the capabilities and limitations of the developed factory concepts, and determines chiefly their transformability and how difficult and strenuous the required FPPs of these factory concepts are, as sub- and superstructures can be moved/relocated through the MAS (and thus 'area and substructure characteristics', which are a further fundamental enabler).

From a BFPS-related perspective, this means that the transformability and FPP-capabilities of the developed factory concepts change throughout the BFPSs, as areas and area and substructure characteristics change. These areas and characteristics impact particularly on fundamental enablers, which aggregate the transformability and FPP-capabilities of the developed factory concepts. BFPSs provide information about current factory statuses (static), and in combination with eBFPCs and difficulty factors indicate the required transformations/transformation requirements (dynamic). If and how these requirements can be met and processed (i.e. through which FPPs) depends on the factory concept (always in the context of the reached BFPS). Fundamental enablers, transformation enablers/units and accelerators/acceleration units indicate (dynamic) possibilities of the developed factory concepts in terms of transformability and FPPs within these statuses/BFPSs, e.g. how/through which FPPs displacements can be processed in order to meet transformation requirements. Details about these circumstances are provided throughout section 6.1, which explains the eBFPCs and difficulty factors, and sections 6.2 and 6.3, in which the model and associated concepts are applied. Further details about the model and associated concepts are provided in chapter 5. Further details about their development are provided in subsections 4.3.3 and section 5.4.

To define factory- and transformability-related requirements is also possible with fundamental enablers, transformation enablers/units and accelerators/acceleration units (as these can be assessed with these concepts), which is relevant for RO3. These concepts are also relevant for RO4 (and all other ROs), which can be seen in the following.

4.3.3 TAS- and TFC-related Research Process

This subsection is mainly relevant for RO3 and RO4 (under consideration of RO1 and RO2).

TASs are special area systems, and so far have not been considered in factory planning. TASs were conceptualised in this research and combined with FOs/FSs in order to consider them within the new factory concepts, the TFCs (figure 26).

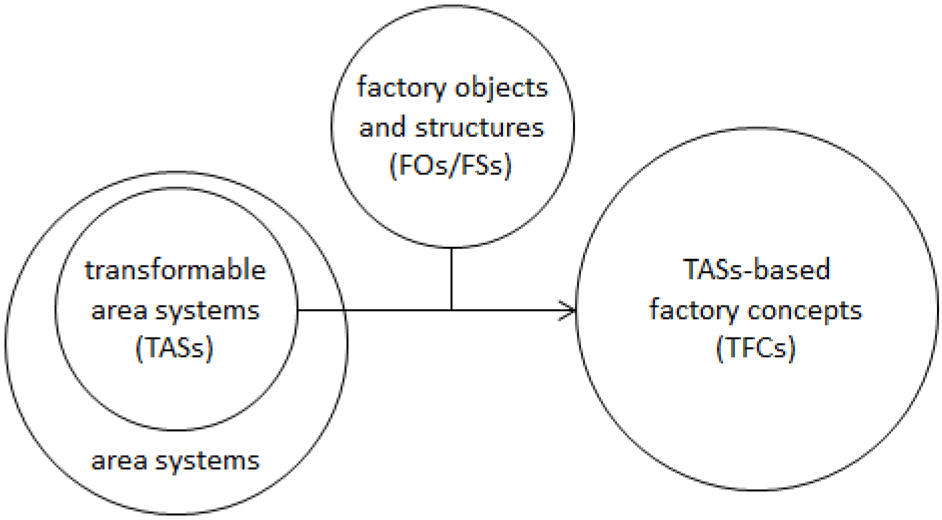


Figure 26: TASs-integration into factory concepts

At a high level, the research process is simple. The model and associated concepts (RO1) are required to assess the (capabilities and) limitations of today's factories (RO2) which lead to the TAS-requirement profile (RO3) which, in turn, is required to conceptualise TFCs (RO3) in order to define their impacts (RO4). RO1 is also required for RO3* and RO4. The TAS-requirement profile defines which requirements must be fulfilled by a TAS. This profile provided the basis to conceptualise TASs and TFCs, as the combination of TASs and FOs/FSs led to TFCs. *Thus, the model and particularly the associated concepts are required not only to assess the capabilities and limitations of the developed factory concepts, but also to formulate factory- and transformability-related requirements and to put them in the shape of the developed concepts.

The interviewees have provided:

1.	. . . the limitations of today's factories (i.e. real-world factory requirements that cannot be met by today's factories) and data which answer how to overcome these limitations.
2.	. . . statements about how the transformability can be improved and about what would be advantageous and desirable (which also indicates the limitations of today's factories).
3.	. . . statements about basic area, substructure, superstructure and factory(/FO/FS) requirements.

These data could be directly used to achieve RO3 and indirectly to achieve RO4, as these data provided a reference/basis of comparison for the latter.

The following text box summarises the essential thoughts and assumptions of the author's basic consideration with regard to transformability.

Today's factories turn into UHPs. The transformability of areas is the root of the problem. An increase of the transformability of areas (and substructures) can solve the problem, as this has a significant impact on the transformability of all FOs/FSs. To validate these assumptions, following steps are required:

(1) examine and critically evaluate backgrounds and framework conditions of real-world factories, factory project cases (including their impacts) and factory developments

(2) identify cases and situations in which the planning, implementation and/or transformation of today's factories is delayed(/slow), limited, both the two latter or disabled (FPP are relevant in this regard)

(3) link the data back to the transformability of factories

In sum this led – through the interviews – to the planning, implementation and transformation inhibitors, the FPPs of today's factories that are required to overcome these inhibitors, the difficulty factors and the eBFPCs (always in the context of BFPSs). These data, in turn, led to the limitations of today's factories and to area and substructure requirements (e.g. transformation requirements), and subsequently to the TAS-requirement profile. This profile was mainly developed and specified through the interview data, as this data was also required for the development of the model and associated concepts.

Based on the TAS-requirement profile (the requirements of which can be assessed with transformation enablers, accelerators and fundamental enablers), available area systems were analysed and differentiated in order to enable a statement regarding whether this profile can be achieved using available area systems and technologies. This could be affirmed, because some area systems comprise the required characteristics to meet the requirements/required capabilities in this profile (particularly area- and substructure-related transformability). It was furthermore possible to develop TAS design options (see subsection 6.3.1 for details about the TAS-requirement profile and these options). TASs are feasible, even though they require further development.

The analyses of area systems took place based on their characteristics and capabilities, which were assessed by partly developing transformation enablers, and developing accelerators and fundamental enablers against the backdrop of this developing profile. The extent to which transformation and fundamental enablers can be matched with these systems was analysed. The fundamental enablers in particular were crucial for accelerators/acceleration units.

The capabilities and limitations of 'TASs for factories' and of TFCs are largely identical because the structural requirements for these TASs and TFCs are largely identical, and because their area- and substructure-related requirements are identical (further technology-related information can be found in appendix 4.3.3). These aspects and the fact that area- and substructure-related transformability requirements of current factories and 'TASs for factories' are identical are crucial.

The analyses of the capabilities and limitations of TFCs were based on the real-world factory project cases provided by the interviewees and also on real-world factory layouts. Both cases and layouts indicated real-world factory developments (see subsection 4.7.4 and section 5.4 for further information).

Where required, the contents of section 6.3 were developed based on the combination of the capabilities of TASs and other FOs/FSs and under consideration of the possibilities provided by given and feasible industrial structures (e.g. large shipyards) and possible transportation via road and/or water.

TASs and TFCs and their capabilities and limitations were analysed through abduction/logic and the systematic analyses of cause-and-effect-relationships, and the application of the model and the associated concepts (particularly transformation enablers, accelerators and fundamental enablers). This took into account the possibilities provided by the previously mentioned industrial structures, which must be large in order to enable parallelised processes (e.g. the parallelised production of TASs, TBSs and other FOs/FSs). Elements of grounded theory were crucial for the analyses; these elements included constant comparison and memoing (also based on layouts) (see subsection 4.3.4 and section 5.4 for details).

Thus, RO3- and RO4-results are based on the application of the model and associated concepts. Furthermore, the RO4- and (partly) RO3-results are based on systematic analyses of cause-and-effect relationships and abduction/logic. This means that the logical combination of the possibilities provided by large industrial structures and the feasibilities of TASs/TFCs has led to realistic/feasible possibilities. The author was particularly discerning in this regard. Impractical and questionable possibilities were abandoned and not considered, which makes the results realistic, valid and reliable. Risks and disadvantages were considered, and further analyses indicated where required (e.g. further technical analyses and feasibility studies that go beyond the scope of this research).

4.3.4 Relations of the ROs, Approach and Methods

The RO-relations and IQs show that all RO-results are based on the interviews. The fact that this also applies to the RO3- and RO4-results can also be seen in the structure of chapter 6 (see section 4.4 for details). In sum and under consideration of subsections 4.3.1, 4.3.2 and 4.3.3, this means that:

I.	The RO2-results (particularly the limitations of today's factories, factory requirements and desires of interviewees with regard to factory capabilities etc.) provided a basis to reach RO3 (which was required as a basis to reach RO4).
II.	The RO2-results (i.e. the capabilities and limitations of today's factories) provided a basis to reach RO4 (as a reference/basis of comparison) and vice versa (which means that the RO4-results (i.e. the impacts of or, in other words, the capabilities and limitations of TFCs), which emerged not only indirectly but also directly from the interviews, provided a basis to reach RO2). *This means that the capabilities and limitations of the developed factory concepts could be constantly compared to one another. When it becomes clearer what today's factories are capable and not capable of, it becomes clearer what TFCs are capable and not capable of and vice versa. It leads, for instance, to other FPPs if the area is mobile compared to the case that it is not. Aspects like this provided a further database for analyses and comparisons and helped to reach the ROs.*
III.	Real-world factory project cases and factory layouts provided a reference and basis for TFC-analyses (*see section 5.4 for further information and details*).
IV.	The RO1-results (i.e. the model and associated concepts*) were required to reach RO2, RO3 and RO4, while the RO2- and RO4-results were relevant for RO1, as they provided (quasi-feedback) data to develop the model and associated concepts (*particularly transformation enablers/units, accelerators/ acceleration units and fundamental enablers).

This explains that the research could not happen linearly, as it was at least and mainly simultaneously required to:

A.	research and assess or, in other words, identify the limitations of today's factories (part of RO2)
B.	define the TAS-requirement profile (part of RO3)
C.	research and assess the impacts or, in other words, the capabilities and limitations of TFCs (part of RO4)
D.	develop and apply the new model and associated concepts (RO1) (*see section 5.4 for further information and details on all these points*)

These factors make this research an interlinked system of the approach, methods, model, concepts and thoughts (or ROs). This system is depicted in a simplified form in figure 27.

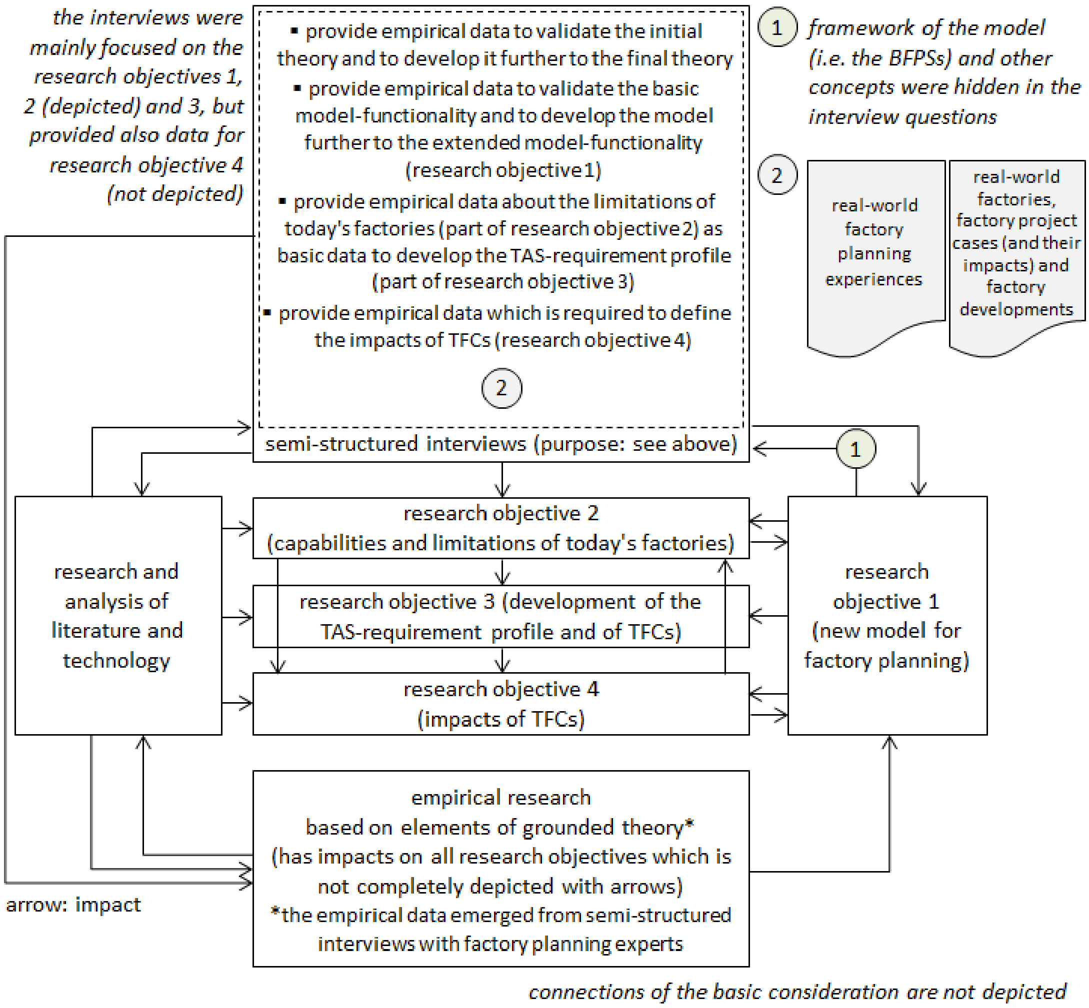


Figure 27: Relation of the ROs, approach and methods

Further details are provided in section 4.4, subsection 4.7.4 and section 5.4.

Table 4 summarises the relevant concepts of this research. These concepts are taken up in subsection 4.7.4 (IQs), while chapter 5 explains them in detail. In section 5.4, these concepts are again taken up and discussed in the context of the used methods and the elements of grounded theory.

concepts (number)	information
developed factory concepts (5)	traditional factory, modern factory, terTFC, terTFC_bw and marTFC
BFPSs (4)	BFPSs are relevant for all developed factory concepts (see chapter 5 for details)
eBFPCs (4)	eBFPCs are relevant for all developed factory concepts (see chapter 5 for details)
difficulty factors (the amount of difficulty factors is not definable)	several difficulty factors and different combinations of these factors exist (i.e. domino effects/chainings) (see section 6.1 for details)
transformation enablers (6)	modularity, mobility, scalability, pluggability, universality and linking ability (of which each can be combined with the developed factory concepts or the developed factory concepts' FOs/FSs (to define/describe transformation units))
accelerators (3)	pre-producibility, pre-testability and reusability (of which each can be combined with the developed factory concepts or the developed factory concepts' FOs/FSs (to define/describe acceleration units)) (see chapter 5 for details)
fundamental enablers (4)	area size, area shape, area and substructure characteristics and movable area size (MAS) (of which each is combined with the developed factory concepts) The definition and description of fundamental enablers encompasses all relevant aspects (with regard to these concepts) that are required to reach the research objectives. The designation fundamental unit(s) is not used in this thesis while the question about if it is sensible to form fundamental units touches a philosophical border and is not analysed further in this research project (see chapter 5 for details). Transformation and acceleration units are formed to the required extent. The formation of acceleration units follows the same logic as the formation of transformation units.
further concepts and information	BMEs, the inner and outer mobility, neutrality, further concepts and substitution processes, the pre-production of parts (etc.) and outsourcing (must be appropriately considered)
Information: The number of considered factory planning theories (including methods, approaches etc.) and FOs/FSs, terrestrial areas, terrestrial and maritime area systems and maritime developments show furthermore the complexity of this research. The research objectives and the limitations of factory planning theories indicate the complexity of this research additionally. To disclose the limitations of factory planning theories was required to show the limitations of today's factories fully. Furthermore, it was required to define several terms.	

Table 4: Number of concepts

To return to a higher level, figure 28 provides a simplified big picture of the research process, based on the factory concepts and ROs. Areas were crucial for this process, which is recognisable as the straight arrows indicate the previously explained main research flow.

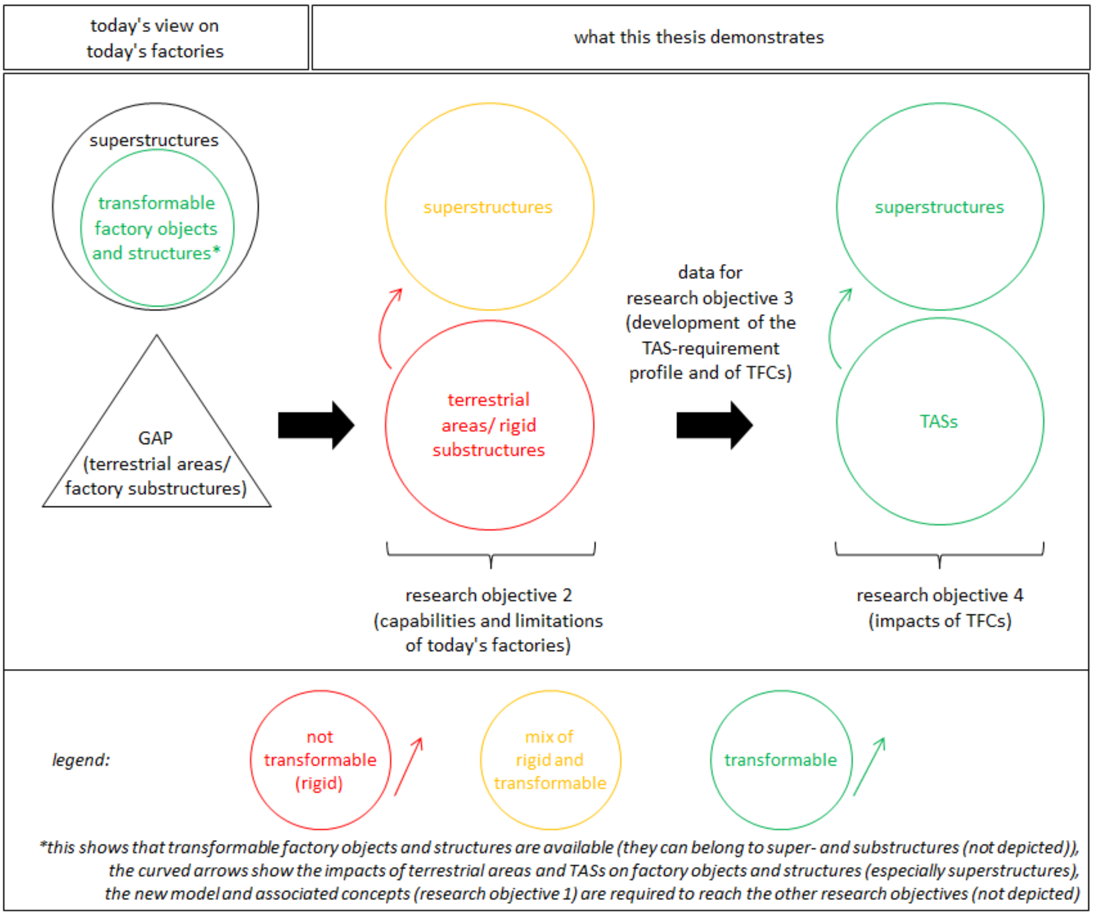


Figure 28: Research Process

4.4 Validation of Research Results

That RO1-, RO2-, RO3- and also RO4-results are based on interview data was explained in section 4.3.

RO2-results (section 6.2) are based on RO1-results (chapter 5 and section 6.1). RO3- and RO4-results (section 6.3) are based on RO1- and RO2-results, as RO1- and RO2-results provide the data required to achieve RO3 and RO4, the same as further data in section 6.3 (while section 6.3 provides also a basis of comparison for section 6.2). Furthermore, the model and associated concepts (RO1) are based on RO2- and RO4-results.

Interview data is mainly provided in sections 6.1 and 6.2, but also in section 6.3. Because of the RO-relations, this data is relevant to all research results and thus for chapters 5 and 6.

The new model is applied under consideration of the basic transformability-related capabilities and limitations (assessed with transformation enablers/units and fundamental enablers) and the basic FPP-capabilities and -limitations (assessed with accelerators/acceleration units and fundamental enablers) of the developed factory concepts. The resulting FPPs can then be defined (as the transformation enablers/units, accelerators/acceleration units and fundamental enablers result in FPPs of the developed factory concepts) and the model applied and validated, which results in consequences for the developed factory concepts. This takes place in section 6.2 for today's factories and in section 6.3 for TFCs. In section 6.4, qualitative project durations, and in section 6.5, lifecycles of the factory concepts are compared and contrasted. This is based on the results of the previous sections. This comparison ends with the rating of the developed factory concepts in section 6.6. The results of previous sections flow into the following sections (table 5).

<table>
<tr><th></th><th colspan="2">(research methodology and) research methods overview per results section</th></tr>
<tr><td>section 6.1
is mainly concerned with research objective (RO) 1 and is relevant for both today's factories and TFCs</td><td>interviews</td><td rowspan="5">research and analyses of literature and technology/ies

grounded theory-based research approach (including coding)</td></tr>
<tr><td rowspan="2">section 6.2
is concerned with today's factories (RO2) and the application and validation of the model and associated concepts (RO1-results).</td><td>interviews</td></tr>
<tr><td>application of the model
and associated concepts</td></tr>
<tr><td rowspan="2">section 6.3
is concerned with TASs and TFCs (RO3 and RO4) and the application and validation of the model and associated concepts (RO1-results)</td><td>interviews (directly and indirectly)</td></tr>
<tr><td>application of the model
and associated concepts</td></tr>
<tr><td>section 6.4
is concerned with both today's factories and TFCs</td><td colspan="2">based on prior sections</td></tr>
<tr><td>section 6.5
is concerned with both today's factories and TFCs</td><td colspan="2">based on prior sections (including section 6.4)</td></tr>
<tr><td>section 6.6
is concerned with both today's factories and TFCs</td><td colspan="2">based on prior sections (including section 6.4 and section 6.5)</td></tr>
<tr><td colspan="3">Information: The developed model and associated concepts (chapter 5) are relevant for all these sections. This is a rough overview.
Further information and details are provided throughout chapter 4 and chapter 5.
The sizes of the cells say nothing about their importance.
Sections 6.4, 6.5 and 6.6 are based on the previous results (further information and details are provided in these sections).
All RO-related research results are based on the interviews and the grounded theory-based research approach in which analyses of cause-and-effect relationships and abduction/logic played (beside induction and deduction) an important role, which is explained throughout chapter 4 and chapter 5.</td></tr>
</table>

Table 5: Methods and RO overview for each results section

The following paragraphs support the data in sections 4.3 and 4.4 to this point, and describe why the research results are multiply and mutually validated.

EBFPCs and difficulty factors are based on the interview data in subsections 6.1.1 to 6.1.5 and in subsections 6.1.7 to 6.1.10, which were combined with available sources. These data allowed only the description in subsections 6.1.6 to 6.1.10 (see appendix 4.4 for details).

The results and interview statements in section 6.1 validate the results and interview statements in section 6.2, and vice versa (particularly through the interview data). Furthermore, sections 6.1 and 6.2 provide a basis for section 6.3, and vice versa. The results in section 6.3 are thus directly and indirectly based on the interviews (consider subsections 4.3.3 and 4.3.4). Interview statements in the main body of text exemplify the findings where required, while related appendices involve further interview data.

BFPSs are a key component of the model, and they provided one basis for the (multi-dimensional) framework analyses (Ritchie and Spencer, 1994; Mason, Mirza and Webb, 2018), as did the developed factory concepts and eBFPCs. These concepts, difficulty factors and other concepts (e.g. fundamental enablers) helped to sort data and supported the content and relational analyses (Gale *et al.*, 2013). Thus, data could be combined into concepts and assigned to the appropriate BFPS (eBFPC and factory concept). This has simplified the combination and linkage of concepts.

BFPSs were multiply validated by all interviewees, or rather confirmed if the experts' knowledge/know-how, years of experience and contact with other experts and specialists are considered. The period of time that is encompassed through the data provided by the interviewees and the real-world factory layouts are also important and weighty. Thus, diverse factories and factory types could be covered through the research, as data about many factories, real-world factory project cases and factory developments were provided. Data of new factories up to factories that are more than 100 years old were analysed. Thus, these data not only double the evidence, but also do more than that. The evidence is given multiple times and furthermore can be found in reality – in the past, the present, and the future. (If today's factories continue to be used and constructed in the traditional way, they will develop into UHPs.) BFPSs, eBFPCs, BMEs, difficulty factors, fundamental enablers and accelerators/acceleration units are therefore evidenced in the real-world data (particularly interview data).

The contents of chapter 6 are evidenced in the interviews. In most cases, eight out of eight interview answers were comparable or led in the same direction.

To construct a story required the consideration of all knowledge elements and their relations. This process particularly required axial and selective coding (see section 4.5) in order to make the storyline fit, while all relevant data were considered. This means that no data were dropped/left out, which could have had an impact on the research results (except for impractical and questionable possibilities with regard to TASs/TFCs). The BFPSs helped to construct this story and consider central phenomena (e.g. displacements and MASs), for which interview statements were crucial. The BFPSs could be validated through the application and validation of the new model and the associated concepts in sections 6.2 and 6.3, as well as the related interview statements. In addition, BFPSs are validated through further interview data in subsection 6.2.6 and section 6.1. These data also validate other concepts and research results.

The data (particularly interview data) in sections 6.1, 6.2, 6.3 and their appendices allows only the formation of one objective picture and related conclusion(s), which are provided throughout chapter 6. The results find their academic rigour in the data. They cannot be rejected or disproved, because the data (especially what the interviewees said) backs up/supports one another.

The main data sources were real-world factory project cases (including project reports and other documents) and real-world factory layouts. Both cases and layouts indicated real-world factory developments, which were also available through other sources, e.g. company reports.

Several methods were applied in order to gather and analyse data, e.g. analyses of documentation, factory layouts, and interviews (consider also the information about coding and grounded theory in the following sections and in chapter 5).

The research results are validated through the interview statements, which are included in tabular format in the main body of text and in several appendices. The tables in subsections 6.1.11 and 6.2.7 summarise how the interviewees viewed the most important topics and concepts, which along with the subsequent data also show that the developed transitions and further research results are valid and reliable.

In addition to the previously provided information about why the collected data are credible and about how the research results were validated (e.g. in subsection 4.3.2), further information is provided throughout section 4.6, section 4.7 (e.g. prerequisites for interview participation, audio recording etc.) and chapter 5.

The strengths of this research are the large number of considered cases and facts, and the levels of detail which ensure valid and reliable research results (Yin, 2012), and deep understanding (Silverman, 2013).

4.5 Coding

Coffey and Atkinson (1996, p. 36) claim, that "coding ... is a first step toward organizing the data into meaningful categories". Thus, coding can be seen as a process of data classification/labelling which enables the identification and definition of categories. Categories must be ordered and properly linked. To continually return to the data in an iterative process (figure 29) ensures proper categories and their purposeful linkage.

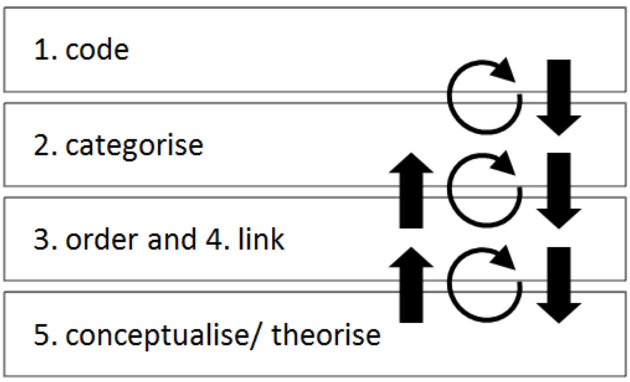


Figure 29: Coding (modified) (based on Coffey and Atkinson, 1996)

Categories can be combined into concepts, which reduce complexity. Coding makes data more tangible and analysable (Coffey and Atkinson, 1996).

The formation of categories and concepts through the purposeful combination of data and identification of relationships, and their grouping to develop and extend theory is differentiated further with 'open coding', 'axial coding' and 'selective coding' (Strauss and Corbin, 1990; Corbin and Strauss, 2015) (table 6).

open coding	develop many relevant categories and concepts (including their properties and dimensions)
axial coding	develop relationships between categories and concepts and between concepts (e.g. based on causal conditions/cause-and-effect-relationships) and link them
selective coding	develop theory through the closure of remaining gaps; to test the single concepts against the backdrop of the established theory is crucial, as the theory must be examined and verified (especially data that is used to close remaining gaps must be valid and reliable); to test the theory and the functionality of the developed model (and associated concepts) which means to test the factory concepts with various real-world factory project cases/eBFPCs against the backdrop of BFPSs in the light of the factory environment is fundamentally important (the same real-world factory project cases/eBFPCs were used for each factory concept to ensure the comparability of the research results); to define the importance of categories and concepts is central in selective coding

Table 6: Open, axial and selective coding (based on Strauss and Corbin, 1990 and Corbin and Strauss, 2015)

These coding procedures are used in grounded theory, and are relevant for the analyses of literature, technologies and interviews. Further elements of grounded theory are described in the following.

4.6 Grounded Theory

Factory planning with a major emphasis on terrestrial areas has barely been researched, and only superficially against the backdrop of area systems. When a topic has been barely researched, grounded theory is an appropriate approach (Goulding, 2002). Grounded theory is unique, as it leads to theory development in the light of the following aspects (Corbin and Strauss, 2015):

1.	The theory is developed based on "data collected during the research process". This characteristic "grounds the theory and gives the methodology its name" (Corbin and Strauss, 2015, p. 7). Thus, the theory is grounded in systematically collected and analysed data (Glaser and Strauss, 1967).
2.	Data can be collected from literature and interviews (Corbin and Strauss, 2015).
3.	"Data collection and analysis continue in an ongoing cycle throughout the research process" (Corbin and Strauss, 2015, p. 7).
4.	The interrelated data collection and analysis happens simultaneously against the backdrop of a growing amount of data until (theoretical) saturation is reached. Saturation is reached when "no new concepts are emerging" and their characteristics and interrelations are clear-cut (Corbin and Strauss, 2015, p. 134).

One requirement of research that is based on a full grounded theory is that categories and their relations are defined (Strauss and Corbin, 1990; Wiesche *et al.*, 2017), which was not completely done within this research. Nevertheless, a grounded theory-based approach can also be justified by the following points:

I.	A critical attitude against the existent factory planning theory prior to the research was a prerequisite for this approach (Strauss and Corbin, 1990).
II.	Factory planning and area systems were combined and make the research cross-disciplinary.
III.	Both area systems and TASs have required an original classification and typology.
IV.	New categories and concepts were developed based on empirical (interview) data and formed/combined to a new theory and model.
V.	Elements of grounded theory such as theoretical sampling, constant comparison, open, axial and selective coding and analytical/memo writing, and the developed model and associated concepts were applied.
VI.	New research and knowledge elements (i.e. categories and concepts) have been permanently included into the analytical/memo writing instruments (i.e. texts, mind, concept and process maps, and factory layouts (see section 5.4 for details)).
VII.	Thoughts could be sorted and relations between categories and concepts and between concepts examined/tested and identified while the theory became richer and more understandable.
VIII.	The research was continued until theoretical saturation has been reached.

The theory is mainly grounded in empirical data (collection and analyses). A number of concepts were available from the start (e.g. transformation enablers, some transformation units, and inhibitors), but the importance of transformation enablers/units has decreased, as new concepts were developed, e.g. fundamental enablers.

4.6.1 Theoretical Sampling and Constant Comparison

Theoretical sampling is a method that is based on an iterative process of adding, deleting, modifying and reordering research elements in order to develop and improve theory (Corbin and Strauss, 2015) and not one which is "starting with a predetermined sampling frame"* (Robinson, 2014, p. 5244) (please consider: the BFPSs helped to allocate data and were furthermore open to change). The aim of this method is to collect all data which are required for a complete development of all categories and concepts (including their properties, dimensions and relationships) which are relevant for the theory development (Strauss and Corbin, 1990; Corbin and Strauss, 2015). *Thus, this theory development takes place without a predefined choice and combination of elements. In an ongoing process of data collection and analysis, emerging categories and concepts determine which data should be acquired and from where/whom. Data can be collected from places, events and people. Theoretical sampling is a process of successive decisions about which sources should be selected and in which sequence they should be analysed, based on the knowledge to date. These decisions build upon one another during the research process, where selection criteria become more specific (Wiedemann, 1991) which leads to a further data collection in order to close remaining open issues in the emerging theory (Glaser and Strauss, 1967).

Constant comparison deals with a close connection of data and codes/categories. Data pieces are constantly compared to one another in order to identify differences and similarities. Similar data are grouped into categories and concepts, while it is important to take care of meaning that is shared between coded texts and to ensure that developed categories and concepts fit the growing data pool (Glaser and Strauss, 1967; Strauss and Corbin, 1990; Corbin and Strauss, 2015). Constant comparison supports the categorising of actions, events and statuses into classes. These classes can be "predefined" or emerge "as a result of coding or analytic memoing" (Miles, Huberman and Saldana, 2013, p. 285).

4.6.2 Theoretical Saturation

Coding procedures and constant comparison are important during theoretical sampling. In combination, they correspond to a stepwise approach until theoretical saturation is reached (Strauss and Corbin, 1990). Possible disadvantages of grounded theory and selective coding were eliminated through constant cross-checks of categories, concepts and links, and tests of the model and theory (Flick, 2014).

The constant testing of assumptions, concepts and relationships through different cases while including new data was supported by the model. Analytical/memo writing was essential for developing the concepts, model and theory (see section 5.4).

Theoretical saturation was finally reached, as:

A.	. . . sufficient data could be gathered and formed to categories and concepts.
B.	. . . all important categories, concepts, patterns and key factors/issues could be identified and considered and as no new essential issues came up which could change the research results (e.g. the developed model and theory).
C.	. . . the research results were multiply examined/tested and could be validated through the interview and further data (see chapter 6 and its appendices) which makes this research valid and reliable (particularly the interview data is important in this regard).
D.	. . . the main characteristics of categories and concepts and the main relationships between categories and concepts and between concepts could be identified.
E.	. . . the extended model-functionality could be developed and is given.
F.	. . . all the research elements/contents built a comprehensive theory (as comprehensive as possible in the light of the framework conditions of this research project and the considered amount of data and its complexity).

4.7 Interviews

Interviewing encompasses systematic preparation, execution and processing of conversations with specific content-related objectives (Schawel and Billing, 2012) and can be used to validate or falsify developed contents of an initial theory and to extend a theory through the identification of new generally valid patterns (Bryman and Bell, 2015).

This research project uses qualitative semi-structured face-to-face interviews with factory planning experts. These interviews have an investigative and explorative character, and are also partly problem-centred (Witzel, 1985; Hölzl, 1994; Kurz *et al*., 2009). A neutral communication style was used, and impulses were given to go in-depth without biasing answers (Lamnek, 2005).

Semi-structured interviews allow probing through open conversations (Patton, 2002). Key interview themes were developed before the interviews (Flick, 2014) while new themes emerged during the interviews (Saunders, Lewis and Thornhill, 2009). The partially standardised questionnaire helped to organise the knowledge of the subjects (Mey and Mruck, 2011), and simplified the comparability of the interviews and the data-based generalisability. Expert knowledge, real-world experiences and cases have a special importance in gaining knowledge (Meuser and Nagel, 2009), as do views and ways of acting (Witzel, 1985). Interviews with experts compensate for a smaller number of interviews (Aghamanoukjan, Buber and Meyer, 2007). The interviewer and the interviewee have different roles and different degrees of freedom (Mayring, 2002). The interviewee can talk relatively openly, while the interviewer must follow his structure, at least partly. In problem-centred interviews, prior knowledge is available that must be validated and deepened. Therefore, problem-centred interviews lie on the interface between induction and deduction (Kurz *et al.*, 2009). Consequently, theory-based research and empiricism are combined. RO2-related questions involve mainly a problem-centred character. RO1- and RO3-related questions are rather solution-oriented, while RO4 focuses on the impacts of TFCs. Nevertheless, answers which referred to problems also involved important data for these ROs (Hölzl, 1994). The following points are based on Hölzl (1994):

(1)	Essential aspects of this problem-centring were developed prior to the interviews.
(2)	A stepwise collection and examination of data and development of contents and relationships of data took place.
(3)	This applies to single and several interviews (and to the entire research process which underpins the grounded theory-based approach).
(4)	The openness of the interviewer was crucial, as the importance of elements and relations is defined by the interviewees. Thus, the interviewer was open to changes of his initial concepts, model and theory.

4.7.1 Selection of Interviewees

Only people who were recognised as experts were interviewed (Meuser and Nagel, 2005). The probability of receiving good answers increases if experts also recognise the interviewer as an expert. The interviewer should at least have a basic knowledge of the expert and specialist fields that are relevant to the research (Pfadenhauer, 2002, 2007). The competence of the interviewer is crucial (Meuser and Nagel, 2009). He is familiar with factory planning theory, knows related terms and their meaning, and is experienced in factory planning practice, industrial construction and engineering, process/production optimisation and professional project management. These are good interview prerequisites, as the interviewees are more likely to acknowledge the interviewer as a competent partner if he has practical experience (Meuser and Nagel, 2009), which is essential in order to receive adequate answers (Honer, 2000).

The expertise and competence of experts is based on comprehensive knowledge, vast understanding, and years of experience in their field of knowledge (Hitzler, 1994; Pfadenhauer, 2007). Expert interviews are a chief source of information, as experts have access to other experts and specialists, and data which are hardly accessible or to which access is normally denied (Meuser and Nagel, 2009).

Eight factory planning experts were interviewed. Three were former senior consultants, and all of them perform consulting functions in their companies (mainly due to their specialist knowledge). These experts were recommended by people from the author’s business network, who informed the author about the professional positions and specialist fields of these experts; this increased the probability of receiving good answers.

In order to receive a broad spectrum of different expert perspectives, the choice of interviewees was based on the initial theory, RO1, RO2, the initial TAS-requirement profile (RO3), and the required knowledge and experience of the interviewees in factory planning and relevant specialist fields (Meuser and Nagel, 2009). Thirty-two experts were identified. Eight of these were invited and all eight agreed to participate. Further experts would have been interviewed if eight interviews had not been sufficient. However, this was not required (see subsection 4.7.5 for details). Only factory planners with extensive professional expertise and experience in factory planning were interviewed. Table 7 shows details about the chosen experts.

interview partner (IP)	job/ role/ professional position (employers, including former ones, in brackets)	years of work experience in industrial enterprises	years of work experience in factory planning	main fields of work experience/ core competencies and specislist fields (specialist field (sf)) (experience with regard to forms of enterprises in brackets)	academic degree(s)
IPpilot	factory planner (different SMEs and car OEMs)	> 20	> 15	plant development, industrial construction/ planning and construction processes (sf), Greenfield and Brownfield projects (different OEMs, suppliers and further SMEs; world-wide)	engineer architect
IP1	senior factory planner (different car OEMs)	> 40	> 20	approval processes (sf), construction and building law, industrial construction/ planning and construction processes, Greenfield and Brownfield projects (different OEMs, suppliers and further SMEs; world-wide)	business economist
IP2	team leader international factory planning, former senior factory planner (different car and truck OEMs)	> 30	> 20	site selection (sf), plant development (sf), industrial construction/ planning and construction processes (sf), Greenfield and Brownfield projects (different OEMs, suppliers and further SMEs; world-wide)	construction engineer, industrial engineer
IP3	senior factory planner (different SMEs and car OEMs)	> 20	> 20	site selection (sf), plant development (sf), industrial construction/ planning and construction processes (sf) , Greenfield and Brownfield projects (different OEMs, suppliers and further SMEs; world-wide)	engineer architect, real-estate economist
IP4	strategy planner, former senior factory planner (different SMEs and car OEMs)	> 30	> 25	site selection (sf), plant development (sf), industrial construction/ planning and construction processes, automation technology (sf), maintenance (sf), technical infrastructure (sf), Greenfield and Brownfield projects (different OEMs, suppliers and further SMEs; world-wide)	electrical engineer
IP5	senior project leader factory planning (different car OEMs)	> 30	> 10	plant development, industrial construction/ planning and construction processes (sf), maintenance, procurement, Greenfield and Brownfield projects (different OEMs, suppliers and further SMEs; world-wide)	business economist
IP6	CEO of a factory, production and logistics planning consulting company (former CEO of an internationally operating transportation and logistics (t&l) company) (different SMEs, car OEMs and t&l companies)	> 25	> 15	site selection (sf), plant development (sf), industrial construction/ planning and construction processes, process optimisation (sf), warehouse/ material flow technologies (sf), transportation systems (sf), Greenfield and Brownfield projects (different OEMs, suppliers and further SMEs; world-wide)	business economist
IP7	senior factory planner (different SMEs and a car OEM)	> 20	> 15	approval processes (sf), construction and building law, Greenfield and Brownfield projects (different OEMs, suppliers and further SMEs; world-wide)	engineer architect
IP8	head of the national and international factory planning of a car OEM (different car OEMs)	> 40	> 40	site selection (sf), plant development (sf), industrial construction/ planning and construction processes (sf), process optimisation (sf), Greenfield and Brownfield projects (different OEMs, suppliers and further SMEs; world-wide)	doctor of engineering

Table 7: Selected interviewees

All OEM employees who have not worked for SMEs have experience with them (e.g. suppliers and planning offices), while all interviewees have a technical know-how and economic knowledge. Furthermore, two interviewees have completed commercial and two technical vocational education prior to their academic degree.

The chosen interviewees are experts in factory planning as they:

prerequisite 1	. . . have an industrial experience of 20 years or more years.
prerequisite 2	. . . have a work experience of 10 years or more years in factory planning.
prerequisite 3	. . . have knowledge about factory sections, departments, the site selection, plant development, industrial construction, planning and construction processes, effective factory and factory layout planning (i.e. the effective arrangements and linking of FOs/FSs in the context of the general structure), lean processes, production, logistics, energy and media flows, and are familiar with FPPs (also approval processes) and the management of factory projects. *Thus, the information in the previous table relates to the main fields of work/work experience, core competencies and specialist knowledge/ specialist fields of the interviewees.*
prerequisite 4	. . . have experiences and knowledge about (4a) numerous factories with different sizes and structures involved (e.g. factories with preferably all sections, s&d plants etc.), and about (4b) a large number of factory developments. Therefore, it was crucial that the interviewees . . .
prerequisite 5	. . . have experienced a large number of factory planning projects (especially Brownfield projects).
prerequisite 6	. . . are responsible for the planning, execution/implementation, controlling and management or coordination of factory planning projects. *These people are often involved in several projects at the same time.*
prerequisite 7	. . . have access to information about FPPs, and to factory and project documentations (i.e. factory developments, project progressions, backgrounds and lessons learned).
prerequisite 8	. . . have access to other experts and specialists and can clarify who can provide required information (also approval authorities etc.).

These were the prerequisites for participation. The interviewees’ responsibility and experience in terms of making decisions and recommendations makes their answers particularly reliable, as they could have learned from past experiences (Hitzler, 1994; Pfadenhauer, 2007). The interviewees provided input from other experts and specialists, which increased the validity and reliability of the answers.

In sum, approximately 19.25 hours of audio data and 148,000 words were generated, which shows the in-depth character of the interviews and the research.

Information about 12 OEMs, 19 SMEs and 58 factories from around the world were received.

4.7.2 Interview Process

It is important to inform stakeholders about a research project (Gill and Johnson, 2010). The interviewees in this study received the informed consent, questionnaire and information about the interview purpose, scope, contents, agenda, process, structure, premises, rules and subject prior to the interviews to enable them to prepare. The research aim and objectives were not disclosed, as this could bias the interviewees (Silverman, 2010). The interviews had an open character as the initial theory and concepts were not disclosed. Furthermore, several key questions were disguised as subquestions (the questionnaire can be found in appendix 4.7.2_01, as well as information about the purpose of the interviews and the premises, rules and subject). Thus, the interviewees retained their own 'big picture' and defined the importance of contents without being biased by the interviewer (Kurz *et al*., 2009). The importance of issues therefore changed through the interviews. New topics and data came up, which developed the research contents and directed the research.

Interview sessions were scheduled to last 120 minutes, and the actual interviews were planned to take 85 minutes in order to achieve the minimum requirements of the interviews. Nevertheless, the interviewees were requested to block additional 60 minutes in their calendar as a further buffer, which was utilised in seven of the eight interviews. The interview place should be comfortable, quiet without disturbances and could be selected by the interviewee or in coordination with the interviewer (Fichtel and Staltmeier, 2008).

I.	Personal introduction (interviewee and researcher)	5 minutes
II.	Present the research project, answer open questions and resolve uncertainties (interviewee and researcher)	10 minutes
III.	Explain the interview process and structure (researcher)	4 minutes
IV.	Read and sign the 'Informed Consent' (interviewee)	4 minutes
V.	Perform the interview (interviewee and researcher)	85 minutes
VI.	Conclude the interview (interviewee and researcher)	2 minutes
	Buffer time	10 minutes
Total time		120 minutes

To create a convenient and trustworthy atmosphere/environment, small talk, professional backgrounds and job experiences of the interviewee and interviewer were exchanged in the personal introduction (Gill and Johnson, 2010). The research project was then briefly presented, open questions answered and uncertainties resolved (Saunders, Lewis, and Thornhill, 2009).

After the explanation of the interview process and structure, the interviewees were given time to read and sign the 'Informed Consent' (appendix 4.7.2_02). Participation was voluntary, and to withdraw from the interview was possible at any stage of the research project. In addition, it was possible to end the interview ahead of schedule, to refuse to answer questions, reject audio recording (completely or in places) and to contact the author/interviewer before and after the interview to ask questions and resolve uncertainties. The interviewees were informed that there were no known privacy risks in participating in the research project, because company/employer and interviewee data (e.g. individuals' and company names) was anonymised, which ensured privacy protection (Aghamanoukjan, Buber and Meyer, 2007). This was supported by the opportunity to make 'off the record' statements (Bryman and Bell, 2015). Once the informed consent was signed, the interview took place. All interviewees agreed to the audio recording.

Before the actual interview, each interviewee was asked about her/his motivation for participating. All interviewees stated that they are either interested in the research topic, factory planning and/or new developments. IP4 added that flexibility and transformability are very useful for her/his work. The points about audio recording, privacy and data protection were repeated, and it was emphasised that the focus lies on real-world cases and experiences, and on the openness of the interviewees. The interviews then began, and when all questions were answered, the interview was concluded. The interviews were transcribed and each transcript was reviewed and signed by the respective interviewee to ensure its accuracy. The main steps of the interview process/approach are described in Schawel and Billing (2012).

4.7.3 Interview Structure

Interview sections must sufficiently cover the concerned field of knowledge, while a few questions per section should encompass the most important aspects (Mey and Mruck, 2011). The questionnaire is structured into five sections:

1.	Basic questions with regard to factory planning (including introductory question)
2.	The transformability of factory objects and structures (including backgrounds)
3.	Factory projects and factory development
4.	The impacts of factory developments
5.	The future of factories (with concluding questions)

The first section is concerned with basic questions about factory planning and factories. The intention of this section was to receive information about factory requirements, project durations, difficulties, forecasts and BFPS-1. In section 2, FOs/FSs were examined. The focus in this section was on transformability-related capabilities and limitations of FOs/FSs (e.g. fixed points), and on the heterogeneity in factory planning. Terrestrial areas and FOs/FSs that are covered by, embedded in or related to these areas played a large role in this regard (e.g. the technical infrastructure, s&d plants, foundations and further objects and substructures of different factory sections etc.). Furthermore, real-world factory projects, exchange areas, substitution processes and fundamental enablers were considered. In section 3, real-world factories, factory projects and their characteristics and developments over time were investigated. BFPS-2, BFPS-3, BFPS-4 and difficulties were in the foreground. The impacts of transformations on areas and substructures in particular could therefore be examined. This section in particular provided the data required to enhance BFPCs. Impacts of factory developments on different factory characteristics/capabilities were investigated in section 4. Difficulties were emphasised, and the interviewees were asked about the reasons why factories develop into UHPs. Section 5 is concerned with the possible future of factories. The transformability of areas and substructures was explored. The interviewees were given the opportunity to express what is required and desirable in this regard based on their own knowledge/know-how and experience. Furthermore, accelerators/ acceleration units were thematised. In addition to providing information about the limitations of today's factories, this section was essential for the TAS-requirement profile. In sum, the intentions behind each section could be met. The known concepts were not disclosed, while new ones emerged from the interviews. The following subsection provides more detailed information.

4.7.4 Interview Questions

The following paragraphs describe the process of the development of the interview structure and questions. The latter two provided the foundation and logic for this research. IQs must be closely related to ROs (Aghamanoukjan, Buber and Meyer, 2007). ROs must be translated into IQs, while interview data must be continuously assessed in the light of their possible meaning (Hopf, 1978, 2016). The questionnaire guided the semi-structured interview process. Figure 30 depicts the logic and structure of the questionnaire, and how the five interview sections relate to the developed concepts, model and initial theory in order to address the ROs. The concepts, model and initial theory were not revealed to the interviewees.

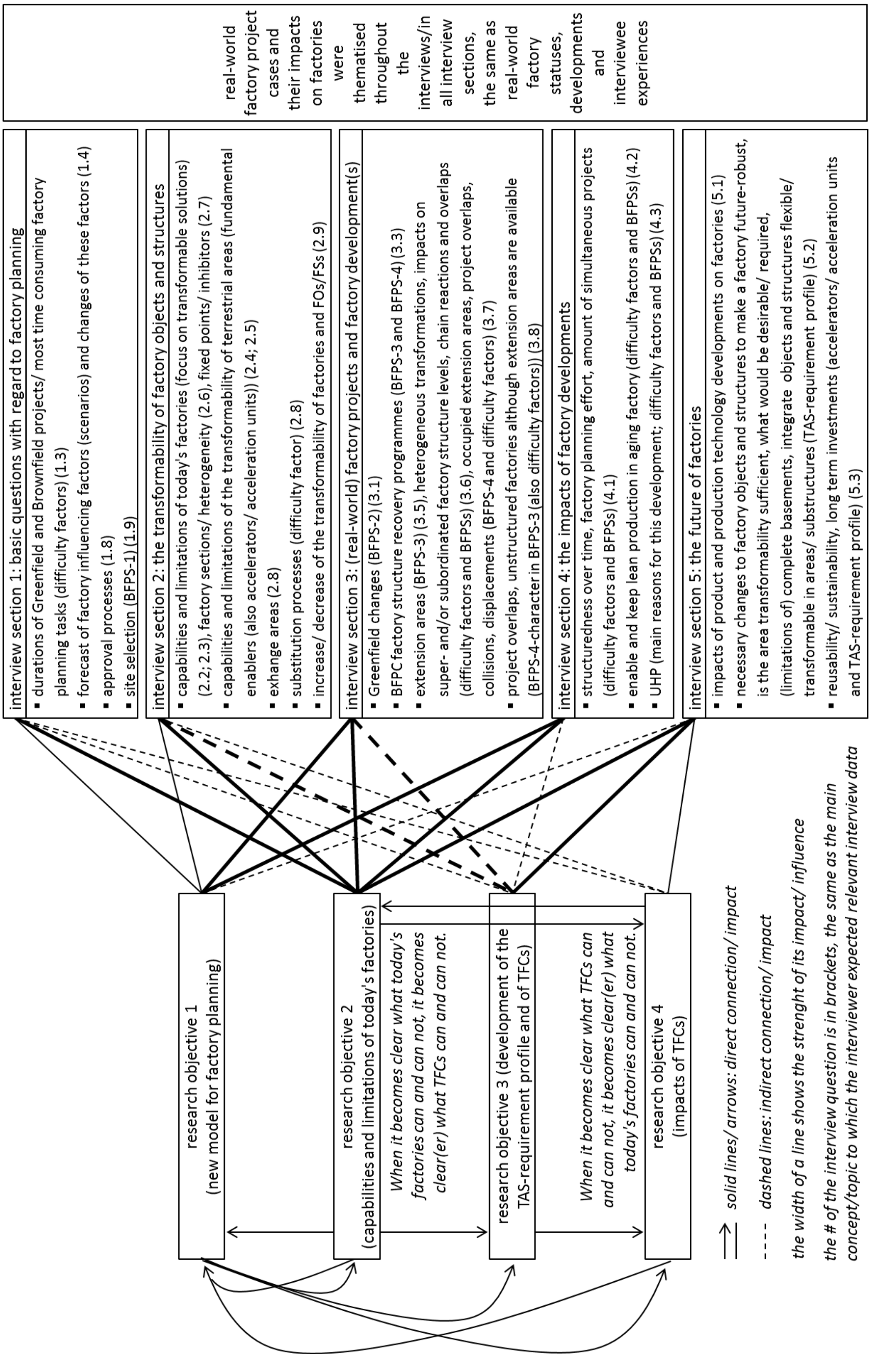


Figure 30: Connection between ROs and interview sections

The interview sections and questions were developed based on the ROs during phase 1. Identified facts, probabilities and assumptions helped to develop reasonable IQs. The conclusion from the literature and technology review and the basic model-functionality played a main role in this regard. These views helped to develop categories and concepts and to identify rough relationships between them, which could then be examined and further developed in the interviews. Thus, the intention behind each question was clear (Schawel and Billing, 2012).

BFPSs built the main framework for the research and the interviews. That the BFPSs make sense and that the model works in principle was a working assumption that could be verified through the interviews. In sum, no assumption or concept was rejected/disproved. BFPSs were fully validated by all interviewees.

The number of cases required in qualitative research depends on the research problem (Silverman, 2010). Numerous real-world factory projects, their impacts and other information about factory developments were supplied by the interviewees, and this provided the majority of data for the analyses. These data were analysed and explored with all factory concepts. The author placed an emphasis on exceptional cases, as these helped to identify exceptions to rules (Glaser and Strauss, 1967). Nevertheless, it emerged from the interviews that in these times there are no real exceptional cases, as the world changes continuously and significantly. The grey zone/dilutive effect between BFPS-3 and BFPS-4 could be specified further, which led to a further development of BFPSs. (Quasi-)Exceptional factory project cases supported this process.

BFPSs were in the author's mind during the interviews and analyses (not only as each project happens in a certain BFPS). Data could thus be gathered and analysed as BFPSs provided a platform for emerging concepts, so that these could be sorted in the context of all data.

Projects that were discussed revealed difficulties, through which the new concept of 'difficulty factor(s)' was developed. One focus was on these difficulties. Overall, the model was tested through numerous real-world factory projects (per developed factory concept), while these cases and their impacts provided information about difficulties and factory developments. BFPSs supported the development of BMEs, difficulty factors, fundamental enablers, accelerators/acceleration units and of the TAS-requirement profile (see section 5.4 for details).

Relations of ROs and IQs are summarised in table 8. Details about the IQs are then provided.

In sum, the following statements can be made based on the interviews: The impacts of real-world factory project cases are much stronger, more serious and occur more frequently than assumed (particularly in late BFPSs, i.e. BFPS-3 and BFPS-4). The transformability of areas is much more important than assumed for factories throughout the BFPSs and against the backdrop of the factory environment, as areas and substructures are much more often and more extensively impacted by transformations than assumed.

topic/theme/ concept (mainly related research objective(s) (RO))	interview question(s) (IQ) that involves this topic/theme/concept (further ones and/or information in brackets)
BFPSs (all ROs (while BFPSs belong to RO1))	BFPS-1: IQ 1.9 BFPS-2: IQ 3.1 (also IQ 1.3) BFPS-3: IQ 3.3; IQ 3.4; IQ 3.5; IQ 3.8; IQ 4.3 BFPS-4: IQ 3.3; IQ 3.4; IQ 3.5; IQ 3.7; IQ 3.8 (indirectly); IQ 4.3 all BFPSs: IQ 1.3; IQ 1.6; IQ 1.7; IQ 2.1; IQ 2.2; IQ 2.6 (indirectly); IQ 2.7; IQ 2.8; IQ 2.9; IQ 3.2; IQ 3.3; IQ 3.6; IQ 3.7 (indirectly); IQ 3.8 (indirectly); IQ 4.1; IQ 4.2; IQ 4.3 (indirectly); IQ 5.1 (indirectly); IQ 5.2 (indirectly)
capabilities and limitations of today's factories (RO2)	IQ 2.2; IQ 2.3; IQ 2.4 (fundamental enablers: area size, area shape and (terrestrial) area and substructure characteristics); IQ 2.5 (this question led to the fundamental enabler MAS); IQ 2.7 (fixed points/inhibitors) (see each further line in which RO2 is mentioned)
accelerators (all ROs) and acceleration units* (RO2)	IQ 2.4; IQ 2.5; IQ 5.3 *of today's factories
fundamental enablers (all ROs) and fundamental enablers** (RO2)	IQ 2.4; IQ 2.5 **of today's factories
heterogeneity in factory planning *** (all ROs)	IQ 2.6; IQ 3.6 ***or, in other words, of factories/FOs/FSs
exchange areas (all ROs)	IQ 2.8 (How factories grow (i.e. different types of growth) and why emerged from the interviews. This interview question provided high-level and detailed explanations/backgrounds to eBFPCs. That the combination of the heterogeneity and different types of growth and transformations would be crucial for this research was unknown)
difficulty factors (all ROs)	IQ 1.3; IQ 3.6; IQ 3.7; IQ 3.8; IQ 4.1; IQ 4.2; IQ 4.3
TAS-requirement profile (RO3)	IQ 2.1; IQ 5.2; IQ 5.3 (All questions which led to answers that disclosed the limitations of today's factories were crucial for RO3. The same applies to desires of the interviewees with regard to transformability and FPPs (and further direct statements). Numerous desires which reflect the needs in factory planning emerged from the interviews.)
*Information: Not all ROs, topics/themes/concepts and IQs are presented. Not all concepts were known before the interviews (details are provided****) and not all information about indirect impacts of interviews/interview statements on ROs is presented (but are explained ****throughout chapter 4 and chapter 5 and in the following tables in which the IQs are explained more detailed). Follow-up/probing/specifying questions were asked. Answers to these questions provided further insights. To receive an as complete picture as possible about real-world factory projects and their impacts (which led to eBFPCs), limitations of today's factories, factory developments etc.was aimed. 'Capabilities and limitations of today's factories' led to today's factories' 'transformation units, acceleration units and fundamental enablers' (and accelerators) and vice versa.*	

Table 8: Relations of ROs and IQs

The IQs that relate to a BFPS(s) in particular were crucial for the research, as data (e.g. cases and their impacts) could be categorised and analysed, and compared in the context of the BFPSs. All ROs and most interview statements are at least to some extent related to the BFPSs.

What can be generally said about the links between the IQs and ROs is that each time that the interviewees provided RO2-related data (e.g. information about how transformations can be processed with today's factories), it helped to achieve RO4, as a reference/basis of comparison was provided, while RO4-related data provided a reference/basis of comparison which helped to specify RO2-related contents (this explains the RO2-RO4 relation). As previously explained, RO1-related data provided a growing and improving basis for all other ROs, while the connection between RO2 and RO3 must also be considered.

In the following, the development of IQs, the intention behind each IQ, and how the IQs relate to the ROs and concepts will be explained. Introductory/opening and concluding questions are explained in subsection 4.7.5.

interview question 1.3	How long does the planning and implementation of a factory take and what are the most time-consuming tasks?
Brownfield equivalent	What are the most time-consuming tasks in Brownfield projects?

These IQs were developed, as it was assumed that particularly lengthy/time-consuming processes help to reveal difficulties in factory projects and limitations of today's factories (RO2), which was the intention behind these questions. Project durations were described in the context of BFPSs and specific situations (RO1).

interview question 1.4	How would you assess the foreseeability of factory influencing factors/ of factors that are decisive for factories (e.g. markets, competitors, products, production figures, new product technologies, new production technologies etc.)?
subquestion	What happens if such an influencing factor changes?
interview question 1.5	What is a routine operation in factory planning (mechanisms of normal/regular operations)?
subquestion	What could be an interruption of such a routine operation?

IQ 1.4 and IQ 1.5 address the reliability of scenarios, and were developed based on the assumption that forecasts are hardly possible, and to ascertain whether changes belong to normal functioning in factory planning, as routine operations and interruptions of routine operations indicate 'mechanisms of normal functioning' (Walter, 1994; Meuser and Nagel, 2009). These questions are furthermore linked to RO2.

interview question 1.7	Are factories constantly growing?

The intention behind IQ 1.7 was to gather information about factory developments. It was assumed that factories mainly grow over time; this led to IQ 1.7 which is linked to RO1.

interview question 1.8	Are approval processes required every time that building land/ terrestrial areas are impacted?

IQ 1.8 was developed, as the author wanted to receive specific information about approval processes. IQ 1.8 is linked to RO2 and RO4.

interview question 1.9	What is there to say about the importance of the site selection (particularly against the backdrop of a factory lifecycle of 15 and more years)?
interview question 1.9 from the author's view	*What is there to say about the importance of BFPS-1 (particularly against the backdrop of a factory lifecycle of 15 and more years (or, in other words, against the backdrop of long factory lifecycles))?*

The author wanted to gather information about BFPS-1. This was the main intention of IQ 1.9, which is linked to RO1 (BFPS-1), RO2 and RO4 (directly usable statements).

Directly usable statements could be considered for all of the following IQs that are linked to RO4.

interview question 2.1	Transformability – how important is this (cap)ability for factories?
subquestion	For which objects and structures is transformability particularly important, and why?

IQ 2.1 is concerned with the importance of transformability for factories, and the subquestion with the transformability of FOs/FSs. The author has assumed that the answers to these IQs would provide information about transformation requirements and how these can be processed with today's factories under consideration of current and modern solutions (RO2). These IQs are furthermore linked to RO1 (BFPSs), RO3 (TAS-requirements from directly usable statements) and RO4. Directly usable statements could be considered for all of the following IQs that are linked to RO3.

interview question 2.2	Where do you see opportunities and limitations of transformability (i.e. existing degrees of freedom and limitations)?
interview question 2.3	Are transformable buildings and building contents (e.g. modular and mobile production cells) capable of meeting all of the transformation requirements of a factory?
interview question 2.3 from the author's view	*Are TBSs and TFOs/TFSs capable of meeting all of the transformation requirements of a factory?* *(such views can furthermore be developed by the reader)*

The main focus of these IQs was to gather information about the capabilities and limitations of today's factories, and to identify the limitations of modern solutions (i.e. transformation requirements and how these can be processed with today's factories under consideration of current and modern solutions). These IQs are linked to RO1 (BFPSs), RO2 (capabilities and limitations of today's factories; inhibitors/fixed points/RFOs/RFSs; TFOs/TFSs) and RO3.

interview question 2.4	Which possibilities and limitations do you see in relation to the transformability of terrestrial areas?
subquestion 2.4.1 (sq 2.4.1)	How important is the area size and why?
subquestion 2.4.2 (sq 2.4.2)	How important is the shape of the area, and why?
subquestion 2.4.3 (sq 2.4.3)	How easy is it to find large enough area(l)s in the right region?
subquestion 2.4.4 (sq 2.4.4)	How relevant is the soil condition/quality of areas?
subquestion 2.4.5 (sq 2.4.5)	What impact does it have on the transformability of an object/ structure if this object/structure is positioned in the area/ground?
interview question 2.5	Are there cases where it would be sensible if factory objects/ structures that are larger than containers would be movable?

The author has assumed that area size, area shape and soil condition/quality of areas are important for the transformability of factories and FPPs, but it was unclear to a certain extent why and how these elements interact with one another. This led to the development of these questions. The intention of IQ 2.4 and the related subquestions was to gather information about the importance and the relations of these elements (particularly in the context of transformability and FPPs). The intention of IQ 2.5 was to receive information about the importance of the mobility of FOs/FSs (particularly of those which are larger than containers). These IQs are linked to RO1 (BFPSs and particularly fundamental enablers, but also accelerators and acceleration units of today's factories (RO2)), RO2 (capabilities and limitations of the transformability of terrestrial areas and thus of today's factories), RO3 and RO4.

interview question 2.6	Is it possible to unify factory sections such as a press shop and an assembly shop (e.g. their substructures/foundations, building dimensions, column grids, technical facilities, machines, and equipment)?

It was assumed that the heterogeneity of factories is important for factory developments, which led to the development of IQ 2.6. The intention behind IQ 2.6 was to gather information about the heterogeneity of factories and a deeper understanding of the heterogeneity of factories in the context of factory transformations. IQ 2.6 is linked to RO1 (BFPSs and impacts of real-world factory project cases), RO2, RO3 and RO4.

interview question 2.7	What are the fixed objects and structures of a factory (fixed points) which can hardly be transformed or only with great expense?

IQ 2.7 was developed to find out how many and which fixed points exist in today's factories. The possibilities provided by TFOs/TFSs were considered in follow-up/ probing/specifying questions. Furthermore, questions about Industry 4.0 were asked in this context. Several interviewees delivered up-to-date information about Industry 4.0-developments and current and modern solutions in factories. Thus, the modern factory and further current and modern developments could be examined. IQ 2.7 is linked to RO1, RO2, RO3 and RO4.

interview question 2.8	How would you assess the importance of exchange areas?

IQ 2.8 was developed to detect the reasons why exchange areas are required. A further intention of this question was to receive general information about the transformability of areas and substructures. IQ 2.8 is linked to RO1 (BFPSs and impacts of real-world factory project cases), RO2, RO3 and RO4.

interview question 2.9	What could lead (a) to an increase and (b) to a decrease of the transformability of factories?

The intention of this question was to gather information about the transformability of areas and about the relevance of areas for transformations. The Interviewees' perspectives with regard to the limitations of today's factories should lead to relevant information to develop the TAS-requirement profile. IQ 2.9 is linked to RO2, RO3 and RO4.

interview question 3.1	Can planning assumptions/premises (Planungsprämissen) change during a Greenfield project and have an effect on the resulting factory?

This question was developed based on information in the literature and on the developed BFPSs. The intention of this question was to receive information about BFPS-2 and the reliability of forecasts. IQ 3.1 is linked to RO1 (BFPS-2), RO2, RO3 and RO4.

interview question 3.2	How often do transformations take place?
interview question 3.3	Are large factory projects required during a factory lifecycle?

IQs 3.2 and 3.3 were developed based on the BFPSs to find out how often transformations occur, and whether the area (i.e. the reached BFPS) has a connection to the number of transformations. Furthermore, these questions should deliver information about real-world transformation requirements and changes (i.e. the reliability of scenarios/transformations of transformations). IQ 3.2 is linked to RO1 (BFPSs and impacts of real-world factory project cases), RO2 and RO3. IQ 3.3 is linked to RO1 (eBFPCs, BFPS-3 and BFPS-4), RO2, RO3 and RO4.

interview question 3.4	Can unplanned changes occur during Brownfield projects?

The intention behind IQ 3.4 was to gather information about the reliability of forecasts and about how often changes occur during Brownfield projects, and about which changes occur and how they impact on factories. Different questions back/support one another (e.g. IQ 3.2 and IQ 3.4). IQ 3.4 is furthermore a control question to IQ 1.4. IQ 3.4 is linked to RO1 (BFPS-3 and BFPS-4), RO2, RO3 and RO4.

interview question 3.5	How sensible is it to purchase doubling areas or larger areas (i.e. area reserves of additional 100% and more)?

IQ 3.5 was developed based on the information in the literature. The intention behind this question was to receive information about the importance of areas for factory developments and transformations. Furthermore, factory developments were analysed through this question (see also IQ 1.7). IQ 3.5 is linked to RO1 (BFPS-3 and BFPS-4), RO2, RO3 and RO4.

interview question 3.6	Is it possible, common and sensible to hold out/reserve technical infrastructure networks and supply and disposal facilities/plants for all possible factory developments (e.g. against the backdrop of an initial and final factory configuration)?
subquestion 3.6.1 (sq 3.6.1)	How does a capacity increase of a factory have an impact on factory objects and structures?
subquestion 3.6.2 (sq 3.6.2)	Can it happen that overarching structures (e.g. an energy centre or drainage) need to be transformed?
subquestion 3.6.3 (sq 3.6.3)	Do factory sections differ in the case of a transformation?
subquestion 3.6.4 (sq 3.6.4)	Can a physical chain reaction occur in the case of a transformation?

IQ 3.6 was asked, as the author wanted to know how today's factories can be and are prepared for future factory demands/transformation requirements. Sq 3.6.1, sq 3.6.2 and sq 3.6.3 were asked in order to gather further information about the heterogeneity of factories (see also IQ 2.6) and their heterogeneous transformations and growth. Sq 3.6.4 was developed to gather information about chain reactions/domino effects and was therefore of particular importance to gather information about difficulties in factory planning, i.e. difficulty factors. It was assumed that the answers to IQ 3.6 and these subquestions would provide information about the difficulties in factory planning and about the heterogeneity and heterogeneous transformations and growth of factories. IQ 3.6 is linked to RO1 (BFPSs), RO2, RO3 and RO4.

interview question 3.7	What are the characteristics of a factory if all extension areas are occupied?
subquestion 3.7.1 (sq 3.7.1)	Which transformations are possible and how if all extension areas are occupied?
subquestion 3.7.2 (sq 3.7.2)	Have you ever had a project which other projects overlapped with?

IQ 3.7 was asked in order to receive information about BFPS-4, about the impacts of transformation requirements in BFPS-4 and about the possibilities of handling these impacts with today's factories under consideration of TFOs/TFSs, which were considered in follow-up questions. Sq 3.7.1 and sq 3.7.2 were asked to gather information about project overlaps, collisions, displacements etc. and about whether these occurrences are related to BFPS-4. It was assumed that the answers

to all these questions would provide information about the importance of areas for transformations and required FPPs. It was furthermore assumed that overlaps and other difficulties occur more when areas are occupied. IQ 3.7 is linked to RO1 (BFPS-4), RO2, RO3 and RO4.

interview question 3.8	Do project overlaps occur when only certain areas of a factory are occupied (e.g. areas in the centre of a factory whereas extension areas are still available at the periphery/outer borders)? *This question was only asked if overlaps were discussed in 3.7 (which was always the case).*
subquestion	Are unstructured factories a result when extension areas are available?

IQ 3.8 was asked to gather information about BFPS-3 (particularly about the characteristics of factories which have reached BFPS-3), about the impacts of transformation requirements in BFPS-3 and about the possibilities of handling these impacts with today's factories under consideration of TFOs/TFSs. Both questions were asked in order to gather information about project overlaps, collisions, displacements etc. and whether these also occur in BFPS-3. The author wanted to know whether there is a dilutive effect between BFPS-3 and BFPS-4. These questions are linked to RO1 (BFPS-4-related impacts in BFPS-3), RO2, RO3 and RO4.

interview question 4.1	How does the structure of a factory develop over time?
subquestion 4.1.1 (sq 4.1.1)	How does the factory planning effort develop with the age of a factory?
subquestion 4.1.2 (sq 4.1.2)	How does the number of simultaneous projects (and operation phases) develop over time?

IQ 4.1 was asked to gather information about the BFPSs of today's factories and to double-check the correctness of the already received information. The focus was on characteristics of factories throughout the BFPSs, impacts of transformation requirements throughout the BFPSs and the possibilities of handling these impacts with today's factories. It was assumed that the answers to IQ 4.1, sq 4.1.1 and sq 4.1.2 would provide a common picture of today's factory developments. These questions are linked to RO1 (BFPSs), RO2, RO3 and RO4.

interview question 4.2	Is it possible to enable and maintain lean production (preferably with waste-free processes) in an aging factory?

IQ 4.2 was asked to gather information about the BFPSs of today's factories and to double-check the correctness of the already received information. This question was furthermore asked to collect information about the development of factory structures (i.e. FOs/FSs) throughout the BFPSs and about the possibility to keep process flows lean. IQ 4.2 is linked to RO1 (BFPSs), RO2, RO3 and RO4.

interview question 4.3	United huts plant(s) ('Vereinte Hüttenwerke'/'Vereinigte Hüttenwerke') – why does this expression exist?

This question was asked to gather information about the main reasons why today's factories develop into UHPs. It is commonly known in factory planning that factories develop into UHPs, even though the reasons for this development were not analysed deeply. A further intention behind this question was to receive information about factories which have reached this status and about whether and how this status can be left. IQ 4.3 is linked to RO1 (BFPS-3 and BFPS-4), RO2, RO3 and RO4.

interview question 5.1	What are the impacts of current developments in product and production technologies on factories (e.g. electric mobility, 3D printing, metal printing, electrochemical metal machining processes and so forth)?

This question was asked to gather information about current and future factory requirements and challenges and how these requirements and challenges can be handled with today's factories and current and modern developments, e.g. Industry 4.0-developments. IQ 5.1 has a strong connection to IQ 1.4 and IQ 1.5, e.g. foreseeability and changes of influencing factors and how these changes can be handled. IQ 5.1 is linked to RO2, RO3 and RO4.

interview question 5.2	Are changes of factory objects and structures necessary to make a factory future-robust/future-proof?
subquestion 5.2.1 (sq 5.2.1)	Is the transformability of terrestrial areas sufficient against the backdrop of long-term factory developments?
subquestion 5.2.2 (sq 5.2.2)	What would be desirable?
subquestion 5.2.3 (sq 5.2.3)	Would comprehensively implemented basements lead to advantages?
subquestion 5.2.4 (sq 5.2.4)	Would it be advantageous if factory objects and structures could be integrated into areas/substructures in a flexible/transformable manner?

IQ 5.2 was developed to find out the interviewees' views about whether the transformability of today's factories is sufficient, and to also discover their perspectives on if and how the transformability of factories can be improved. Sq 5.2.1 was developed to learn the interviewees' views on the transformability of terrestrial areas and the general importance of areas for the transformability of factories. With sq 5.2.2, sq 5.2.3 and sq 5.2.4 (systemic questions) the interviewer tried to lead the interviewees to perspectives (Mey and Mruck, 2011). To receive information for the TAS-requirement profile was the major intention behind these questions. IQ 5.2, sq 5.2.1, sq 5.2.2 and sq 5.2.4 were developed based on the author's knowledge about area systems. IQ 5.2 is linked to RO2, RO3 and RO4.

interview question 5.3	How important is the reusability of factory objects and structures (mainly with regard to sustainability)?
subquestion 5.3.1 (sq 5.3.1)	Is the reuse of factory objects and structures only sensible if these objects and structures are transformable?
subquestion 5.3.2 (sq 5.3.2)	What is your opinion about long-term investments?

IQ 5.3 was developed to find out where the reusability of FOs/FSs has its limitations and to what extent it is actually pursued. Sq 5.3.1 was developed to receive information about the relations of the reusability and transformability of factories/FOs/FSs. Sq 5.3.2 was developed to gather information about long-term investments and the possibility of making long-term investments. To receive information for the TAS-requirement profile was the major intention behind these questions. A further intention of these questions was to gather information about

the sustainability of today's factories, and what level of sustainability is at all possible against the backdrop of the human-globe system. IQ 5.3 is linked to RO1 (accelerators and acceleration units), RO2, RO3 and RO4.

Further information about the development of IQs is provided in subsection 4.7.5 (see also section 5.4 for further information).

4.7.5 Interview Analysis

In factory planning, decisions and FPPs lead finally to FOs/FSs and therefore to an explicit knowledge, also about planning mistakes. Tacit knowledge in particular is relevant, as interviewees often do not know what they know. Tacit knowledge is not directly/readily available and must be brought to the surface through appropriate questions (Nohl, 2009).

To recount and provide information about cases and experiences can only happen in open interview situations. Such situations require semi-structured interviews which allow a flexible use of the questionnaire – the thematical guide – (Meuser and Nagel, 2009) and a sufficient depth (Aghamanoukjan, Buber and Meyer, 2007). Narratives disclose the experts' ways of acting. During narrating the expert becomes aware of her/his tacit knowledge step by step (Meuser and Nagel, 2009).

Assessments of different situations provide sufficient justifications. The aim was to gather significant expert knowledge about important issues, cases/events and patterns in the complex interaction (Bryman and Bell, 2015) of factory planning and factories/FOs/FSs against the backdrop of changing requirements. Rich descriptions and arguments for sound rationales and justifications come up in a dialogue (Mey and Mruck, 2011). The steps of interview/data analyses of Meuser and Nagel (2009, pp. 476–477) were followed by the author (table 9).

step	description
1. transcribe	put audio records of the interviews into writing/texts (coding was first done with the transcribed texts)
2. paraphrase	faithful rewording of speech/text passages (with own words) in order to reduce data and achieve a greater clarity
3. code** ***	paraphased passages enable a thematical labelling and sorting* while codes are assisting tools to fulfil these tasks; coding is done in single interviews; to go back and forth in the text is permitted and required; (re-)coding can be required after further interviews which means that coding is done after further interviews (see below)
4. develop categories (categorise)** ***	compare statements/paraphrased passages thematically and bundle equivalent ones to categories; search for commonalities, and for contrasts/differences. Look for and develop (codes and) categories further; to subsum data under a key term which has an overall validity leads to categories (and concepts) while new codes can emerge during the process
5. develop concepts (conceptualise)***	look for and analyse connections/links and relationships between categories and group categories in order to define concepts
6. develop theory (theorise)	create interrelations between the developed concepts, involve all relevant existing theories (e.g. from the literature) and interprete and assess them; finally, complete the picture of your theory; data and contexts are combined to theories

* a thematical sorting/ordering is already given through the questionnaire

** codes(/categories) were affixed to explanations and statements of the interviewees; various codes were used (based on the knowledge to date); as one consolidates data, is a critical review and, if required, a revision of allocations necessary; the shared context of experts ensures the comparability of interview data, but codes can already be developed in single interviews (e.g. the first interview) while new codes can emerge through further interviews

*** during interview analyses, codes become categories; furthermore, categories can become concepts and vice versa (even codes can become concepts); this means that the importance of contents changes during analyses

all six steps in sequence are required; it is also required to go back to earlier steps to examine and validate the appropriateness of patterns/generalisations and their grounding/foundation in data; the single steps are not always clearly delimitable as overlaps exist

Table 9: Steps of interview/data analyses (based on Meuser and Nagel, 2009)

The data of all interviews led to a common construction of theory (Mey and Mruck, 2011). According to Nohl (2009), the following data are important:

#	important data(-types)
1.	thematically similar data/passages (and their differences and/or similarities)
2.	cases which led to the same patterns or have been handled identically/similarly, especially when the cases were different
3.	topics in which own concepts were considered in the interview questions
4.	contents/topics which the interviewees have emphasised on or were engaged in answering a topic extensively or metaphorically

Table 10: Important data (based on Nohl, 2009)

Furthermore, topics that were provided by the interviewees without asking (Nohl, 2009) were given special attention. Routine operations and interruptions of routine operations indicated 'mechanisms of normal functioning' (Walter, 1994; Meuser and Nagel, 2009). Questions about good and bad experiences disclosed problems (Kurz *et al.*, 2009). The same applies to questions about what did or did not go well in factory projects. Such questions were asked during the interviews.

The quality of obtained data in an interview depends on how the interviewer forms the interview. Structuring does not mean to dominate interviews. Specific questions lead to focused information, but can also restrict answers (Mey and Mruck, 2011). Therefore, the interviewer tried to be both communicative and restrained, as the interviewees' flow of speech should not be interrupted (Froschauer and Lueger, 2003; Aghamanoukjan, Buber and Meyer, 2007). Openness is furthermore important (Schlegel, 2015).

There is a point in time when sufficient information about a topic is gained or more information cannot be received. A hint about such a point in time can be provided orally or through other signs. If the received information was insufficient, the interviewer invited the interviewee to continue speaking (Aghamanoukjan, Buber and Meyer, 2007) or used the techniques of Easterby-Smith, Thorpe and Lowe (2002) and Mey and Mruck (2011) (see below).

Meaning was clarified with follow-up questions, so that the interviewee could reflect and re-think answers. Probing questions were required for more information and clarification. Specifying questions were used to verify the correctness of responses and to receive deeper insights (Easterby-Smith, Thorpe and Lowe, 2002). Systemic questions brought the interviewee to consider another perspective (e.g. 'What would occur if...?'; 'Have you thought about...?') (Mey and Mruck, 2011) and led to important data for the TAS-requirement profile.

The interviewer had expectations about which answers might be given. Based on these expectations, optional questions were developed, especially as a back-up after filter questions (Aghamanoukjan, Buber and Meyer, 2007). Depending on the answer of the interviewee, these were asked without or with modification, or not at all. Optional questions were only visible in the interviewer's questionnaire.

The following techniques also helped to elicit reliable answers without biasing the interviewees (Easterby-Smith, Thorpe and Lowe, 2002):

#	techniques to receive reliable answers
1.	pause/silence (wait until the interviewee speaks/give the interviewee time)
2.	repeat questions (e.g. to validate statements and/or to ensure a correct interpretation of the question)
3.	ask for explanation (e.g. What do you mean by . . . ?)
4.	ask for deeper insight(s) (e.g. Could you explain . . . more concrete/specifically? What happened afterwards? Can you tell me more about . . . ?)
5.	ask questions to reflect answers
6.	Say in own words (rephrase/paraphrase) what the interviewee said (to ensure a correct interpretation of the said words). Interviewees consequently rethink their answer and revise it if required (which ensures their correctness).

Table 11: Techniques to receive reliable answers

Additionally, one can ask for comments and assessments (Mey and Mruck, 2011).

To avoid bias, questions were asked neutrally (Easterby-Smith, Thorpe and Lowe, 2002). To ensure the reliability of answers, reformulated (control) questions were asked (Field, 2013; Palant, 2013). If the answers of an interviewee differ completely, they cannot be rated as valid, so the answers are not reliable; this did not occur during these interviews.

The following rules were largely considered in creating(/asking) IQs in accordance with Schmid (1992), Easterby-Smith, Thorpe and Lowe (2002), Gill and Johnson (2010) and Pallant (2013):

#	rules for creating interview questions
1.	avoid complex and/or long questions
2.	ensure that the question is clearly understandable (e.g. not ambiguous)
3.	avoid double negatives as they could confuse the interviewee
4.	avoid topics, contents and terms with double meanings
5.	avoid leading/biasing questions
6.	avoid personal questions

Table 12: Rules for creating IQs

The interviewer tried to be as open-minded and as neutral as possible in order to receive realistic and uninfluenced interview data. He showed interest (Schawel and Billing, 2012), but tried to avoid paraverbal and non-verbal bias (e.g. agreements or disagreements) and to be restrained when the interviewee was in the flow of speech. Respect (Aghamanoukjan, Buber and Meyer, 2007), friendliness and active listening were crucial (Mey and Mruck, 2011). The manner in which it was ensured that the interview results are of high quality, valid and reliable, is additionally explained in appendix 4.7.5.

4.8 Ethical Framework

This research was conducted under the guidelines of the University of Gloucestershire's Research Ethics Handbook. The author has followed the University's expectations and requirements for conducting research as well as the professional codes of conduct of external organisations. The research is based on data which has been acquired legally and confidentiality has been maintained as required. Findings/results are stated against the backdrop of nature protection and in compliance with, and appreciation of animal and human rights. All interviewees were informed about the ethical standards of this research.

The following sentences are based on Easterby-Smith, Thorpe and Jackson (2008) and Bryman and Bell (2015).

Ensuring correctness of interview data: The interviewees have received the transcripts to ensure their accuracy. Only one irrelevant change was made in the transcript of IP6 (even though the audio record was correctly transcribed).

The author has kept translations close to the original statements in order to ensure the correctness of the data and to avoid false or misleading presentation of findings (see chapter 6 for further information). The interviewees were given the opportunity to receive a copy of the final thesis.

Ensuring the anonymity and protecting the privacy of interviewees (i.e. meeting the interviewees' interests so that no harm can come to these people): Information about audio recording was provided along with the invitation email, research information letter and informed consent. Before the interview began, audio recording was again discussed. The interviewees had the right to reject audio recording (also partially). Furthermore, the interviewees could refuse to answer questions and withdraw from the interview at any stage, or end the interview ahead of schedule without justification. Audio records and transcriptions will be destroyed after the final approval of the thesis. Names of the interviewees remain unpublished, and interviewees are not identifiable through the published data. Personal data of the interviewees and data which could lead to the identification of interviewees is kept confidential.

This thesis is neither influenced by the researcher's employer nor by any other organisation, group or person.

5 New Model for Factory Planning

This chapter builds upon chapters 3 and 4 and the critical assessment of existing theories, and explains the developed model and all further concepts that are relevant to this research. The main concepts and their interplay are explained and justified in this chapter. In addition, the way in which the model and concepts were developed is explained; this supports previous explanations.

In section 5.1, the new model is briefly differentiated from existing theories and then described, e.g. how the model is used and how the model and concepts are associated (i.e. the model design). Section 5.2 describes BFPSs, (e)BFPCs, the background to why BFPCs must be enhanced, factory concepts and further concepts that are required to enable the research. Section 5.3 describes fundamental enablers and accelerators. Section 5.4 explains how the model, concepts and further research results were developed and verified. This section explains what data was gathered and how these were analysed with regard to the interviews, elements of grounded theory and/or further contents and methods of chapter 4.

Fundamental enablers and accelerators are used to specify transformability-requirements of factories and FPP-requirements, and to assess the transformability and FPP-related capabilities and limitations of the developed factory concepts within BFPSs, e.g. how displacements can be processed and transformation requirements met. Fundamental enablers were identified as the most important overarching concepts in factory planning. They differ for every factory concept, and based on their availability and features/characteristics (together with accelerators/ acceleration units and transformation enablers/units), they chiefly determine the capabilities and limitations of the developed factory concepts.

5.1 Model Description

This model shares similarities with the ‘0 + 5 + X Planning Model’ of Schenk, Wirth and Müller (2010), such as a differentiation of area types and the specification of BFPCs. Nevertheless, several relevant factory planning aspects were not described by these authors, especially not in combination.

Transformability-related theories are capable of indicating neither the requirements of current factories nor the capabilities and limitations of the developed factory concepts in the way that is possible with ‘fundamental enablers’ and ‘accelerators’.

The limitations of today’s factory planning theories are explained in more detail throughout sections 6.1 and 6.2; these theories are limited when scenarios are used, and in addition several theories do not work in late BFPSs. This is demonstrated in section 6.2.

With the help of the new model, all of the gaps which are described in section 2.4 can be closed. The model is applied in combination with the developed factory concepts. The capabilities and limitations of today’s factories and TFCs can be assessed (RO2 and RO4) using this model and its associated concepts (RO1). The limitations of today’s factories (RO2) provide the main input data for the development of the ‘TAS-requirement profile’. Consequently, TASs and TFCs can be developed (RO3). This is a static multi-dimensional ‘descriptive model’ that is based on the developed BFPSs and eBFPCs. Nevertheless, (dynamic) impacts of transformations on factories and the importance of fundamental enablers, transformation enablers and accelerators can be demonstrated through this model.

The impact of a specific (e)BFPC differs depending on the achieved BFPS, as BFPSs involve specific area characteristics (figure 31). These impacts are required actions, i.e. transformations/FPPs.

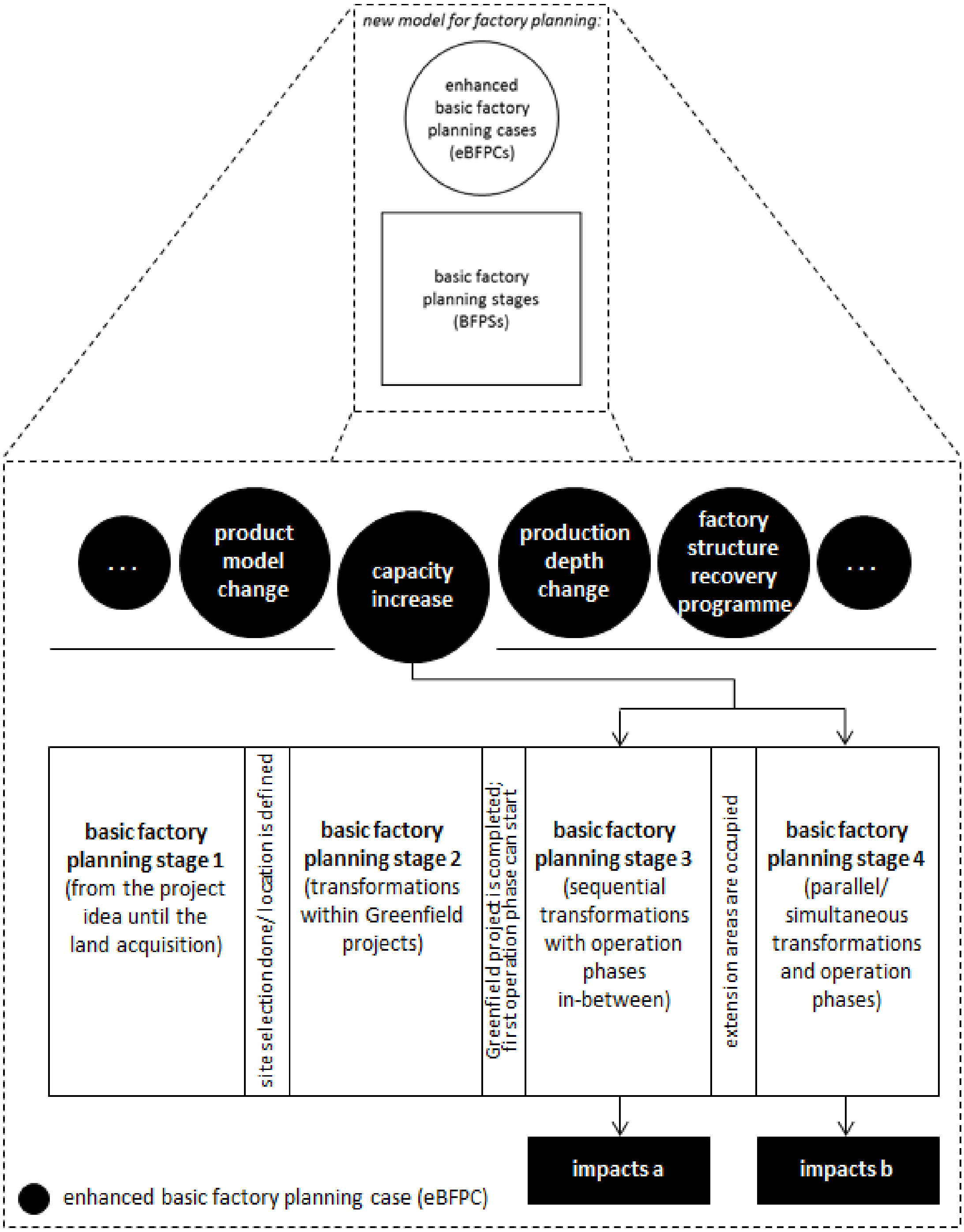


Figure 31: Basic model-functionality – relation between eBFPCs and BFPSs

An on-site production capacity increase which leads to a building extension is generally more easily manageable in BFPS-3 than in BFPS-4, as extension areas are available in BFPS-3. Furthermore, the factory concept in hand is decisive for the required actions, as each factory concept involves specific transformability (especially of areas) and FPP-capabilities. Today's factories lead to impacts other than TFCs. Figure 32 depicts the new model. The BFPSs provide the framework of the model and are specified in subsection 5.2.1.

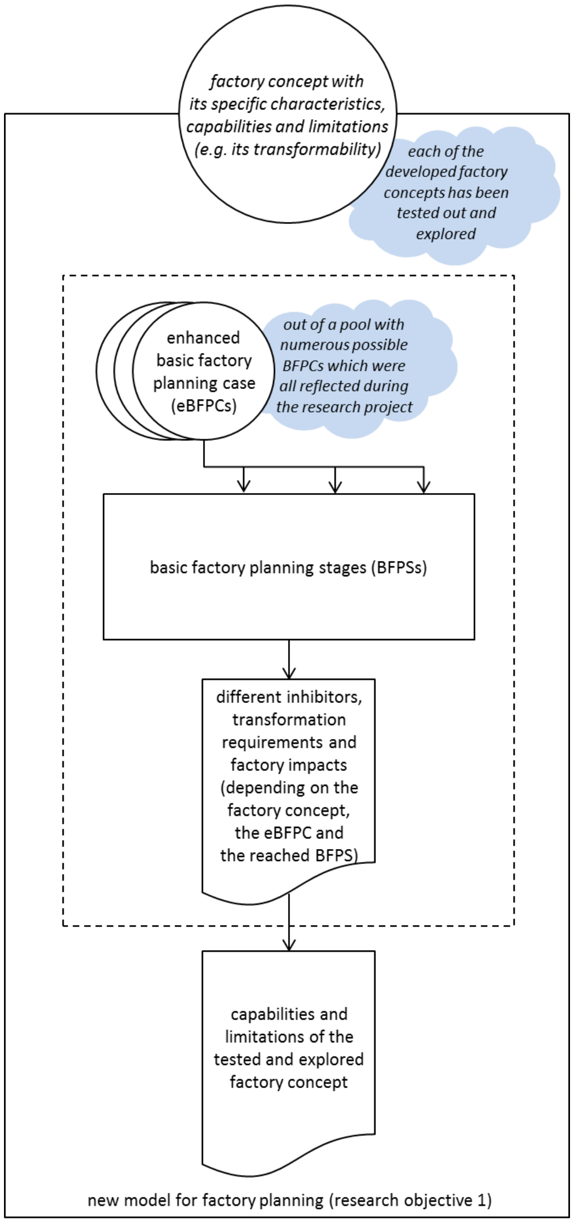


Figure 32: Factory concept-independent view of the new model

Different FOs involve different area and substructure requirements. In the case of a transformation (e.g. a position change), this heterogeneity can lead to different FPPs, depending on the factory concept. The achieved BFPS is also decisive for required FPPs. Thus, the examined factory concept, the achieved BFPS, and the (e)BFPC determine the transformation requirements which lead to BMEs, different further FPPs and difficulty factors which can accompany these events (figure 33).

The impacts on factories are mainly shown with 'displacements', as several eBFPCs involve similar patterns and lead to this difficulty factor.

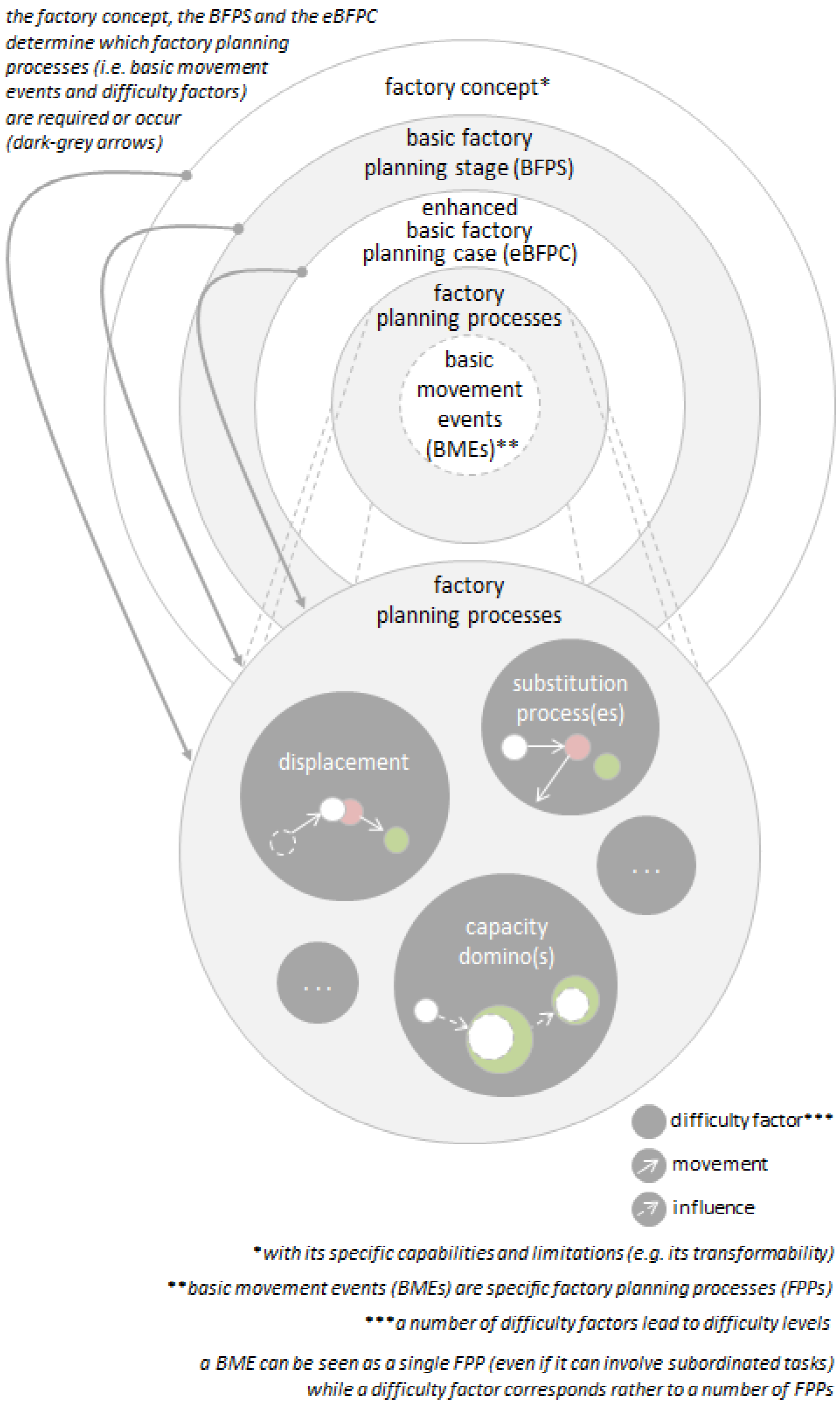


Figure 33: Extended model-functionality – differentiation of FPPs

BMEs occur in each (e)BFPC; movements are always basic elements of implementations and transformations. New objects, for instance, must be moved to their final locations. Such movements can create collisions which – if a single collision is substantially observed and if the joint occurrence of resulting intertwined structures and displacements is ignored – result either in intertwined structures or displacements, which in the end depends on the decision taken. Furthermore, other difficulty factors can occur. Different FPPs can accompany BMEs, depending on the factory concept in hand.

Difficulty factors make factory projects difficult, especially in BFPS-3 and BFPS-4. In the case of today's factories, project durations are partly so long in these BFPSs that new/changing transformation requirements occur before a project can be finalised. In addition, project overlaps and further influences can occur. These circumstances are further difficulty factors. Furthermore, difficulty factors can impact on one another.

Required FPPs depend strongly on the transformability and FPP-capabilities of the factory concept in hand. Therefore, the basic capabilities and limitations of today's factories with regard to transformability and FPPs are assessed and described in section 6.2, and those of TFCs in section 6.3. 'Transformation and fundamental enablers' were applied to assess the transformability, while 'accelerators and fundamental enablers' were applied to assess the FPP-capabilities of the developed factory concepts. Sections 6.2 and 6.3 are furthermore concerned with the application and validation of the model. This requires the results of the foregoing assessment of transformability and FPP-capabilities. Moreover, section 6.3 involves the TAS-requirement profile and relevant interview results. TFC-related risks are considered where required.

Projects can be performed with the objective of 'transforming a factory as quickly as possible' or 'reaching a possibly optimal factory solution', e.g. in terms of production flows. The reality of projects in today's factories lies generally between these two extremes. Other aims are thinkable and can also be relevant, e.g. to transform a factory at the lowest possible cost. This research focuses on optimal factory solutions. Project impacts and durations depend on the given (e)BFPC, BFPS and the specific transformability and FPP-capabilities of the developed factory concepts, e.g. implementation and transformation capabilities.

The new model is able to indicate: (1) which development stages (i.e. BFPSs) are normally passed through by a factory concept during its lifecycle, (2) which (e)BFPCs lead to which impacts within each BFPS, and (3) which (e)BFPCs involve which risks and should preferably not be carried out in certain BFPSs, depending on the factory concept in hand. Consequently, the model enables a decision based on the BFPS, (e)BFPC and factory concept in hand and can thus be used as a 'decision model' in factory planning. Thus, dynamics in factory planning and their importance will be recognisable. Furthermore, it will be understandable why especially complex and complex large-scale projects often delay and overrun their budget.

BFPSs represent the 'as is'-status of a factory with regard to the main area characteristics – first and foremost free available areas which are comprised through the 'area size'. In this model this means that the 'area size' is decoupled through the BFPSs, which helps to indicate the importance of this characteristic and of other area-related characteristics and capabilities – the fundamental enablers. The focus lies on irrevocable decisions (e.g. site selection) and built-up/overbuilt/ covered and free areas before a transformation, i.e. the 'as is'-status of a land plot or a factory with its area. This irrevocability applies mainly to today's factories. Both the BFPS and the (e)BFPC(s) determine the 'to be'-status while the delta between the 'as is'-status and the 'to be'-status determines the required transformations/ FPPs, which furthermore depend on the factory concept in hand. The 'as is'- and 'to be'-statuses have consequently been separated from one another in order to enable the analysis of factory concepts.

With this model it is possible to explain the direct or primary impacts of eBFPCs within BFPSs, e.g. building displacements in the case of an extensive production capacity increase in BFPS-4. The same applies to further impacts (e.g. further difficulty factors), but the model has clear limitations. To define all impacts of all eBFPCs in all their details with all their difficulty factors and the relations between *these factors (e.g. diverse chain reactions and back-couplings) is not possible. This applies especially to complex eBFPCs in late BFPSs. That the required actions, especially in sum, cannot always be completely defined is part of the problem in factory planning. Therefore, 'difficulty levels' were defined in order to indicate how difficult it is with each factory concept to perform factory projects within the different BFPSs.*

Today, there are no reliable possibilities to sufficiently parametrise all relevant natural conditions, nature-related processes (e.g. earthworks when soil conditions are hardly known) and human-related processes in order to define algorithms. This is in the nature of things, and furthermore has to do with the limitations of the performance of the human brain. To think so holistically, consistently, deeply and with such complexity is often almost impossible or impossible, also in groups. Sections 6.1 and 6.2 involve interviewee statements and further data in these regards.

This problem is furthermore recognisable and understandable through the model, but cannot currently be solved. Even the maximum digitalisation of a factory does not lead to significant advantages in this regard (at least not in the case of today's factories), as parameters and algorithms must be defined. Nevertheless, it will be demonstrated that with TFCs the delta between the 'to be'-status and 'as is'-status can, compared to today's factories, be (1) better defined and (2) better handled, as (2a) implementations and transformations can be more easily performed, and often faster, which (2b) simplifies factory planning (it is, for instance, easier to plan and define factory implementation and transformation steps). The 'as is'-status is more easily definable, as TASs are technical systems. This simplifies the definition of parameters, algorithms and related work processes.

Next, the key concepts of this research are described.

5.2 Concept Overview

5.2.1 Basic Factory Planning Stages and Cases

BFPSs are currently not considered in factory planning but are relevant, as they help to analyse and describe the importance of 'fundamental enablers' and other concepts for factory planning.

BFPSs provide a framework that encompasses real-world factory development stages – BFPSs are factory development stages. BFPSs are consecutively passed through and are generally valid if no exceptional cases such as economic crises, booms or other extreme market changes occur, as these events lead to exceptional transformation requirements that can have an enormous effect within each BFPS. Exceptional cases are therefore faded out within the following description of BFPSs but considered in chapter 6, as the developed factory concepts can handle these cases differently due to their capabilities. Factory relocations and off-site cases can have an impact on BFPSs, but have no impact on their general validity if a factory passes through all four BFPSs during its lifecycle. Relocations and off-site cases are considered where appropriate. Furthermore, there is a dilutive effect between BFPS-3 and BFPS-4; this is explained throughout the thesis and must be considered.

Four BFPSs have been defined. 'BFPS-1', which is an ideal stage from a transformability perspective, begins with the idea of a Greenfield project (t=0) and ends with the acquisition of building land. The latter decreases the transformability of today's factories (and some TFCs), as it determines the location and diverse area-related conditions. Before the acquisition of building land, decision changes are largely free of negative consequences, e.g. the decision for a capacity increase which requires additional areas. Therefore, BFPS-1 can be seen as a blank piece of paper on which planning changes can be made – up to the point when the building land acquisition has been completed. It can be claimed that a Greenfield project starts already within BFPS-1, but the splitting and distinction of BFPS-1 and BFPS-2 are important, as this shows the importance of site selection.

The fact that the transformability of today's factories decreases during the planning and implementation of Greenfield projects is not sufficiently considered in factory planning. It is furthermore highly questionable whether a pure Greenfield exists. A transformation requirement can already be given within a Greenfield project. Transformations dissolve pure Greenfields, which leads to the question of where ‘factory planning’ ends and where ‘transformation planning’ begins. Factory planning could be designated as transformation planning, which would more appropriately show the importance of the transformability of factories. To take these circumstances into account, ‘BFPS-2’ has been created. BFPS-2 begins with the acquisition of building land and ends with the completion of a Greenfield project or the beginning of the factory operation phase (t=1). Within this and the two subsequent stages, it is highly relevant that the transformability of today’s factories decreases throughout the planning and implementation of a Greenfield project.

‘BFPS-3’ is a stage with at least one Brownfield project, while BFPS-3 can also involve a series of several subsequent Brownfield projects with operation phases in between. BFPS-3 begins with the first decision to plan and perform a transformation after t=1. BFPS-3 ends with the occupation of the final available area. Consequently, free areas are still available at the beginning of Brownfield projects that take place within this stage, until the point in time when the final area is used, e.g. for a building. Extension areas must be acquired from the beginning (BFPS-1/BFPS-2), as project durations would be significantly increased in the case of a later acquisition. One could assume that Brownfield projects which require further areas within BFPS-3 are – if everything happens as planned – largely dominated by transformation processes that take place within extension areas, while other transformation processes occur only partly within already existing structures. Thus, one could furthermore assume that BFPS-3 is almost collision and demolition free. Chapter 6 will answer whether this is true.

The final stage is ‘BFPS-4’ which involves different Brownfield projects that can run in parallel to one another and to diverse operation phases. Occupied extension areas are the starting point for BFPS-4. The border between BFPS-3 and BFPS-4 is blurred, as single transformations can, as a matter of principle, also take place at the beginning of or during BFPS-4, while parallel/simultaneous transformations can also appear within BFPS-3. The condition that areas are occupied leads not only to mutual exclusions of ideal factory statuses with regard to one factory at different points in time (this occurs already in earlier BFPSs); ideal positions and other characteristics of smaller (in relation to the entire factory) FOs/FSs can also exclude each other mutually. This intensifies the problems in factory planning if transformability is insufficient, which means if all relevant transformation requirements cannot be fulfilled. Consequently, FOs/FSs inhibit other FOs/FSs. This can lead to more and more collisions, intertwinings and/or demolitions within today's factories. Furthermore, project overlaps are often unavoidable.

Problems with regard to today's factories are more intensified the more advanced the BFPS that has been reached by such a factory. The BFPSs are depicted in figure 34.

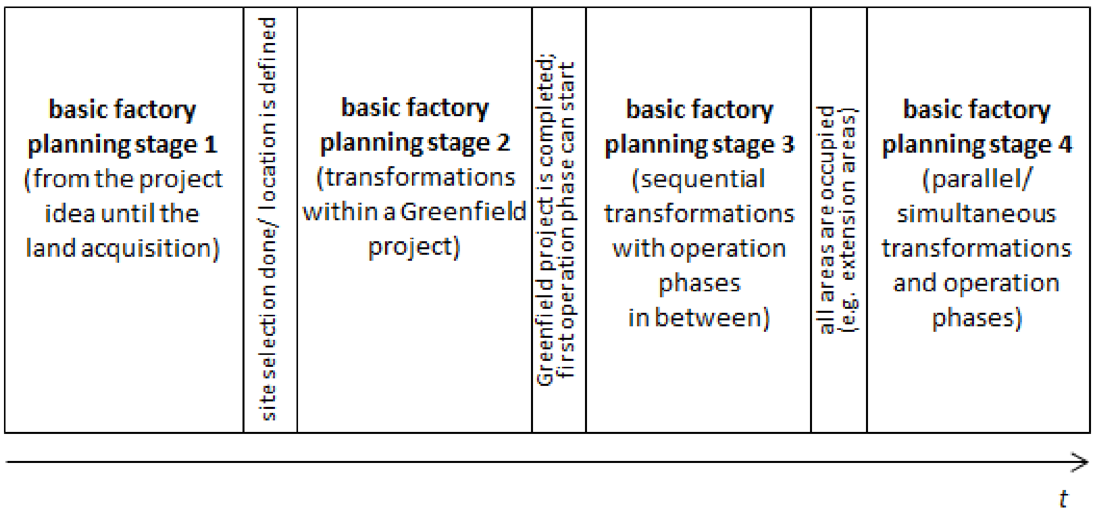


Figure 34: Basic factory planning stages

Projects and operation phases within the single stages are not only related to direct processes and associated FOs/FSs, e.g. production processes within production lines and sections. Such projects and phases are also related to indirect and supporting processes and their associated objects and structures. These objects and structures are, besides others, s&d plants, technical infrastructure networks and service buildings.

It is recognised in factory planning theory that redesigns and reconstructions, extensions, reductions and revitalisations of factories occur, i.e. BFPCs B to E. Nevertheless, real-world factory project cases are not as clearly delimitable, as is partly done in the current factory planning literature. Helbing's (2010) BFPC-8, for instance, is rather realistic, as it involves a mix of tasks that can appear in different factory project cases, even if possible impacts of this case are not described in detail. It will be shown that almost every (e)BFPC is characterised by different elements that can appear in different (e)BFPCs (e.g. diverse BMEs and difficulty factors), and that these (e)BFPCs correspond therefore rather to a mix of characteristics of different BFPCs (or project cases) each, instead of being clearly delimitable. Furthermore, different BFPCs can appear at the same time within one factory and lead to a mix of cases or a programme(s) (especially in late BFPSs). This has not been highlighted in the current literature. Newly appearing BFPCs can furthermore impact on a defined programme(s) and lead to the question of whether such a programme(s) should be redefined. In sum, relevant elements and further aspects with regard to BFPCs have not been identified nor described. This leads to the requirement to enhance current BFPCs in order to indicate the most important factory project cases for factories and factory planning and to explain how they are related to the BFPSs. The main purpose of these enhanced cases is to fulfil their function within the new model.

Although it has been recognised that the complexity of factories increases over time, the structural reasons and backgrounds as to why this complexity arises and increases have not been identified so far. These reasons and backgrounds are described in sections 6.1 and 6.2, as numerous factory- and factory planning-related characteristics are reflected there against the backdrop of the BFPSs of today's factories, e.g. how the transformability and transformation intensity change over time.

5.2.2 Factory Concepts

This subsection provides an overview of the developed factory concepts. First, two factory concepts which represent today's factories are described: the traditional and the modern factory. These factory concepts have been developed based on chapter 2. Two TFCs are then presented: the terrestrial TFC (terTFC) and the maritime TFC (marTFC). The factory concepts, their main components, and classifications of these components are depicted in figure 35.

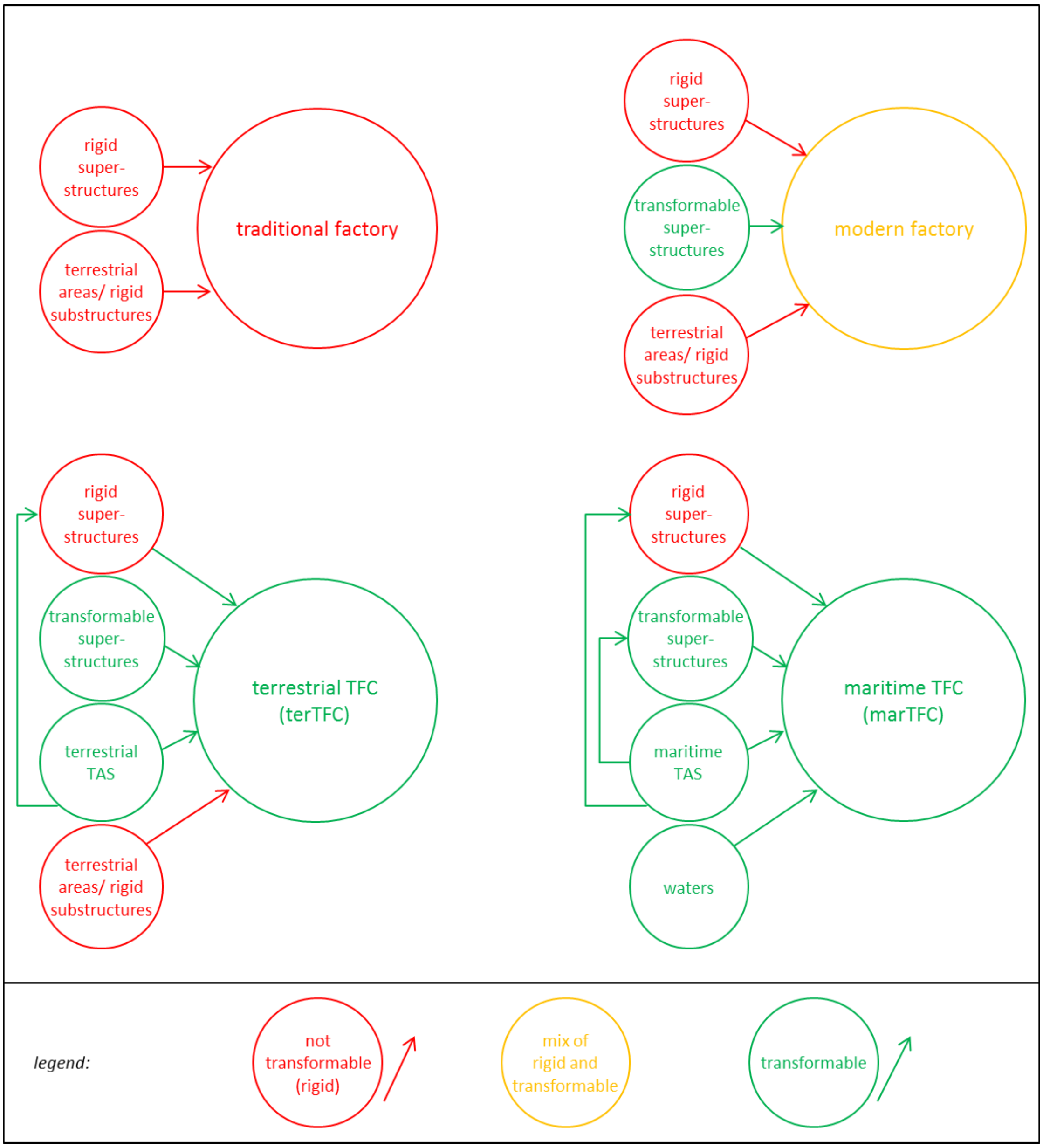


Figure 35: Factory Concepts

The traditional factory represents the majority of existing factories (if TFOs/TFSs within automotive OEM plants are excluded) and is based on rigid (i.e. not transformable) sub- and superstructures. This factory concept involves FOs/FSs that can only be destructively transformed after their implementation. The transformability of this factory concept is consequently limited.

Transformation requirements are demanded by the complex and ever-changing factory environment. This environment is influenced by continuously increasing market complexity and ongoing market changes, which has led to the development of transformable solutions. As a group, these solutions are designated as 'transformable superstructures'. These superstructures involve transformable building systems (TBSs), transformable factory objects (TFOs) and transformable factory structures (TFSs), and are identical for the three remaining factory concepts which have been developed in order to address the ROs: the modern factory, terTFC and marTFC. TFOs and TFSs within buildings are designated as TBCs. The counterparts of TFOs/TFSs are rigid FOs/FSs (RFOs/RFSs) that are designated as RBCs if they are located within buildings. RFOs/RFSs inside and outside buildings also make up the modern factory, while TFOs/TFSs lose their transformable functionality partly or completely if they are partly or completely integrated into or covered by terrestrial areas (which involve rigid substructures) (figure 36).

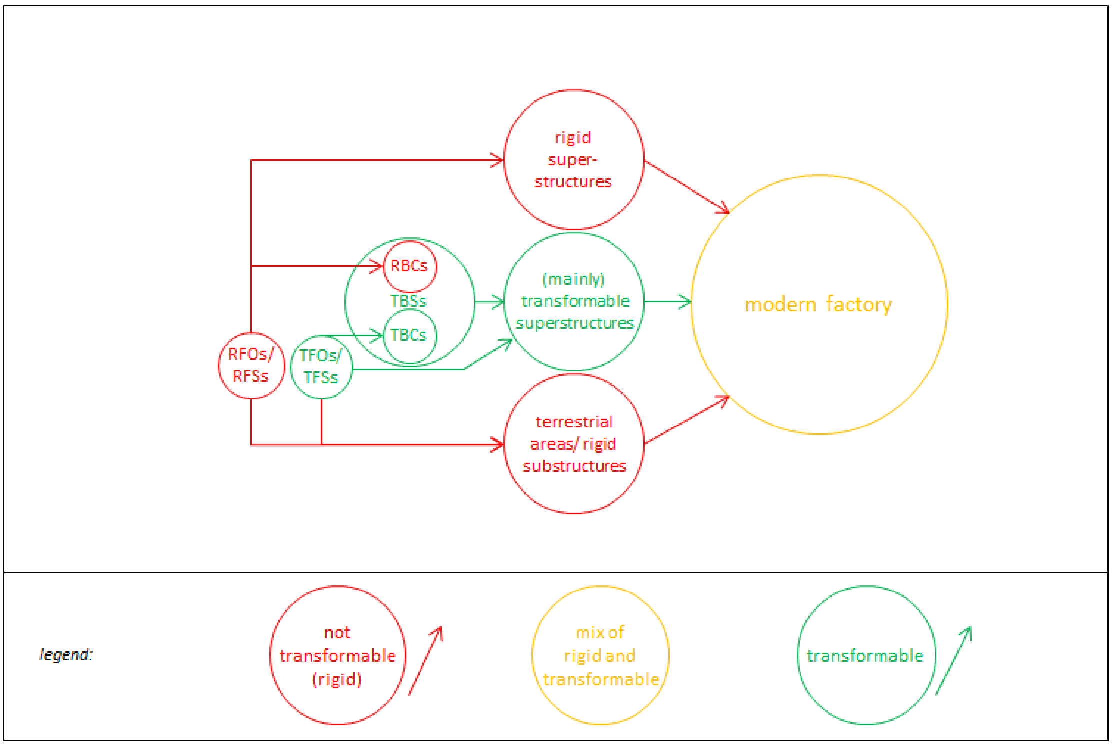


Figure 36: FOs/FSs of the modern factory

One reason for the definition of the traditional and the modern factory concepts is that transformable superstructures are not extensively implemented in practice. The difference between these factory concepts with regard to their transformability is unknown, even though they are both based on the same areas: terrestrial areas. This could be the main reason why TBSs are hardly implemented in practice, as it is highly probable that terrestrial areas limit the potentially achievable transformability of transformable and rigid superstructures and other FOs/FSs inside and outside buildings and within areas. It is assumed that potential advantages of transformable solutions are limited and even disabled by terrestrial areas. The extent to which modern factories are able to meet higher transformation requirements compared to traditional ones is answered in section 6.2.

It is assumed that the full potential of TFOs/TFSs can be achieved through the use of TASs. The difference between the modern factory and TFCs is the area. The areas of TFCs are TASs. TASs build the bases for TBSs and other FOs/FSs inside and outside buildings and are technical systems that substitute terrestrial areas. These systems are based on standardised pluggable TAS-elements (i.e. TAS-modules) and enable active transformations of areas. In addition, TASs provide pluggable interfaces to TBSs, TBCs, outdoor TFOs/TFSs and TFOs/TFSs within TASs. TASs are an equivalent counterpart to these transformable solutions, as they share similar basic characteristics in terms of transformability as well as further characteristics with regard to other capabilities such as pre-producibility and pre-testability. This compatibility leads to TFCs. TerTFCs are based on terTASs and marTFCs on marTASs. Rigid sub- and superstructures can also be combined with TFCs. The transformability of RFOs/RFSs inside and outside buildings and within TASs can be increased through the capabilities of the latter. The terTFC beside waters (terTFC_bw) is a further factory concept which is comparable with the terTFC, with the difference that it involves an interface with and connection to a body of water (or waters), which leads to several advantages and disadvantages. These are described throughout section 6.3.

5.2.3 Further Concepts

FOs/FSs can generally be located (a) inside buildings, (b) outside buildings and (c) within areas. RFOs/RFSs can, for instance, be conveyor systems and closed conveyor bridges between buildings, technical infrastructures, s&d plants, production lines, process facilities and further FOs/FSs that are rigidly bound with the ground, e.g. a drain or a machine that requires a special foundation and cannot be relocated without great effort (today's factories). These objects become inhibitors if they must be transformed or if they impede transformations. Whole buildings and even whole factories can become inhibitors. In such a case, several FPPs are required to perform a transformation. These objects and structures are consequently only destructively transformable once constructed. TFOs/TFSs can be inhibited by RFOs/RFSs. If RFOs/RFSs are located inside TBSs, the transformability of the latter can decrease. In addition, if TFOs/TFSs are positioned within terrestrial areas and/or RFOs/RFSs, their original transformability advantages are decreased or lost. Furthermore, if it is necessary to move/relocate a TFO/TFS or RFO/RFS (e.g. to store it temporarily elsewhere to enable a transformation) and a free appropriate area is not available, such an object/structure also inhibits transformations.

Transformation enablers and accelerators depend on the technical and spatial characteristics of the different factory concepts' objects and structures (especially areas and substructures), as these characteristics lead finally to the capabilities and limitations of each factory concept, which is recognisable through the corresponding units. Transformation enablers/units can be used to describe the elementary transformability of different FOs/FSs, e.g. terrestrial areas and TASs. Accelerators/acceleration units primarily increase the implementation and transformation velocity. Fundamental enablers can involve and combine the capabilities of both transformation enablers/units and accelerators/acceleration units, and can increase the possibilities provided by these concepts. Pre-producibility, for instance, has wider impacts the larger the MAS. The same applies to pre-testability and reusability.

Fundamental enablers play a leading role in factory planning, and depend on the given area characteristics and the area-related transformation capabilities of the respective factory concept. Substructures (including areas) determine the transformability of superstructures. Fundamental enablers must not be confused with transformation enablers: Transformation enablers can be used to describe elementary or subordinated transformation capabilities of factories and FOs/FSs, while fundamental enablers are more far-reaching and comprehensive. Some transformation enablers (e.g. pluggability and universality) can also accelerate the planning, implementation and/or transformation of factories. However, these are not designated as fundamental enablers, as fundamental enablers also lead to a fundamental improvement of sub- and superstructure-capabilities. This is described in more detail in subsection 5.3.1 and chapter 6.

‘Accelerators’ such as pre-producibility are hardly or not at all combinable with terrestrial areas, particularly if an appropriate site has not been acquired. On the other hand, TASs can be pre-produced, which leads to an acceleration unit but can also require time for the definition of an appropriate configuration with functions and interfaces. Thus, by considering transformation and acceleration units and fundamental enablers, data can be developed in order to provide a relevant basic knowledge about all factory concepts. Basic capabilities and limitations of the factory concepts can be described by means of these units and enablers which determine required FPPs, as the different factory concepts either enable these units and enablers or not, depending on their characteristics. Accelerators are mainly relevant for TFOs/TFSs and TASs, while numerous advantages of TASs can be carried over to RFOs/RFSs.

Table 13 summarises the concepts of this research (apart from the factory concepts). The inner and outer mobility were taken from the literature in order to support the assessment of the developed factory concepts. Inhibitors have been developed further: TFOs/TFSs, for instance, can become inhibitors while RFOs/RFSs can become mobile.

inhibitors *(literature-based but developed further*)*	inhibitors are (mainly**) fixed/rigid factory objects and structures but also laws and regulations which disable direct/immediate implementations and/or transformations (mainly through their characteristics) and require factory planning processes that need to be performed to reach a required intention or status

* Inhibitors, as they are discussed in the current literature, are developed further in this thesis and involve an extended meaning.

** Transformable factory objects and structures can also inhibit a transformation if they need to be relocated/moved and no appropriate area is available/free to enable such a move. It is on the other hand thinkable that objects/structures that would inhibit a transformation within one factory concept can be dissolved by another factory concept by means of its capabilities which lead to new opportunities with regard to mobility. Numerous different inhibitors are thinkable.

factory planning processes (FPPs) *(literature-based)*	processes that require time, financial and further resources for the planning and implementation and/or replanning and transformation of factories; these processes depend on the capabilities and limitations of the factory concept in hand
transformability *(literature-based)*	transformability refers to the ability (e.g. of a factory concept) to transform factory objects/structures (e.g. to unplug, move and (re)integrate objects/structures); see the information below for further details
inner and outer mobility *(literature-based)*	the inner mobility refers to the ability to move/relocate factory objects/structures within one location (this mobility-type is therefore relevant for inner factory transformations) while the outer mobility is concerned with the ability to move/relocate factory objects/structures to other sites (e.g. new ones)
transformation enablers *(literature-based but modified)*	characteristics of factory objects/structures (e.g. the modularity and mobility) that influence their transformability either negatively or positively, depending on their availability and peculiarities; transformation enablers lead in combination with factory objects/structures to transformation units
transformation unit *(literature-based)*	when a factory object/structure (e.g. that needs to be transformed) can be combined with a transformation enabler, a transformation unit is created; a transformation unit enables the transformability-potential of a factory object/structure that is provided by a transformation enabler
accelerators *(new***)*	characteristics of factory objects/structures that accelerate the planning, implementation and/or transformation of factories (e.g. the pre-producibility and pre-testability); accelerators lead in combination with factory objects/structures to acceleration units

*** accelerators are described in the literature (e.g. pre-producibility and pre-testability), but their importance has not been highlighted through an own concept.

acceleration unit *(new)*	when a factory object/structure can be combined with an accelerator, an acceleration unit is created; thus, (cap)abilities that accelerate the planning, implementation and/or transformation of factory objects/ structures are enabled (e.g. the preproduction of TASs)
fundamental enablers *(new)*	fundamental enablers combine the capabilities of transformation and acceleration units; fundamental enablers (e.g. the movable area size (MAS)) are overarching supra enablers, as they determine the transformability of areas, substructures and superstructures, and as they significantly impact on the planning, implementation and/or transformation of factories
rigid factory objects and structures (RFOs/RFSs) *(new****)*	these objects and structures are fixed and cannot be relocated without earthworks and/or demolitions; RFOs/RFSs are due to their characteristics (e.g. size and weight) either hardly or not at all movable (today's factories); rigid building contents (RBCs) summarise RFOs and RFSs within buildings or refer to these
transformable factory objects and structures (TFOs/TFSs) *(new****)*	these objects and structures are at least modular and mobile (or movable/transportable); TFOs/TFSs can be combined with TASs and partly integrated in these systems (e.g. a modular pipe networks within a TAS)
transformable building systems (TBSs) *(new****)*	these systems involve the latest technical status of transformable building solutions and are modular, mobile (or movable/transportable), scalable and pluggable; transformable building contents (TBCs) summarise TFOs and TFSs within buildings or refer to these; the designation TFO can involve TBSs;
terrestrial areas *(new****)*	terrestrial areas can involve different characteristics (e.g. different area shapes/forms, soil conditions and layers such as rock layers etc.); terrestrial areas can comprise substructures such as solid foundations (e.g. reinforced concrete foundations), pits, drains and technical infrastructures
area systems *(new****)*	an area system is a technical system that substitutes terrestrial areas but does not meet the TAS-requirement profile (which involves diverse minimum requirements in terms of system characteristics and functions/capabilities which need to be fulfilled by an area system to be classified as a TAS)
transformable area systems (TASs) *(new)*	technical systems which substitute terrestrial areas and meet the TAS-requirement profile (which involves diverse minimum requirements in terms of system characteristics etc. by which transformability and FPP-capabilities can be improved/increased in comparison to terrestrial areas and area systems)

**** these concepts were developed based on technology- and/or literature-based data

(continued)

basic factory planning stages (BFPSs) *(new)*	BFPSs are real-world factory development stages that are consecutively passed through by today's factories and are generally valid if no exceptional cases or special events such as economic crisis, booms or other extreme market changes (e.g. extensive labour or product market shifts) occur.
enhanced basic factory planning cases (eBFPCs) *(enhanced)*	eBFPCs are roughly defined kinds of factory project cases that follow different patterns and can involve different basic movement events and difficulty factors; these cases can help factory planners to orientate themselves and manage factory projects more effectively
basic movement events (BMEs) *(new)*	these events are small reasonable elements by which factory project cases/eBFPCs can be broken down and described more detailed; movements are always basic elements of implementations and transformations while diverse works can come along with these events which means that further factory planning processes can be required (BMEs are certain factory planning processes)
difficulty factors in factory planning *(new)*	these factors are required actions which make the planning and implementation or re-planning and transformation of factories difficult, laborious, time-consuming and expensive
difficulty levels in factory planning *(new)*	to define all impacts of all factory project cases/eBFPCs in all details with all their difficulty factors and relations between these factors (e.g. backcouplings and diverse chain reactions) is not possible. This applies especially to complex cases/eBFPCs in late BFPSs. That the required actions, especially in sum, cannot always be completely defined is part of the problem in factory planning. Therefore, difficulty levels were defined in order to indicate how difficult it is to perform factory projects per factory concept within the different BFPSs.

Table 13: Concept overview

The concepts in table 13 are reflected against the backdrop of all factory concepts in order to define generally valid patterns. Thus, in order to research and assess the capabilities and limitations of all developed factory concepts with regard to their planning, implementation and transformation is enabled, while transformability has significant impacts on the latter three (or on feasible FPPs). Combinations of acceleration units and fundamental enablers (e.g. of the pre-producibility of areas in combination with the MAS) are important in this regard.

5.3 Fundamental Enablers and Accelerators

5.3.1 Fundamental Enablers

Transformation enablers/units can indicate an elementary transformability, but the extent to which the mobility of large FOs/FSs (including areas) is important is not recognisable, as is the importance of other fundamental enablers and accelerators. Neutrality and universality in particular are born out of necessity, as the transformability of today's factories (particularly of their areas) is limited, and as there is hardly another option with today's factories. These transformation enablers focus on compromise solutions to solve heterogeneity-needs against the backdrop of changing transformation requirements which lead to changing flows and area/substructure works. Nevertheless, in the case of TASs/TFCs, these enablers experience new possibilities, even if this is not necessarily required, e.g. due to the 'MAS(s)'.

Crucial real-world factory requirements and capabilities have been either not identified or not synthesised, highlighted and made assessable. This leads to an underestimation of their importance. The importance of the area size and geometry is partly recognisable in Hernández (2002) and Grundig (2015), while the importance of area and substructure characteristics is recognisable in several works. However, their importance is not as synthesised, highlighted and made assessable as it is in this work. Furthermore, the fact that it would be advantageous if large areas were movable/mobile is indirectly recognisable at the most in the current literature and/or lacks academic rigour. Nevertheless, it is recognisable that it is necessary to move/relocate FOs/FSs and to change factory locations.

Area-modularity and area-mobility are not possible with terrestrial areas (this does not refer to the transportation of soil). The pluggability of area-modules is also not considered, but is relevant. What has not been identified is that if the area could be combined with modularity, mobility and pluggability (which enable the area-scalability and area-linking ability), it would have a significant influence on all known transformation enablers, TFOs/TFSs and RFOs/RFSs (and numerous transformation units).

Fundamental enablers (figure 37) depend partially on transformation enablers and have a special role, as they can enable and/or accelerate the planning, implementation and/or transformation of factories, depending on the factory concept in hand with its specific capabilities in terms of fundamental enablers, and on the specific case and framework conditions. Fundamental enablers impact on FPPs and transformability.

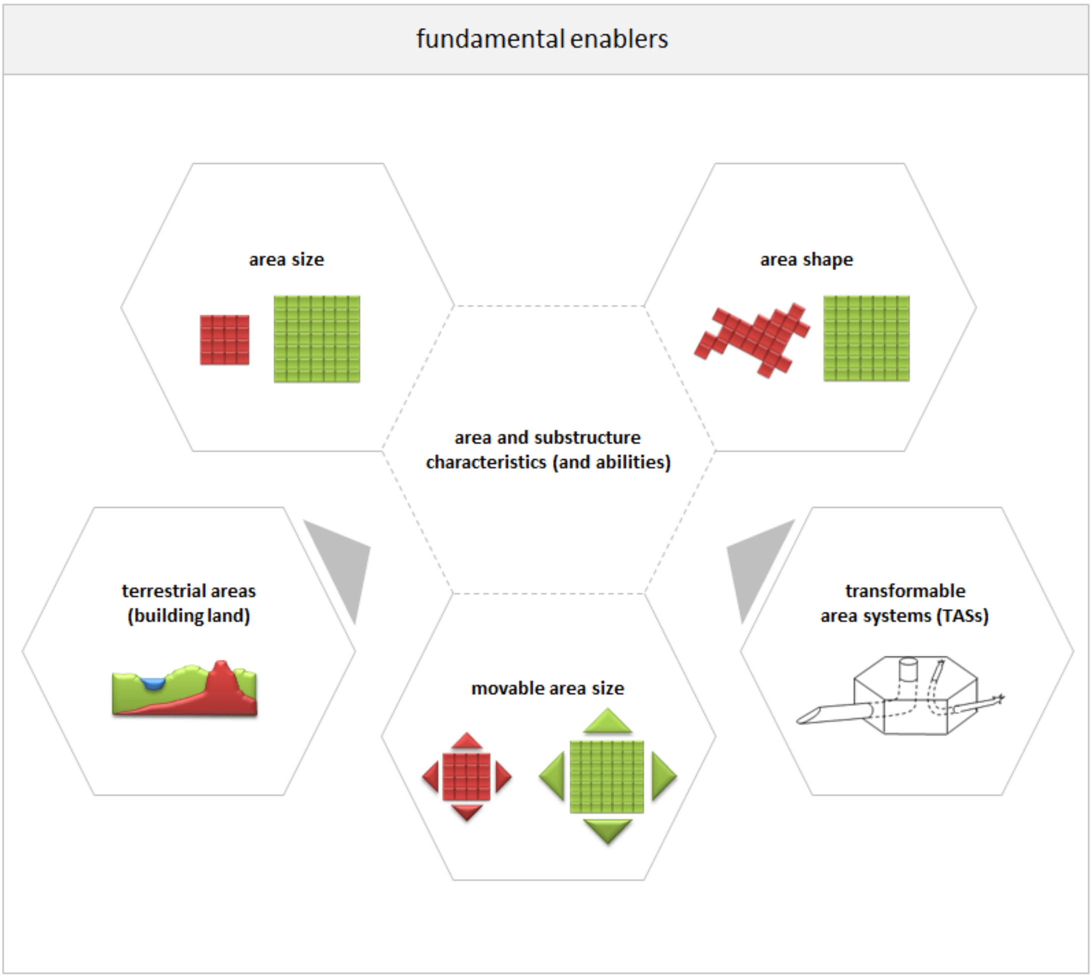


Figure 37: Fundamental enablers

The ‘area shape’ has an impact on buildings, which in turn have an impact on building contents, their arrangement, process flows and their crossings. Buildings should preferably be square-shaped/rectangular but not too narrow, the same as areas. This enables faster implementations and transformations.

The ‘area size’ decides which implementations and transformations are possible and how. If insufficiently free areas are available at the right position(s), displacements and other difficulty factors occur. Off-site areas and/or outsourcing are normally required if a factory lacks areas or areas located at the right layout positions. Transformability and transformation velocity are generally increased if more areas are available. Extension/exchange areas are also required for cases in which the capacity remains the same. It emerged from the interviews that even a BFPC-B can require additional areas.

‘Area and substructure characteristics (and capabilities)’ are either rather spatial/nature-related (terrestrial areas) or technical (TASs) and therefore either unknown/hardly known/knowable or completely known/knowable (no surprises). TerTFCs are concerned with both, the same as marTFCs if these are connected to the shore. Furthermore, these characteristics are either pre-defined and partly definable (e.g. through an increase of the load-bearing capacity through the implementation of additional structures, which increases the knowledge about area and substructure characteristics) and afterwards transformable in a limited way – which applies to terrestrial areas – or definable and largely transformable (e.g. through the exchangeability of floor layers) – which applies to TASs. Furthermore, areas decide about a rather inconsistent (terrestrial areas) or a rather consistent area and substructure quality (TASs). The form is important. A flatness of areas without slopes and/or with definable slopes can be advantageous, the same as a sufficient load-bearing capacity. Moreover, other area-related and/or soil conditions (e.g. contamination and inhibiting structures) are determined by an area and are decisive. In addition, free spaces and the ‘area content integratability’ (i.e. the ability to integrate objects and structures beneficially into areas) are crucial. Area and substructure characteristics either ‘simplify and accelerate’ or ‘inhibit and delay’ implementations/transformations. The level of transformability of area and substructure characteristics determines how advantageous they are. Furthermore, fundamental enablers complement one another.

The ‘MAS’ involves areas and substructures, and is important because of area extension, exchange and other BME-related transformation requirements, for which the heterogeneity in factory planning is crucial. The concept MAS covers all possible area-related mobility units. Through this fundamental enabler, area-mobility is enhanced by considering and combining the area size, area shape and area and substructure characteristics. The MAS is important, as it indicates the size(s)/dimension(s) at which areas and substructures (i.e. areas with their contents) are movable/mobile. The larger this ‘variable size’, the fewer area, substructure and superstructure works are required.

It emerged from the interviews that it is more important to move/relocate small and large areas, objects and/or structures (e.g. buildings including their sub- and superstructures) than acknowledged in the factory planning literature, and that heterogeneous areas and substructures (i.e. area and substructure differences) are crucial in this context.

The importance of the area size, area shape and of area and substructure characteristics was repeatedly emphasised by all interviewees (relevant data was provided mainly explicitly). Furthermore, the fact that the area- and substructure-transformability and particularly the MAS are crucial for factories emerged from the data (based on explicit and tacit knowledge). These fundamental enablers determine transformable spaces (while spaces are basically determined by the area size) and transformable spaces in the correct positions/locations (MAS(s)). This is only one example to demonstrate that fundamental enablers complement one another. Free spaces and beneficial contents are sensible in many cases, but if transformation requirements change, these spaces and contents can become inhibitors. This shows why not only the area-mobility (which has not been identified so far), but also and especially MASs, are significantly important. Everything, and not only production-related FOs/FSs, can be impacted two- and three-dimensionally. For buildings and other objects, areas and substructures are like roots for trees. If one wants to move/relocate them, it can hardly happen without their roots. Factories are like an ever-changing garden with different plants, while areas provide a basis for sub- and superstructures.

5.3.2 Accelerators

Figure 38 depicts the accelerators pre-producibility, pre-testability, and reusability.

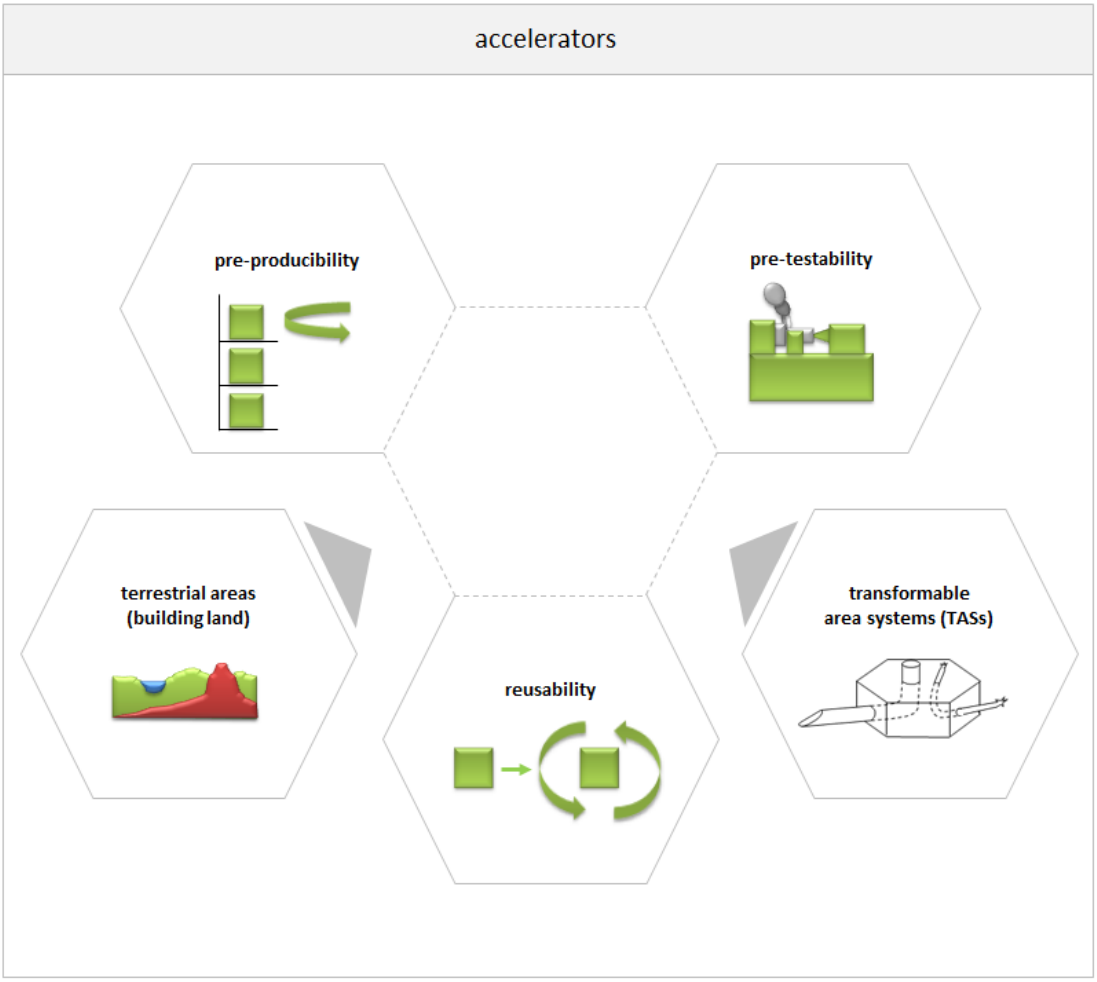


Figure 38: Accelerators

Scanlan (1974) and Hildebrand (2005) have indicated the importance of all three capabilities. The possibility of pre-producing huge structures, installing required FOs/FSs, pre-testing these, and relocating factories has been described (Scanlan, 1974; Sredic, 2011), but not with regard to factory planning theory. In combination with fundamental enablers and against the backdrop of real-world factory and transformation requirements, the extent of the relevance of accelerators can be recognised. These requirements also indicate the relevance of fundamental enablers.

Acceleration units are created through the combination of FOs and/or FSs with accelerators. Acceleration units, especially when combined with the MAS and area and substructure characteristics, impact on FPPs and transformability, and on implementation and transformation velocity (a sufficient area size is a prerequisite). Pre-producibility leads to maximum benefit if pre-produced FOs/FSs are movable/ mobile. MASs have a significant impact on acceleration units. The larger the MAS (e.g. of single and/or combined TAS-/TFC-elements) the better, especially if no restrictions exist. Waterways are better than roads in this regard. Pre-testability is also better the larger the MAS. In addition, the better the area and substructure characteristics, the better the accelerators can be utilised, as transformability and implementation and transformation velocity are additionally increased through this fundamental enabler. What applies to pre-producibility and pre-testability applies in a similar manner to reusability, which increases the sustainability of FOs/FSs and factories.

5.4 Model and Concept Development Process

In addition to the previous sections and chapter 4, this section describes how the model and concepts were developed. The described contents and analyses in section 5.4 are recognisable in sections 6.1, 6.2 and 6.3 (e.g. through the application of the model and associated concepts), and also in sections 6.4 and 6.5.

The number of new concepts and their interplay validate the grounded theory-based approach. Grounded theory-related coding procedures and constant comparison were crucial for the interview analyses. Theoretical sampling was generally applied, which is furthermore validated as the author has returned to and (re-)analysed the transcripts several times.

The following subsections explain what data was gathered and analysed and how the analyses were conducted. Furthermore, the methods and elements of grounded theory that were used are identified.

5.4.1 General Information

BFPSs are important, as they frame the data. The manner in which the capabilities and limitations of today's factories change and how factory requirements and required capabilities change throughout a factory lifecycle can be indicated through the BFPSs.

The limitations of today's factories could be mainly identified through analyses of cause-and-effect relationships*. Two questions were generally relevant in this regard:

(1)	What is the impact(s)/effect(s) of this cause(s)?
(2)	What is the cause(s) of this effect(s)/impact(s)?

These questions were primarily focused on in the interviews in order to identify causes and effects/impacts* (*see the following subsections). The knowledge generated could be used in subsequent interviews through improved questions, e.g. more specific questions. The TAS-requirement profile (RO3) solves these causes. The following general questions therefore dominated the interviews:

(a)	What should today's factories be capable of as it is required? *rather solution-related and more general*
(b)	What is not possible with today's factories, but required? *rather deficit-related*

5.4.2 Importance of Displacements

Transformation requirements lead to new/changing arrangements of FOs/FSs and links between them. One focus was on difficulty factors caused by BMEs (see subsection 6.1.7). Displacements were identified as being particularly important difficulty factors, as these were very often described by all interviewees.

Displacements have different sizes, depending on the case/situation and the achieved BFPS. These difficulty factors were relevant for the analyses of the developed factory concepts and were analysed in the light of the transformability and FPP-capabilities of the factory concepts. Displacements can also occur if only inner parts of a factory are occupied, i.e. despite free areas at the periphery.

Causes were backtracked and effects/impacts tracked through follow-up/ probing/specifying questions if these could not be directly identified in the initial interviewees' statements. Displacements, domino effects and other difficulty factors could thus be identified and information about them collected. The backtracking helped to identify the root causes of displacements etc., which led to the development of BMEs.

Transformation enablers were taken from the literature. Accelerators were developed based on the literature. Acceleration and transformation units and fundamental enablers of today's factories were mainly developed based on the interview data, abduction/logic and analyses of cause-and-effect relationships. It was necessary to develop transformation units in order to identify their real limitations.* The TFCs' units and enablers were developed based on the literature and technology, interview data, analyses of area systems, TASs and TFCs, abduction/logic and analyses of cause-and-effect relationships**. *It is crucial that fundamental enablers impact on transformation enablers/units and accelerators/ acceleration units** (**see below and subsection 5.4.3).

Causes and effects/impacts were aggregated to appropriate concepts, e.g. difficulty factors. Such concepts have simplified the consideration of required FPPs, as these are bundled, or in other words quasi-described in an aggregated form through concepts.

What are the developed factory concepts capable of and what are their limitations?

This was the question which required an answer.

It is now possible to determine the transformability and FPP-capabilities of the developed factory concepts with the new concepts. Capabilities and limitations of the developed factory concepts were aggregated in formable transformation units, accelerators/acceleration units and fundamental enablers. This aggregation allows comprehensive answers to the capabilities and limitations of the developed factory concepts with regard to their transformability and FPPs, and thus to required FPPs on an aggregated but sufficient level in order to enable an assessment of the developed factory concepts and to reach the ROs.

Minimum and maximum capabilities of the developed factory concepts helped to develop the transformation units, accelerators/acceleration units and fundamental enablers of the developed factory concepts. The area size, area shape, area and substructure characteristics and the MAS are variable(s). Minimum and maximum MASs, for instance, indicate that constant comparison and open and axial coding were applied. The same applies to the other concepts. Thus, MASs and other concepts were developed based on the interview data and the grounded theory-based approach. Abduction/logic and the analyses of cause-and-effect relationships were crucial in this regard. Small and large displacements emerged from all interviews and provided the data required*** to develop these concepts, e.g. MASs (***particularly direct statements/descriptions of impacts of real-world factory project cases).

FPPs are simplified through acceleration units and fundamental enablers of TFCs. As TFCs enable MASs, there is no need to always change area and substructure characteristics through laborious, time-consuming and expensive works, as in the case of today's factories. Such works can be avoided through simple transformations, e.g. movements.

5.4.3 Cause-and-Effect and Layout Analyses

It was fundamentally important to analyse the developed factory concepts with various real-world factory project cases against the backdrop of BFPSs in the light of the factory environment. The same cases were used for each factory concept in order to ensure the comparability of the research results. Furthermore, real-world cases which occurred in BFPS-3 were analysed based in BFPS-4 and vice versa.

For the analyses of today's factories, sufficient data emerged from the interviews, e.g. numerous real-world factory projects and their impacts. A comprehensive picture of cause-and-effect relationship could thus be acquired.

These data were furthermore used for analyses of TFCs. Factory layouts were developed based on the interview data. This was first carried out with software (e.g. visTABLE®touch) and later sketched on paper, as the author realised that a higher aggregation level is sufficient. Moreover, detailed layouts of real-world factories which depicted the development of these factories over time were available. BFPSs which were passed through by these factories were recognisable. These layouts were used to repeat/reenact cases with TFCs and to analyse cause-and-effect relationships, i.e. layout/case analyses under consideration of areas, sub- and superstructures. This explains why no in-depth results are provided about the MASs of TFCs; the MASs can differ (see section 6.3). MASs depend on the specific uses and technical details of FOs/FSs, e.g. FOs/FSs within factory sections. Analyses can therefore be endless. Thus, only 100% valid/certain results were included in this thesis. Overall, these analyses can be seen as analytical/memo writing with factory layouts. This was performed during the whole research process in addition to analytical/memo writing with texts, and with mind, concept and process maps.

Situations were analysed and equivalent outcomes were combined into generally valid concepts and patterns. Capabilities provided by large industrial structures (e.g. shipyards) were considered, as these enable the parallelised processes that are crucial for some TFC-related capabilities. Therefore, the use of elements of grounded theory in combination with abduction/logic and analyses of cause-and-effect relationships were, besides the aforementioned procedures, required for the analyses of TFCs (see below).

Ever repeating patterns with regard to factory project cases, their impacts and factory developments could be identified for each factory concept, and the model and associated concepts could be developed at the same time. Besides the abovementioned procedures, the capabilities and limitations of the developed factory concepts with regard to technical and spatial transformability, transformation velocity and FPPs throughout the BFPSs could be identified and assessed through the application of the model and associated concepts.

Figure 39 depicts the concept development lines throughout the research phases.

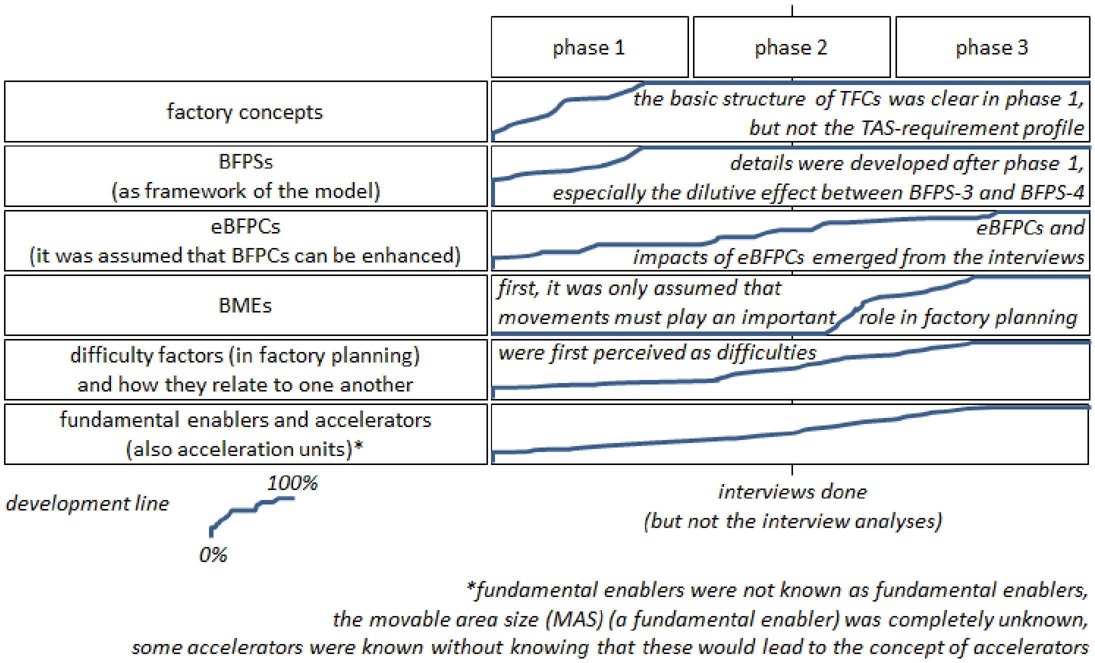


Figure 39: Progress of the concept development

It is seldom possible to define all relationships between research elements, and this is not required if a research is not based on a full grounded theory approach (Wiesche *et al.*, 2017).

What can be said is that the BFPSs, the general research approach, and the RO-relations framed the research and analyses. Theoretical sampling, open, axial and selective coding and constant comparison were applied to develop the model and associated concepts. These were simultaneously developed, applied and developed further, while new categories and concepts emerged at the same time (see appendix 5.4.3 for further details about the model and concepts' development).

5.5 Chapter Summary and Conclusion

This chapter explains the developed model and concepts, how the concepts interact with one another, and how they were developed.

- The BFPSs are key, as they are both the frame and framework of the model.
- The fact that (I) the eBFPCs lead to different impacts which differ furthermore per BFPS is important. These impacts are mainly described by means of difficulty factors;

- (II) the developed factory concepts can handle these impacts differently which (III) has an enormously important effect on 'wider or second level impacts', as chain reactions/domino effects can be reduced and/or cut by TFCs. This will be explained more fully throughout chapter 6 and requires a deep-dive into eBFPC and difficulty factors (section 6.1).

The factory concepts' transformation units, acceleration units and fundamental enablers differ for every factory concept, determine their transformability and FPP-capabilities (which differ), have impacts on FOs/FSs in the case of factory implementations and transformations, and are considered throughout chapter 6. This explains why the factory concepts can handle the impacts of eBFPCs (e.g. difficulty factors) differently. Factories must be green, efficient and transformable, and kept that way. Fast factory implementations and transformations are crucial for their survival. By means of the application of these concepts and the model in sections 6.2 and 6.3, chapter 6 provides answers to the question of whether the developed factory concepts can meet these requirements and if so, why and how or why not. This will increase the clarity about these circumstances.

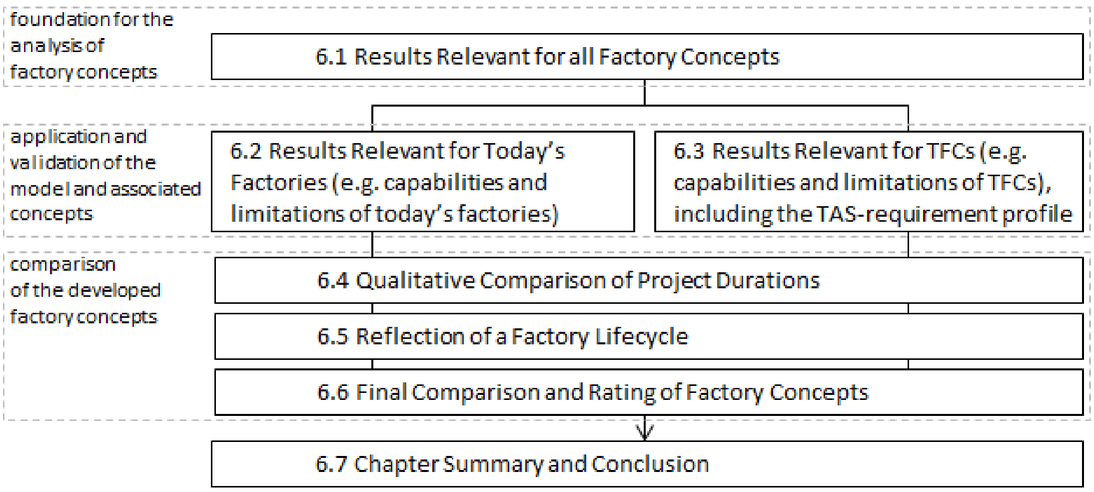
In simple terms, it is all about movements (position changes) of FOs/FSs, the impacts of these movements on areas, sub- and superstructures, and about how the developed factory concepts can handle these movements and impacts. Chapter 6 brings clarity to these issues. What is important in this context is that difficulty factors, which lead to a further deep-dive in section 6.1, are aggregated to difficulty levels for every BFPS and developed factory concept, which reduces the complexity of this research.

In order to significantly reduce the complexity of this research, it would have been required to omit the eBFPCs. Nevertheless, why and how difficulty factors emerge would then not be understandable, and in particular would not be backed up with empirical data. The thesis would lack the relevant background and the results would not be traceable. EBFPCs and difficulty factors lead to a further development of factory planning. This development requires the level of complexity that occurs in parts of this thesis.

6 Concept Development and Model-based Research Results

This chapter contains the research results and is based on new data that emanated from the research (mainly the interviews).

Along with chapters 3 and 5, section 6.1 provides a foundation for the analysis of the developed factory concepts in sections 6.2 and 6.3. Section 6.2 is concerned with today's factories and section 6.3 with the TAS-requirement profile and TFCs. Sections 6.2 and 6.3 are also concerned with the application and validation of the model and associated concepts, and except for their first subsection therefore involve an identical structure. Sections 6.4, 6.5 and 6.6 are concerned with a comparison of the developed factory concepts, based on their capabilities and limitations and also on previous research results. These sections build upon one another. Section 6.4 compares the durations of factory project cases that can be achieved by the developed factory concepts. Section 6.5 reflects their lifecycles with regard to different factory configurations that are required over time. Section 6.6 summarises the previous results and compares the developed factory concepts based on the developed model and associated concepts. Section 6.7 summarises and concludes this chapter.



Section 6.1 is mainly concerned with RO1, section 6.2 with RO2 and the application of the RO1-results, section 6.3 with RO3, RO4 and the application of the RO1-results, and sections 6.4 to 6.6 with both today's factories and TFCs, and all ROs.

The model and associated concepts are applied to a real-world factory environment in which the capabilities and limitations of the developed factory concepts are considered. This is possible through the purposive combination of BFPSs (which frame the research), eBFPCs and difficulty factors, and through the consideration of transformation enablers, accelerators and fundamental enablers, through which the capabilities and limitations of the developed factory concepts can be assessed. The fact that today's factories involve capabilities other than TFCs and require therefore other FPPs is crucial in this context. This chapter shows why the transformability of areas is the most important and the most required factory capability.

The text and appendices of chapter 6 build upon one another. The appendices involve real-world data (chiefly interview statements) which illustrate the reality of situations and validate the main body of text, which was developed mainly based on the interview statements. The contents of the appendices are summarised in the main body of text. Exemplary anonymised interview statements are included in tabular format, and these provide additional perspectives on the themes and concepts where required. The tables have not been assigned numbers as they clearly relate to the accompanying text.

The author has kept translations close to the original statements so that readers can interpret these themselves. Furthermore, the terms 'her/his' are used in the translations to protect the interviewees and for reasons of equality. Commas in the interview statements can indicate short pauses in speech, while missing commas can emphasise the flow of speech. Information in brackets help to understand the context of statements where required.

The interview data back/support one another. If all data are considered and objectively combined against the backdrop of the research paradigm realism, there can be no other research results. The author has endeavoured to combine relevant data in each appendix and to summarise them in the main body of text. Nevertheless, as a result of the large amount of interview data, some relevant aspects are also involved in other appendices and interview statement examples in the main body of text, which is partly indicated.

The author recommends reading appendix 'Assistance for the reader' before starting to read section 6.1. Printing this appendix or copying it into a separate document can support the reader in keeping sight of the big picture. The same applies to section 5.5.

6.1 Results Relevant for all Factory Concepts

Subsection 6.1.1 indicates how often changes of the factory environment and transformation requirements occur, and which ones. Based on real-world data, this subsection validates the suggestion that scenarios are not reliable. This forms the basis for subsection 6.1.2, which proves that scenario techniques are inoperative. These subsections verify the inability to define required 'to be'-factory statuses when project durations exceed a certain timeframe, which is often the case with today's factories. Subsection 6.1.3 explains why, and validates the idea that factories are constantly growing (which is important as these grow out of themselves). This is also substantiated by subsection 6.1.4, which verifies that from a transformation-related perspective, the growth of factories is not only driven by capacity-related area extension requirements, and explains why the term 'breathing factories' can be used. Furthermore, the reasons for many transformations are explained, as well as why area and substructure works in particular are required, and how often this is the case. This is particularly problematic in combination with subsection 6.1.3 and subsection 6.1.5, which shows that factories are heterogeneous and develop heterogeneously. The contents of the subsections prior to subsection 6.1.6 are not described in the factory planning literature and, particularly in combination, are not obvious. This combination explains why area transformations are required, and why area-transformability is important. Subsection 6.1.6 combines the contents of subsections 6.1.4 and 6.1.5 (with regard to subsection 6.1.3) and builds a bridge to subsection 6.1.7. The subsections prior to subsection 6.1.7 provide a basis from which to more fully understand the patterns in subsections 6.1.7 to 6.1.10 (i.e. eBFPCs and their impacts, e.g. the difficulty factors), and vice versa. Subsection 6.1.7 (eBFPCs) makes the impacts of recurring real-world factory project cases tangible, as area transformation requirements are specified. BFPSs are considered. To enhance BFPCs is necessary in order to encompass relevant matters of the previous subsections in a generalised manner, and to describe what the most important cases are and why, and where they lead to. Mixed and off-site cases (subsection 6.1.8) provide additional understanding of the complexity of the reality of real-life situations. Subsection 6.1.9 summarises the contents to this point and provides a lead-in to subsection 6.1.10 (difficulty factors), which makes the impacts of eBFPCs more tangible and explains aspects which create difficulties and complexities in factory planning. Difficulty factors are generally valid patterns which indicate how excessive project durations are formed and why these arise.

To summarise:

- Subsections 6.1.1 and 6.1.2 prove that scenario techniques are inoperative.
- Subsections 6.1.1, 6.1.3, 6.1.4 and 6.1.5 provide the general background for why transformations occur and which ones.
- Section 6.1.6 (transition) summarises and combines the main points up to this point.
- Section 6.1.7 (eBFPCs) makes the transformations that are required more tangible, as it shows what types of transformations occur in which of the most relevant cases and to what these lead, while section 6.1.8 demonstrates that the reality of factory projects and in factory planning is not as simple as shown in section 6.1.7.
- Section 6.1.9 (transition) summarises and combines the main points up to this point, while section 6.1.10 explains in deeper detail what leads to the complexity of factory projects and in factory planning, i.e. which elements and element combinations.

  This complexity is processed further with difficulty levels in sections 6.2 and 6.3, while relevant concepts are taken into account where required.

6.1.1 Number of Changes and Transformation Requirements

IP6 argued that numerous factors change continuously, consequently leading to the permanent change of a decision matrix, i.e. changing factors, factor characteristics and factor values. IP2 also mentioned a matrix in this regard, while all other interviewees also validated permanent changes of different factors. Information about changes was provided numerous times by each interviewee. The number, frequency, speed and manner of the changes in factors can be seen in the real-life cases and data contained in this thesis.

Strategy planners and/or managers make decisions regarding factory capacities and products etc., but this does not mean that actual requirements are met. It emerged from all interviews that design freezes and points of no return are knocked over. No good manager would remain committed to premises which would lead to an unsuitable factory or jeopardise it if there were new requirements and a better option(s).

Continuous changes lead to the most time-consuming tasks, increased project durations and to a knock-over of design freezes and points of no return. The following statements exemplify this finding (see appendix 6.1.1_01 for details):

interview partner (IP)	IP1	Continuous changes occur not only during planning but also during physical implementation and transformation phases.
	IP5	It is clear that continuous changes must be considered. The planning is most time-consuming, as we have continuous planning changes.
	IP7	Decisions are taken and afterwards discarded. Furthermore, decisions are postponed. This is the normal case.
	IP8	Changes of planning premises are normal, the same as changes in decisions and decision-making processes.

It emerged from the interviews that changes often occur. IP7 argued that nothing is static and that factories are similar to computers; you buy one today and it is outdated tomorrow. It is the same with factories, even if the timeframes are somewhat longer. It emerged from the interviews that it can be reasonable to plan 1 to 3 years in advance, even though in most cases this leads to great constraints. The following statements exemplify this finding (see appendix 6.1.1_02 for details):

interview partner (IP)	IP1	Forecasts are imprecise. There are so many influencing factors. It is for instance not only the competition but there are many other influencing factors and it is always a new situation. One influencing factor can possibly be forecasted, but to forecast all together in combination is impossible.
	IP2	It happened in most cases differently than planned. The future cannot be predicted and decisions are taken delayed, as it is possible that one knows something better next week. It is hardly possible to forecast a market – in many cases not a year.
	IP3	Forecasts are not possible. To predict the future is not possible.
	IP4	Changes happen more and more often. Forecasts and premises are not reliable. The market becomes increasingly volatile. The market changes often massively within two to three years and sometimes within one year. Changes belong to the planning.
	IP5	The sales department changes output figures up to one and a half years after the first figures were declared.
	IP6	The market is very volatile, very largely uncertain, and changeable. To assess the development of factory influencing factors is thus impossible.
	IP7	It is impossible to make reliable forecasts. The future is unknown.
	IP8	Changes, which occur during the implementation of a factory, underpin the agility and dynamics of markets. Long-term forecasts make no sense. Market changes and so forth make it impossible for automotive OEMs to plan in development steps.

Smaller and larger transformations occur continuously. The following statements exemplify this finding (see appendix 6.1.1_03 for details):

interview partner (IP)	IP2	Transformations always happen within car plants. There is always something being demolished, or elsewhere something is being newly constructed.
	IP5	Transformations are performed three years before and three years after the SOP of a new model. Five to six years are required to transform a factory for a new model. Transformations always happen (IP5 repeatedly rotated his index fingers). A product model drops out and another product model comes up. Brownfield projects which are concerned with . . . always happen, e.g. renovations. Technical infrastructures and steelworks are mainly impacted by these projects. . . .
(continued)		

interview partner (IP)	IP5	Furthermore, . . . projects . . . happen permanently. Product model projects . . . require, as a general rule, new buildings and happen with each model change (i.e. with each 'product model change' (eBFPC)). Moreover, we have smaller transformations . . .
	IP7	Transformations happen annually and steadily.
	IP8	Small transformations and those that are processed by process owners happen permanently. Continuous improvement processes always happen. A product model changes all six to seven years. Nevertheless, after three years I start to transform the factory for the next model (i.e. the successor product or, in other words, follow-up product) and before that I have optimisations and transformations which are related to the current model, and also later in parallel to the works that are required for the next model I have optimisations and transformations which are related to the current model. Many other transformations are required within a plant.

It emerged from the data that the higher the BFPS, the more and the larger (factory) changes and transformations occur (the exception proves the rule). All interviewees have validated that changes occur during planning and implementation phases of Greenfield projects (BFPS-2). It also emerged from the interviews that such changes have considerable impacts on factories.

interview partner (IP)	IP1	Changes appear for sure within the three years that are required for a Greenfield.
	IP2	. . . it happens in Greenfields that you need to demolish a wall or that lines need to be shifted . . . Permanent changes happen in many projects from the start till the end. . . . Before the Greenfield was finalised it came to the requirement to implement these additional sections. This was not planned and led to suboptimal flows. And suboptimal is really a nice expression for the actual factory characteristics . . . This production scope was insourced as the conditions have changed. Shifts in the assembly shop were required. Furthermore, the truck-unloading docks were changed and several buildings adapted.
	IP3	This factory was built new, but never in use.
	IP8	The required capacity has decreased significantly. It was necessary to transform this Greenfield completely in order to produce another product. . . . this led to vast demolitions.

Numerous cases emerged from the interviews. A well-balanced extract avoids a unilateral representation of what is happening in factory planning. So-called 'worst cases' happen often. Nevertheless, larger Brownfield transformations (i.e. transformations of transformations) occur more often. The interviews showed that the larger and more complex a factory becomes, the more and the larger transformations occur, and these increase in complexity. Real-world factory project cases in appendix 6.1.1_04 (Greenfields) and appendix 6.1.1_05 (Brownfields) verify these findings, and also demonstrate that the exception proves the rule. These appendices show that new transformation requirements impact on FOs/FSs when physical works have already been started, partly completed or completed, which is additionally backed up by appendix 6.1.1_06.

Furthermore, compromises were often described by the interviewees. Compromises were agreed between process planners or process owners/users and factory planners. Compromises are controlled adaptations of plans or transformations of FOs/FSs. Within today's factories, uncontrolled transformations occur. This emanated from the interviews (appendix 6.1.1_07), underpins the general 'line of least resistance attitude' of people (if there is no other clear decision) and shows that a high transformation velocity is aimed for.

The interviews showed that transformation requirements appear more often and are much worse than the factory planning literature suggests. Numerous requirements come in a mix and change permanently, which leads to new transformation requirements. Many key factors cannot be known upfront. It is often unclear which capacities and which products will be required, which technologies will come up and which laws and regulations will change. Changes increase project durations and project durations, in turn, increase the risk of new/changing transformation requirements. This is evidenced in the interviews (appendix 6.1.1_08).

The higher the BFPS the higher the risk for changes and planning mistakes, as project durations generally increase together with the BFPSs. This emerged from the interviews and is verified throughout this document. Overarching systems, sections and numerous subordinated FOs/FSs become – in the case of today's factories – inhibitors. What is reasonable today will be wrong over time (after project completions anyway, but also during projects). This has negative consequences for factories (i.e. their FOs/FSs and characteristics) and factory planning. The following statements show that right actions become wrong over time (appendix 6.1.1_09):

interview partner (IP)	IP3	It is the classic case to look back and to say: We should have done it differently.
	IP6	These machines, foundations and pipes are not required anymore . . . Not even six months after their finalisation, these roads were opened to include pipes.
	IP4	It is not that nice if you construct a building for several million (Euro) and realise that its functions, dimensions, and location are not required anymore, as the requirements have changed. This leads to the worst case: You need to demolish the building (based on a real-world case).

Cross-linked factors and their links and relations change and lead to extensive transformation requirements. Changing requirements are normally not a major problem for Greenfields, but can be catastrophic for Brownfields due to increased project durations, complexities (e.g. through difficulty factors) and changes of the factory environment. Brownfields can become never-ending stories, which is evidenced in the appendices of this subsection. This is in line with Burggräf (2012), as changes can lead to new bottlenecks (p. 46) and changing/new FPPs, which lead to longer project durations. These durations increase the risk of the occurrence of new transformation requirements, which in turn, lead again to increased durations and so forth. This leads to project durations of certain Brownfield projects, which have never been disclosed in the factory planning literature. Furthermore, not only the 'to be'-status of a factory but in some cases – especially in late BFPSs – its 'as is'-status can also no longer be defined, which means that it can happen that factory planners do not know at all what is required to be done.

This subsection shows the high number of transformations, the importance of the transformability of areas and substructures (because numerous small and large areas and substructures that are impacted increase the duration and complexity of transformations), and that the transformation velocity of today's factories is low. The primary purpose of this subsection was to show that factories experience constant and unknown transformation requirements. Furthermore, the interviews have shown that extensive transformation requirements which are partly processed without a comprehensive control are a result.

6.1.2 Inoperativeness of Scenario Techniques

Real-world data in the previous subsection validates the suggestion that scenarios are not reliable. This is furthermore substantiated by the fact that there is no routine operation in factory planning, and that the only routine is change (appendix 6.1.2_01). Statistical intervals, which are used for the pharmaceutical industry, and a comparison of the data that is required to make forecasts in the pharmaceutical and in the automotive industry (appendix 6.1.2_02) indicates the enormous data complexity which must be handled in order to make anticipations for automotive OEM plants and similar factories. Demographics and the purchasing power of groups of individuals might help to determine factory/production capacities for product models, types and time periods, e.g. required production units per model and type for one year. Nevertheless, knowledge of these factors is not sufficient to anticipate and determine the required products and production quantities (which is already difficult), and particularly not a required factory configuration, which depends on further factors, a few of which are depicted in figure 40.

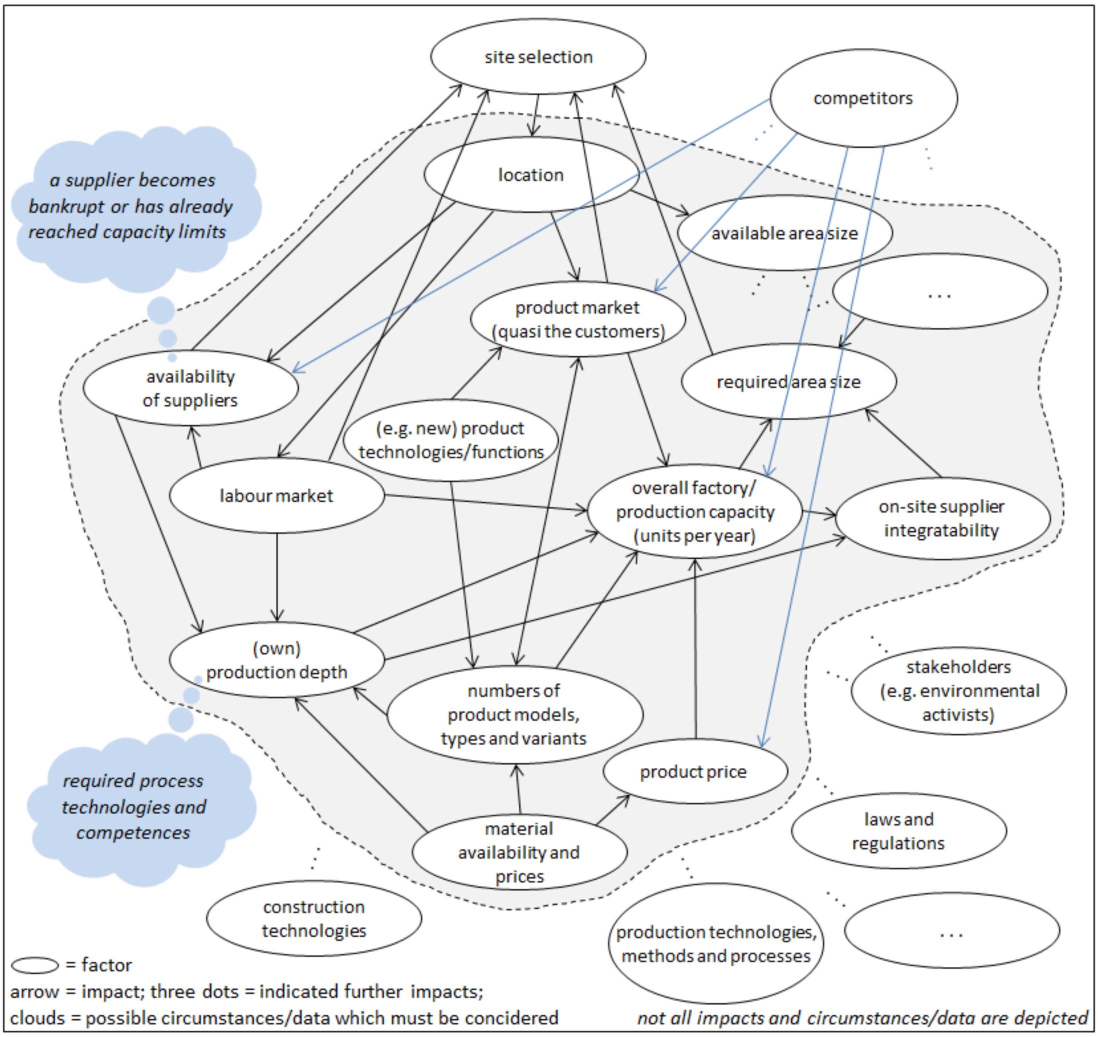


Figure 40: Cut-out of factors and influences relevant for scenarios in automotive factory planning

One problem is that site selection cannot be reversed with today's factories, while problems increase throughout the BFPSs.

Vester (1999, cited in Hernández Morales, 2002, p. 98) claims that twenty to forty key factors suffice to fully describe a complex system. Vester (2012, p. 19) also claims that thinking in terms of relationships is a prerequisite, but this cannot solve our problems. This thinking approach must be transferred to planning practice and finally into required actions. The data complexity and interactions between data must be considered. In this context, a correct aggregation level plays an essential role. To achieve this involves a correct consideration of relevant superordinate system levels and a correct level of detailing (p. 19). However, more than that is required. Combining the knowledge elements of Vester (2012), Barrow (2013) and Wiles (2013a, 2013b), minimum subsequent works are required for a definition of reliable scenarios:

- consideration of relevant superordinate system levels
- detailing to a reasonable data pool(s)
- exploration, assessment and definition of relevant factors (e.g. variables), and of links and influences between these factors
- The definition of these factors, links and influences requires the consideration of different probabilities of occurrences at specific points in time, because it is not only the point in time when a factory needs to be completed that is relevant.

This is required in order to define necessary configurations for a factory in t=1 (and optionally in t=3, t=5, t=7 and so forth. These statuses must be considered in earlier factory configurations, or at least in earlier configurations of today's factories), and the data is required in t=0+X (X=<1). T=0 is the start of a Greenfield project. In t=1, the factory is implemented and operates at least until t=2. T=2 is the starting point of the transformation phase, which begins with the recognition of a transformation requirement that leads to the initiating idea for a transformation and consequently to the start of the first Brownfield project, which is finalised in t=3. Between t=3 and t=4 is a further operation phase. Between t=4 and t=5 the next Brownfield project takes place and so forth. Several Brownfield projects and operation phases can run in parallel.

If one has only 10 key influencing factors, each with a probability of occurrence of 90%, (which is unlikely even if these single factors and their probabilities could be defined), the chance is less than 35% (=$0,9^{10}$) that these factors will occur as they were forecasted and therefore, that a scenario appears as anticipated. Ten factors are insufficient and 90% is not realistic. It also remains unclear how (a) the probabilities of (especially complex) factors and (b) the influences of these factors on one another can be defined (while (b) can impact on (a) and vice versa).

Reliable scenarios require many further factors, many more details per factor and many more impacts than depicted in figure 40. Throughout the BFPSs, the manageability and processing of data becomes worse. If and how these factors etc. can be appropriately considered and processed has not been seriously considered in the factory planning literature. Reliable scenarios and scenario funnels are currently hardly definable for automotive OEMs. Single prediction intervals and scenario funnels are widely distributed and scattered. In sum, they lead to an overall scenario funnel which grows over time (figure 41), while the probability of reaching required factory configurations decreases as the limited transformability of today's factories decreases further over time (not depicted).

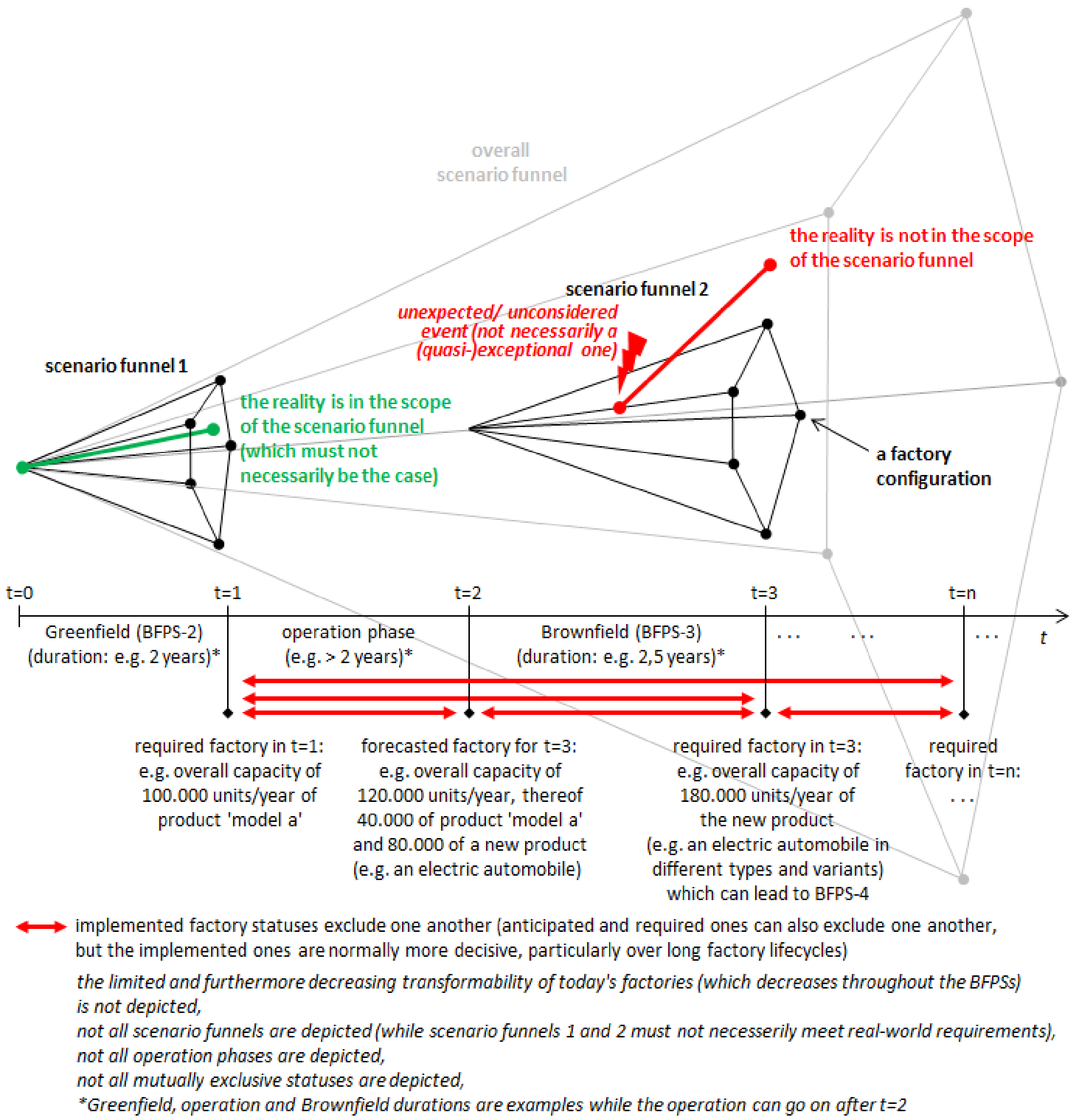


Figure 41: Scenario funnels in the context of transformability aspects

Furthermore, different factory configurations exclude one another.

The interviews showed that the development cycles of single factors not only differ, but that they are also exposed to erratic, considerable and/or unexpected fluctuations. A change in one factor can impact on other factors. Furthermore, one change in one factor can lead to large changes in numerous factors. In both cases, a scenario funnel can be left. Unexpected/unconsidered events are not necessarily exceptional. It emerged from the interviews that such cases occur quite often, while (quasi-)exceptional cases also occur.

The question is whether a scenario funnel meets real-world requirements at all from the beginning. To define the future sufficiently with a finite number of scenarios is doubtful, while today's factories cannot meet all of the possible factory configurations which could be required, and particularly not additional ones which will be required over time. Moreover, the limited and furthermore decreasing transformability of today's factories is not considered in this context and exclusions of different factory configurations/statuses are hardly considered. Due to the described circumstances, from a logical perspective there is a very low probability that a scenario funnel is correct. The probability that a correct scenario funnel can be reached by a current factory when its physical implementation or transformation has begun is even lower. Even if a scenario funnel was right, one change can make it wrong, and numerous changes occur over a period of one year for example, which is far too short for many factory projects. Furthermore, the choice of one configuration excludes concurrent ones (i.e. other optional configurations at the same time) the more, the more the physical implementation or transformation proceeds. Moreover, the chosen configuration excludes others which occur over time.

Statement of interview partner 2: When all areas are occupied, there is no capability to breathe and no optimal arrangement of areas is possible anymore, as no exchange areas are available to restructure areas. This thing (the factory) languishes. It can only be transformed in parts and not holistically.
(continued)

interview partner (IP)	IP2	. . . You always deviate from the ideal process and somehow use the existing building structures, areas and sizes, and you adopt them. Thus, one is away from what is ideal.
	IP5	Decisions were taken and objects constructed which one would like to change afterwards, but this is not possible. The factory has been extended and now we cannot go back and say: Let's do this in a different way.
	IP6	We went in this direction and have used these areas. The galvanisation is where it is. It is a fixed point that cannot be changed just like that. Despite all physical restrictions that are given is it anyhow not possible to change the location of this process as it has only been approved for this specific position. It cannot be relocated due to other processes and aspects related to labour safety.
	IP7	A historically grown factory cannot be an ideal factory.
	IP8	This factory became a UHP as only reactions to current requirements took place. The factory was extended and transformed, but there were no thoughts about a new overall structure. The extension steps were too small to justify a factory doubling or a new factory. . . . Market changes and so forth make it impossible for automotive OEMs to plan in development steps. . . . Future plans for factory developments are inhibited and can even be disabled through unplanned changes. . . . Transformability is limited wherever spatially and historically grown structures are. Everything leads to UHPs. The factory gets larger and more unstructured and thus more complex.

Besides other aspects, the use of incomplete and subjective data which are also reduced shows that the use of scenarios in factory planning is not scientific (appendix 6.1.2_03). To forecast the future in complex problem situations is thus not only not exactly possible, as claimed by Burggräf (2012, p. 173), but hardly possible; in a chaotic and disordered world even less so (see appendix 6.1.2_04 for the domains of the ‘Cynefin framework’). To develop different factory alternatives based on past, current and possible future developments mainly involves risks if it is carried out in the way that the factory planning literature suggests. The use of scenarios can help to better react to ‘possible futures’, which is an expression used by Fink (2002a). Nevertheless, the use of scenarios in factory planning requires vast improvement.

Factory planning is based on questionable data which are used for the planning, implementation and transformation of factories, while FPPs require time, and time can make initial planning data invalid. This subsection confirms that it is hardly possible to define the required 'to be'-factory status(es). To anticipate the future is doomed to failure, since the implied factors and their manifold links and influences are hardly definable and processible as a whole. Thus, this attempt is not practical for defining required factory characteristics and future transformation scopes, e.g. required area characteristics in two years' time and FPPs required to achieve them. Factories work in the end, but the interviews have shown that problems are on the daily agenda and that real-world requirements can hardly be met, and at times not at all. The situation becomes worse throughout the BFPSs. The limited transformability of today's factories decreases further over time, while different factory configurations exclude one another. Thus, not only the question about the period of time that can be anticipated is relevant, but also the question about the period of time that is sensible to anticipate. It must also be considered that (quasi-) exceptional cases occur. All of this often makes situations in factory planning hardly manageable or unmanageable; this emerged from the interviews and is also recognisable in the following pages.

The factory environment changes continuously, and factory planners try to consider these changes. This leads to transformations, if transformations can be made possible. To transform today's factories towards all of the factory configurations that are required throughout long factory lifecycles requires extensive demolitions, reconstructions and new constructions, while project durations lead to further and more serious problems (see subsection 6.2.6). Thus, it is necessary for future factories to be more transformable than today's factories.

Scenario techniques appear mainly as reliable methods in the factory planning literature, and are often used without sufficient critical reflection and adequate doubt. The mistaken belief that scenarios lead to significant advantages in factory planning has now been dispelled. Today, scenarios in factory planning are either hardly reliable or not at all reliable. Unknown developments dominate the current era, while factory environments are rather chaotic than complex.

Scenarios can, of course, still be used, but it makes less sense in the light of huge complex factories if one is realistic, since planning with scenarios will result in many factory configurations, of which not all can be covered by outdated factory concepts. Scenarios can be used in combination with TFCs, which reduce the uncertainty (see subsection 6.3.6 for further information).

6.1.3 Factory Growth Compulsion

It emerged from the interviews that enterprises must grow continuously against the backdrop of their competitors and the adjustment of our economic system:

interview partner (IP)	IP2	Shareholders invest their funds somewhere else if your profits and therefore your company do not grow. There is only one way to stay competitive and receive funds. The way to grow.
	IP6	Investors expect that margins grow over time. If this does not happen, they withdraw their capital and invest it where they expect to make a larger profit.
	IP3	Company taxation leads to the circumstance that enterprises would rather grow than pay profit taxes.

This is in line with Hanke (1997). A further growth compulsion occurs through safeguarding aspects, profit-orientation, and competitive pressure:

interview partner (IP)	IP5	One tries to get as many products and as much work for the own factory as possible. The longer a location or a factory exists, the larger it becomes. The work council becomes more powerful and forces further growth. . . . Competitiveness requires areas. Competitiveness requires growth.
	IP4	Countries and regions are interested in strengthening a location as it is safeguarding the region, the infrastructure, and the people.
	IP8	We cannot be competitive if we do not grow. *Information: Factories were meant with the word 'we'.*

Furthermore, more renovation and other transformations are required with increased factory age and larger factory size, whereas capacity-unrelated area extension requirements and further aspects cause growth.

The main point becomes ‘forms of transformations’, which lead to an enlargement of factory sizes and require a high area- and substructure-transformability, which must be the higher the higher the reached BFPS.

Next, area extension requirements are further differentiated. In addition, aspects which explain the designations alternating and breathing factory are described.

6.1.4 Types of Factory Growth and Transformations

Helbing (2010) describes area and space requirements of FOs/FSs, considers their geometry and movements, as well as movements of their elements (e.g. robot arms) and their impacts on diverse systems and other FOs/FSs. However, area and substructure transformation requirements and their impacts on factories are not highlighted, even though these are crucial for factory planning and provide the required input data for the definition of what factories should be capable of.

It emerged from all interviews that the area size as well as the area- and substructure-transformability are significantly important for transformations. Global events lead to an increasing dynamisation of factory areas, sub- and superstructures, which must be extended, reduced and/or otherwise transformed.

interview partner (IP)	IP2	Areas should be as large as possible, but they should not be built too large due to cost and risk reasons.
	IP3	It is the normal case that the factory grows. Even if you do not want that the factory grows, it grows due to different transformation requirements. . . . The factory gets bigger and bigger, even though the production figures remain the same. This is the normal case for body shops and other shops (sections).
	IP4	One should have areas – healthy free areas to be able to rotate, to breathe. Which extension- and exchange-possibilities do I still have; limitations in both regards exist.
	IP5	Demolitions and new constructions happen continuously. This applies to all factories that I know. Good, new factories require fewer demolitions. Nevertheless, demolitions happen also in new factories. . . .
(continued)		

interview partner (IP)	IP5	Sustainability, no one cares about sustainability and the big question is if it is possible at all to be sustainable. Companies which were really sustainable do not exist anymore and new ones will disappear as they are not competitive. Competitiveness requires areas. Competitiveness requires growth.
	IP6	Transformations happen non-stop. We grow here, we extend there, we construct new buildings and demolish old ones. This is the normal process.
	IP8	We always need areas and we are permanently searching for areas in almost all factories.

Not only are more areas required after a capacity increase or through additional product models, types and/or variants; other transformation requirements such as changing products require (e.g. free) 'exchange areas' to enable transformations without disturbing ongoing direct (e.g. production) and/or indirect processes.

Extension possibilities must be pre-defined (Claussen, 2012). It emerged from the interviews that extension areas are not always required as planned, and are also not sufficient to meet today's transformation requirements. Generally, a capacity increase with (a) unchanging, (b) changing and/or through (c) additional products (models, types and/or variants) can happen. Such changes can lead to completely different area distributions and requirements. Thus, some parts of factories can experience large changes within a few months. The transformability of areas is therefore important.

Every factory system should have an extension area of up to 20%. Extension areas are required for extensions and other transformations, especially because of system element replacements (Helbing, 2010, p. 342). Schenk, Wirth and Müller (2010, p. 119) validate this, as they argue that additional areas must be reserved in two or more directions in order to enable flexibility and transformability. Nevertheless, capacity-unrelated area extension requirements have not been sufficiently emphasised in the factory planning literature.

Capacity-unrelated area extensions can occur in all eBFPCs. 'BMEs' and 'difficulty factors' also occur in eBFPCs, which also leads to their enhancement and a better understanding. What is important in this regard are (extension) areas in the form of 'exchange areas'. These areas are of particular importance for the eBFPC 'product model change' which occurs repeatedly and has permanent impacts on automotive OEM plants:

interview partner (IP)	IP1	Processes follow one another step by step: area works, land levelling, foundations. Afterwards, we start to construct the sections that require the longest duration. . . . When I take a look at different sections, in the main are these the paint, press, body and assembly shop, the requirements are so different that I have also completely different building requirements. . . . There are continuous transformations in body shops . . . Exchange areas are required as these areas simplify transformations. . . . We will demolish several buildings to extend the body shop. This will lead to displacements of diverse functions. These functions will require buildings outside of the factory which need to be found and adapted. It is also possible that new buildings will be constructed.
	IP2	Exchange areas can be required for paint shops, as the largest product determines the characteristics of this section. . . . An exchange area for the body shop is in each case required. Even if it is a flexible one, an exchange area will be required as requirements change that cannot be absorbed by new technologies and robots. Possibilities provided by modular robot cells are limited. Modern body shops are therefore not really transformable. . . . logistics areas and beside these areas a body shop and then you build a new logistics hall or a body shop or you extend the building and then you have an exchange area.
	IP3	In the case of a product model change, different machines and machine arrangements are required in the body shop. Therefore, exchange areas are required. . . . There are several fixed points.
	IP4	We try to avoid substitution processes. This is one reason why we have multiple fields for the body shop. We construct a completely new body shop. Therefore, larger areas are required. . . . Several smaller areas at various positions do not lead to advantages. A large area is required as an exchange area.
	IP5	Difficulties occur when no exchange areas are available. This applies to the assembly shop including end-of-line due to the rain test and other fixed points. . . . In the case of a product model change, the body shop requires a complete change and thus a complete exchange area. Operational sequences, production flows, and logistic flows change.
(continued)		

Statement of interview partner 8: A body shop requires the implementation of a completely new production system, as steel changes to aluminium and as sheet thicknesses change. Other changes occur. This is a change in use from an area perspective.
The following text and appendices in this subsection and in subsection 6.1.7 involve further interview statements and information in this regard.

Exchange/additional areas are also relevant for the other eBFPCs and numerous real-world factory project cases, even if their single elements and key factors can differ:

interview partner (IP)	IP3	Exchange areas increase the transformability of factories. . . . A Brownfield without exchange areas means that transformations must be done within given structures which make transformations more difficult and partly not possible. If exchange areas are available one can implement a new production and demolish afterwards the old one.
	IP4	When machines become so old that spare parts are not available, exchange areas can be required. . . . Exchange areas are often required in the case of transformations.
	IP5	Exchange areas are required to pre-test the production. . . . Transformations within buildings are required if exchange areas are not available. This makes transformations difficult, if these are possible at all. . . . A new construction at an exchange area is preferred in factory planning rather than having a transformation. It is more difficult to perform transformations without exchange areas.
	IP6	Exchange areas are very important, as they lead to transformability and enable transformations which without these areas are not possible at all. . . . Transformations can be disabled without exchange areas. . . . If you do not have exchange areas, your factory is not transformable.
	IP7	Available extension areas, exchange areas, and building volumes are very sensible, as one can bypass many problems. . . . A new (product) model project led to production shifts to suppliers. This will lead to displacements and higher logistics costs.
	IP8	Exchange areas increase transformability and if one does not have them, she/he needs to do a patchwork and extend single separated areas as required (IP8 made furthermore a similar statement that was slightly different and is still to follow).

It emerged from the interviews that implementations and transformations must be accomplished as quickly as possible and that the production should not be interrupted or stopped (appendix 6.1.4_01):

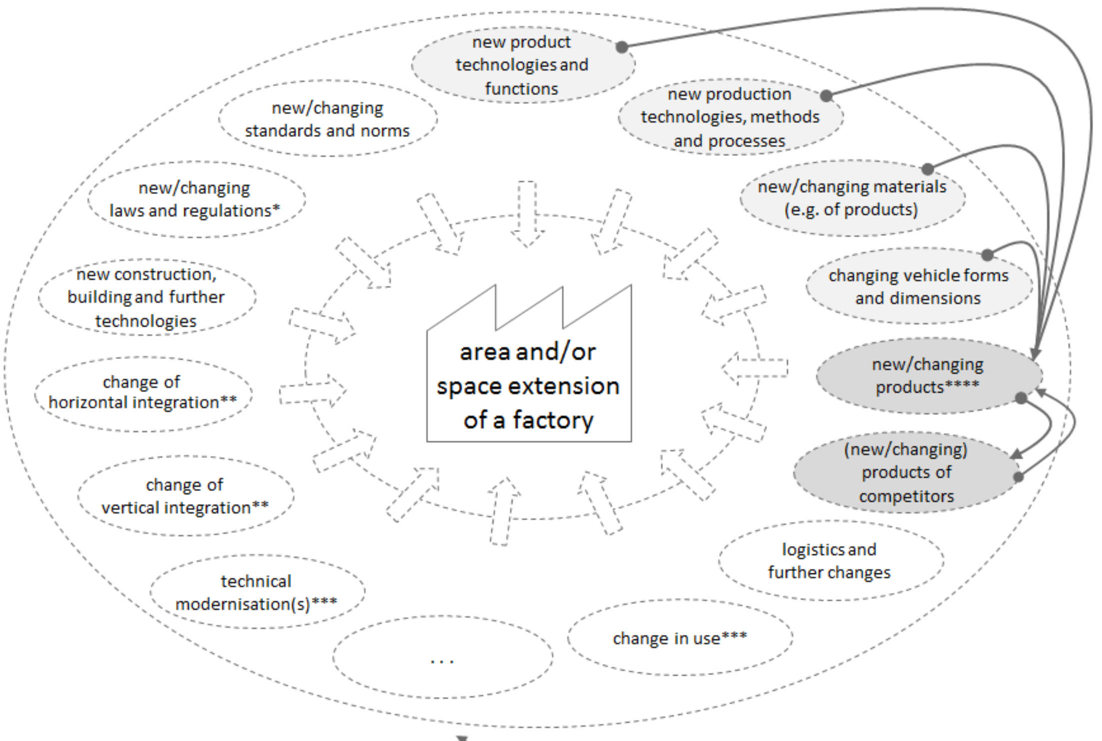
interview partner (IP)	IP8	It is clear that you need to be the first at the market.
	IP5	Transformations must be done as fast as possible. . . . The production must go on. It can cost several million Euro if it is disabled.
	IP4	The production cannot stop.
	IP2	To get as fast as possible into the market is aimed and not three years later as you lose market shares or cannot win them. Others will sell the products that you could have sold.

This is in line with Grundig (2015) and with Romberg and Haas (2005), who demonstrate that an early SOP can significantly increase the profitability of a factory.

Exchange areas are generally required if halts in production related to transformations (e.g. section transformations) would be too long and if no areas for pre-produced parts and/or substitution processes are available, and/or if no outsourcing possibilities exist. The latter three are not always possible and/or reasonable. Inversely, this means that if exchange areas are available, no or at least fewer substitution processes etc. and holiday works are required (appendix 6.1.4_02). Holiday works are at least less decisive.

All interviewees demonstrated their knowledge of ‘exchange areas’ – especially in combination with product changes (see appendix 6.1.4_03 for further exchange area-related statements).

The key influencing factors shown in figure 42 emerged from the interviews as the most important ones that lead to transformation requirements and can lead to capacity-unrelated area (and/or space) extensions.



possible impact of a key influencing factor on another key influencing factor,
not all possible impacts of and between key influencing factors are depicted (a new product, for instance, can have an impact on chosen materials while materials can have an impact on required production methods)

** e.g. the implementation of objects for noice protection and the use of new refrigerants for automobiles*

*** an increased production depth requires more areas; a decreased/lower production depth leads to a reduction of production areas, but requires logistics areas (more logistics areas can be required when the production depth decreases) (see subsections 6.1.7 and 6.1.8); a change of horizontal and/or vertical integration has not necessarily an impact on the overall capacity of a factory (units/year)*

**** in the case of different transformations it can be required to pre-produce and store parts and/or to ensure substitution processes (if possible); outsourcing can lead to supplier extensions; further impacts can come along with a change of vertical integration; other reasons can lead to substitution processes, e.g. machine failures/breakdowns, moves/relocations etc.*

***** other key influencing factors can also have an impact on products, e.g. new standards; products can, for instance, be models, types and/or variants of automobiles (see also subsection 6.1.7, 'product model change')*

subsections 6.1.7 to 6.1.10 involve further information about these aspects

Figure 42: Key influencing factors of capacity-unrelated area extensions

Capacity-unrelated growth is not always initiated by products, but it emerged from the interviews that product-related matters are the most commonly occurring causes of transformations. Different changes (light grey ellipses) come along with new/changing products (the upper dark grey ellipse), while the light grey and several of the other influencing factors can also occur during a product lifecycle. These arrows can also be reversed. Furthermore, the products of competitors can impact on an own factory's products and vice versa. Further information about key influencing factors can be found in appendix 6.1.4_04 and subsection 6.1.7.

That a factory should essentially be able to breathe with its area emerged from the interviews. Transformations of all flows are required from time to time, and these lead to movements (position changes) of numerous FOs/FSs. Overarching networks and systems (e.g. technical infrastructure networks and conveyor systems), buildings, rooms, areas, traffic routes, walkways, building contents, s&d plants, canteens, parking lots, car parks, green compensation areas etc. change, and with them numerous further FOs/FSs, and thus areas and substructures. Optimal positions, required sizes and the number of FOs/FSs change. Factories grow not only towards extension areas; several sections and other FOs/FSs grow out of themselves. Their extension takes place, roughly speaking, out from their centre towards one or several directions. This leads to displacements. FOs/FSs displace other FOs/FSs. Displacements can be intensive and impact not only smaller (container-sized) FOs/FSs: Larger areas and FOs/FSs can also be impacted. Production sections grow into others. Furthermore, production changes into logistics and vice versa (buildings and/or areas). Moreover, sections grow into departments (i.e. office buildings) which are thus displaced – often to locations outside the factory. Many other area changes and exchanges occur. Centralisations and decentralisations also occur. Vast demolitions (e.g. of buildings) are one outcome. The contents of the previous paragraph must be considered in this regard, while different RFOs/RFSs (e.g. s&d plants) remain where they were implemented (appendix 6.1.4_05).

interview partner (IP)	IP1	(If buildings were movable) One could shift a building to the periphery, and instead, put more important ones in the middle. Positionings of objects are a problem because if indirect ones (e.g. office buildings) are positioned at the periphery, growth is disabled; if they are positioned in the centre, they disturb connections between production sections. Factories should be able to breathe. . . . The core grows to the periphery while non-production parts are displaced to the outside of the factory boundary.
	IP2	Changes of uses happen in which a section grows into another. The assembly grows into logistics areas. . . . Production facilities should be relocatable.
	IP3	Body shop, assembly shop, conveyor bridges . . . wastewater system etc., to move these, one would be required to open the ground and areas, install base pipes etc. Canteen planning: ways to the canteen should be not too far. The fire brigade requires also short ways.
(continued)		

interview partner (IP)	IP3	. . . It would be very advantageous if I could move areas as desired.
	IP4	Areas, building structures, roads, walkways, supply networks, production lines and numerous machines are reduced, extended and otherwise transformed in many different ways. Therefore, their transformability is important. . . . A factory development is concerned with the question of how a factory can be made fit for new products and how the arrangement of areas and buildings, and connections between buildings must be transformed over time. . . . The (production) line and the process facilities should be able to breathe by reason of their changing interplay. . . . It would be desirable that the assembly shop can be implemented where the body shop is. Furthermore, it would be desirable to change it into a press shop. The reality is that exchange areas are required. Buildings are pushed away (i.e. displaced) by other buildings. I extend the body shop and reduce the assembly shop or vice versa. This means that I need more body shop areas and that I reduce assembly shop areas or vice versa. . . . The relocatability of objects and structures is desirable. Indirect functions should be close, but if more areas are required, they should be movable so that they can be shifted away. Other objects and structures must be close. Canteens must be reached within a certain timeframe and must therefore be located within a certain radius; the same applies to factory fire brigades.
	IP5	Roads were widened. This required the demolition of adjacent garages and other buildings.
	IP6	Wider roads would be sensible, but it is impossible to implement them. There are buildings all around.
	IP7	It would be sensible if factory objects and structures that are larger than containers were movable, especially as different departments and sections change. Consequently, it would be nice if we could generate free areas in the middle (of the factory).
	IP8	Transformability is important for all production sections, for buffers, and for connecting conveyor bridges. . . . Logistics areas change . . . fixed points such as the rain test change. It would be sensible if different areas could be shifted.

These circumstances explain why in the case of today's factories a large amount of area and substructure works are required. It emerged from the interviews that areas are largely impacted in at least 50% of all Brownfield cases (appendix 6.1.4_06):

interview partner (IP)	IP4	In over 50% of the (Brownfield) cases, large interventions take place, such as adaptations of large pits which, for instance, can be caused by the reduction or extension of production lines.
	IP5	In half of all Brownfield projects, large area works are required.
	IP7	Area works are required in 70% of all Brownfield cases while 60% to 70% of these Brownfield cases are concerned with changes of uses and require huge area and substructure works.

The contents of this subsection must be considered, as they are relevant for almost all BFPCs.

It emerged from the interviews that it is seldom possible to pre-define required areas with required characteristics. Changes of numerous flows, overarching networks and systems, and FOs/FSs (including areas and substructures) can accompany these requirements. BMEs evoke difficulty factors and FPPs. All in all, BMEs, difficulty factors and FPPs lead to the requirement for additional areas and increased area-transformability, which is not given with terrestrial areas but would increase the transformability of sub- and superstructures.

This subsection indicates the outreach of real-world transformation requirements and their frequency of occurrence, and also that the importance and significance of the transformability of areas and substructures are underestimated. From a long-term perspective, doubling areas do not suffice for factory doublings, as areas are also required as exchange areas and for other transformations and requirements. The transformability of available FOs/FSs is not sufficient to absorb all relevant transformation requirements. Vast area and substructure works are the consequence. What makes these required works undesirable and difficult in the case of today's factories are particularly transformations of fixed FOs/FSs against the backdrop of the heterogeneity in factory planning, which includes the heterogeneity of FOs/FSs and thus of factories. This penetrates areas (and substructures) and impacts most factory projects.

'Capacity-related' and 'capacity-unrelated' (space and) area extension requirements and 'aspects of an alternating and breathing factory' have been identified and explained. In combination with the heterogeneity of factories, these requirements lead to vast area and substructure transformations.

6.1.5 Heterogeneity in Factory Planning

Factories involve many different areas and FOs/FSs, which themselves involve many subordinated areas and FOs/FSs. Many of these subordinated areas and FOs/FSs also differ from one another. All these elements occupy different spaces of areas, sub- and/or superstructures (e.g. m³ inside and outside buildings and in the ground) in order to generate or to retain their effective arrangement in the context of a factory.

It emerged from the interviews that a body and an assembly shop can be aligned only partly at the most, but that even such an alignment leads to inefficiencies and difficulties. Evidence in the interviews (appendix 6.1.5_01) indicates that compared to the other sections and to one another, the characteristics of press and paint shops are too different to be aligned:

<table>
<tr><td rowspan="4">interview partner (IP)</td><td>IP2</td><td>One cannot make an assembly shop out of a paint shop.</td></tr>
<tr><td>IP5</td><td>A press shop is as deep as high which does not apply to other factory sections.</td></tr>
<tr><td>IP7</td><td>It would be inefficient and senseless to align a press and an assembly shop. It would mean that an assembly shop must be as high as a press shop and have the same floor loads and substructures.</td></tr>
<tr><td>IP8</td><td>Characteristics of a press shop are not appropriate for an assembly shop.
. . . A press shop and a paint shop involve structures other than a simple assembly shop.</td></tr>
</table>

It is decisive that different sections and FOs/FSs are mutually exclusive (e.g. substructures in an assembly shop are not appropriate for a deep-drawing press) and that a transformation of a user-specific building into another requires funds, time, effort and resources, independent of the factory concept in hand (the developed factory concepts lead to differences in this regard). Furthermore, it emerged from the interviews that office buildings are inappropriate for use as production sections. The same applies to s&d plants, canteens and the like. In addition, there are numerous other FOs/FSs which involve characteristics that are too heterogeneous to be aligned (or exchanged etc.) with other FOs/FSs. Figure 43 depicts the heterogeneity of factories in a simplified manner.

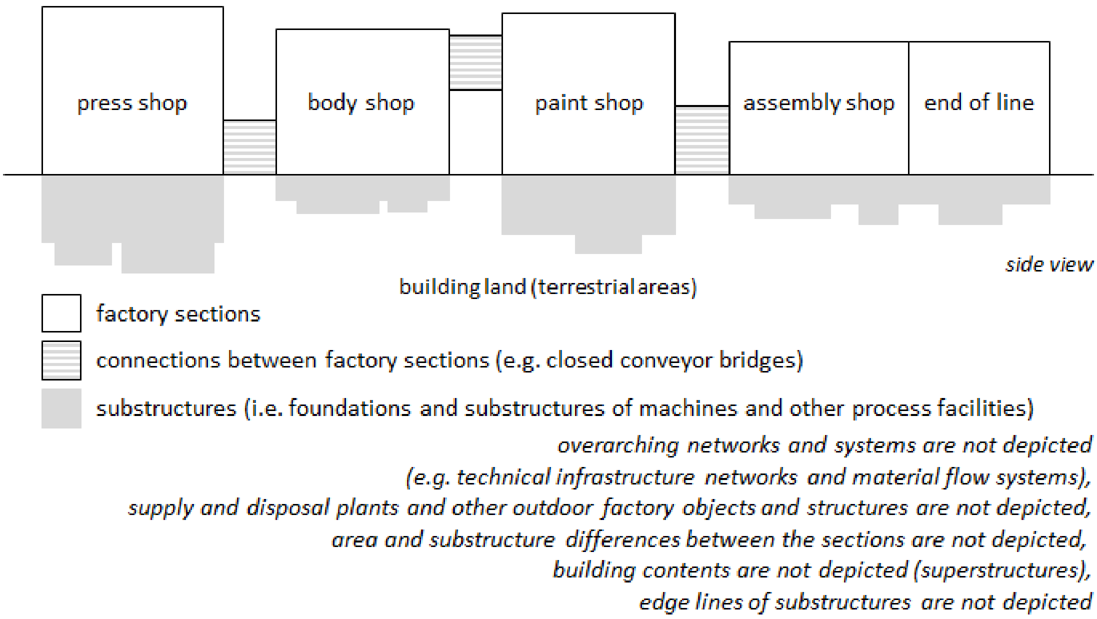


Figure 43: Sub- and superstructures of different sections

Different area and substructure characteristics – particularly floor depths – are critical. Figure 44 provides a structure level-related view of the heterogeneity of FOs/FSs.

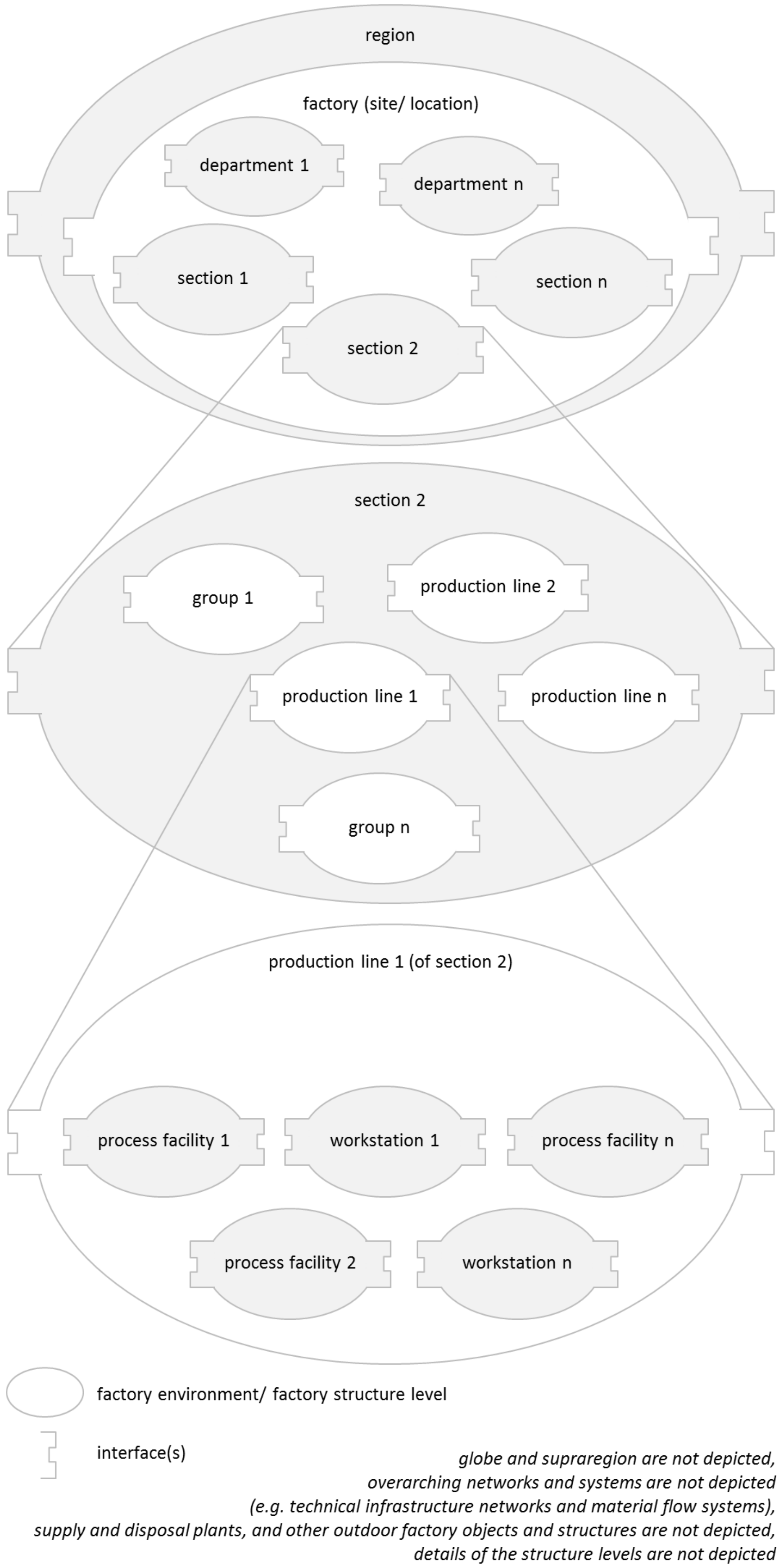


Figure 44: Heterogeneous FOs/FSs

In sum, there are numerous different requirements in factories. Factories encompass FOs/FSs at all structure levels that are too heterogeneous to allow their comprehensive alignment.

In addition, these FOs/FSs and their inputs and outputs change over time, and with them areas, substructures and interfaces. This emerged from the interviews and can be understood more fully if one considers real-world area and substructure transformation requirements and their frequency of occurrence, which means their dynamic against the backdrop of different flows which should be kept efficient.

This subsection shows that neither universality (function and utilisation neutrality) in Hernández' (2002) nor neutrality in Heger's (2006) sense can be reached with areas. Both are more akin to a wish list than realisable, especially if real-world transformation requirements and their dynamics are considered. In general, efficiency acts against universality (and the standardisations that play an important role for this) and vice versa, while efficiency requires heterogeneity of FOs/FSs (including sections, areas and substructures). This heterogeneity, in turn, disables the neutrality of FOs/FSs when FOs/FSs become inhibitors.

The heterogeneity in factory planning (1) has not been considered as required because its significance has been underestimated. Furthermore, (2) the ways in which heterogeneity is attempted to be handled in the light of factory dynamics has not been reflected upon critically enough and not sufficiently thought through (which is recognisable by analysing the transformation enabler universality, which acts against the efficiency of factories). Real-world area and substructure transformation requirements that have occurred over the years have not been sufficiently considered.

The interviews indicate that terrestrial areas and related transformation possibilities are taken for granted, and that these are not sufficiently questioned by factory planners (appendix 6.1.5_02):

interview partner (IP)	IP4	Building moves are not possible.
	IP5	It would be very good if buildings could be moved together with all their robots and other machines, but I do not know how this can be made real.
	IP7	Substructures, one can not even see them. . . . buildings cannot be moved.
	IP8	It would be beneficial if structures could be flexibly integrated into the substructure, but I cannot imagine how this can look.

This could be the main reason why the root of the problem that leads to the limited and furthermore decreasing transformability of today's factories has not been identified, and why stopgap solutions in factory planning are developed every now and then.

Furthermore, heterogeneous transformations and growth occur throughout all factory structure levels. Numerous FOs/FSs are extended and otherwise transformed heterogeneously. In addition, effective transformation and/or movement directions differ. In sum, different FOs/FSs (including sections, areas and substructures) develop and are transformed differently. This increases the complexity and problems that must be handled in factory planning. These findings are evidenced in the interviews (appendix 6.1.5_03):

interview partner (IP)	IP3	Factory sections and departments change differently, building-wise and process-wise.
	IP4	When a paint shop has reached its limit, a new paint shop is required. You cannot just extend it due to the technical processes and the process chain involved. An assembly shop can rather be extended.
	IP6	A factory grows heterogeneously per section. You need to do more in certain sections and less in other ones.
	IP8	The other shops (factory sections) require fewer exchange areas. The whole body shop requires an exchange area. There is no other way.

It is recognisable in every interview that each factory project is different. This is in line with Burggräf (2012, pp. 46–47), who stated that the individual starting situation of a planning project determines the scope and contents of planning activities. Furthermore, the factories that were disclosed by the interviewees 'were different', 'develop(ed) differently' and 'involve(d) different statuses' over time. It can be seen in Friese (2008) that configurations of today's factories strongly determine their transformability and future configurations. In parts, this also applies to TFCs (to terTFCs more than to marTFCs), as sites impact on factories, while sites are also heterogeneous.

6.1.6 Transition to Enhanced Basic Factory Planning Cases

The answers of the interviewees were analysed and combined (also with further real-world data and data from the literature). This has allowed the development of this transition.

Heterogeneity in factory planning has neither been highlighted in the factory planning literature nor been combined with other relevant aspects in the way that it has been done in this research.

The smallest elements such as s&d infrastructure elements belong to the micro level, and process facilities, workstations, production lines and groups to the meso level. The macro level incorporates buildings and overarching networks and systems. Factories are heterogeneous from the micro level through to the macro level. Thus, different FOs/FSs can be found within all factory structure levels. It is not only sections that differ. Production lines and numerous process facilities differ for each section, while further different FOs/FSs such as pits are involved.

Furthermore, heterogeneous transformations and growth occur throughout the micro, meso and macro levels. In addition, effective transformation and/or movement directions differ. In sum, different FOs/FSs develop and are transformed differently. This increases the complexity and problems in factory planning.

Heterogeneous projects also complicate these circumstances, as these projects lead to different transformation requirements. Innumerable different project cases occur alone or in a mix, and it is not known which of these cases will occur, and when. Furthermore, factories develop differently and involve different configurations and statuses over time.

Thus, subsection 6.1.5 indicates how complex factory planning can be, and that impacts of transformation requirements on different FOs/FSs are hardly assessable (even if forecasts were possible). Furthermore, when the 'heterogeneity in factory planning' is combined with the 'types of factory growth and transformations', the amount of area and substructure works that must be processed and why becomes evident (subsection 6.1.3 must be considered). Transformations of different FOs/FSs require such works, as available area and substructure characteristics (e.g. spaces and load-bearing capacities) are not always appropriate and/or in the right positions because these positions change over time. In combination with the heterogeneity in factory planning, different area extension and exchange requirements indicate (a) why today's factories require a large amount of area and substructure works if one wants to have and maintain efficient flows, and (b) what makes transformations complex. Heterogeneity makes transformations difficult if transformability is limited. This is the case if areas and substructures are rigid, as in the case of today's factories which involve a large number of fixed FOs/FSs. In the case of TFCs, less works are required due to the increased transformability.

Transformations are different and have different impacts. The general structure changes continuously. In combination with the heterogeneity, the various flows (which must be kept efficient) are therefore disastrous if the area- and substructure-transformability are limited. Thus, the effective arrangement and linking of FOs/FSs over time is inhibited. The frequency and extent of transformations revealed in the interviews shows that the transformability of the general structure and consequently of areas and substructures is far more important today than is described in the literature. Area and substructure transformation requirements are specified in the following subsections. The enhancement of BFPCs is required in order to encompass relevant matters from the two previous subsections in a generalised manner (which makes these matters more tangible). This is based on real-world factory project cases provided by the interviewees, and provides a basis for the analyses of the developed factory concepts. In addition to BMEs and difficulty factors, the eBFPCs are required concepts that indicate which impacts occur throughout the BFPSs and why.

6.1.7 Enhanced Basic Factory Planning Cases

Current BFPCs are not sufficient to generate an appropriate understanding of the real-world challenges that are currently faced by factories. BFPCs must therefore be enhanced, which takes place in this section. Numerous factory project cases occur. The following recurrent cases were identified as being the most important and most frequently occurring*. They lead to the most common transformation requirements and recurrent impacts on factories. Various BFPCs with different project scopes, characteristics and complexities involve similar patterns which have not been described in the literature. 'BMEs' play an important role in this regard. Some BMEs are described with the eBFPC 'capacity increase', of which at least two can occur in Greenfield projects. BMEs are also relevant to some difficulty factors (and vice versa) which occur either separately or jointly in the eBFPCs and other cases.

The following eBFPCs, which are successively explained and concluded, emerged from the interviews as the most important cases for factory planning (besides remediation which is not analysed):

eBFPC #	name of the case
eBFPC I	'capacity increase' (including the explanation of BMEs)
eBFPC II	'product model change'
eBFPC III	'production depth change'
eBFPC IV	'factory structure recovery programme' **This case occurs frequently in factories that have reached BFPS-4 (i.e. BFPS-4-factories). This case occurs also in factories that have reached BFPS-3 (i.e. BFPS-3-factories).*

These cases differ but also involve similar patterns. Where these cases can lead is explained in the following, and the BFPSs are then considered in order to explain further possible impacts of these cases.

A **'capacity increase'** of a section leads as of a certain percentage to a building extension or the construction of a new building(s). In general, there are three options: Either a second building is constructed in addition to a given one, which results in two large inhibitors (which are both required) and normally in less efficient flows from a section- and an entire factory-related perspective, or one larger new building is constructed (e.g. at an exchange area), replacing an old building. This leads to two large inhibitors, of which one can be transformed or demolished (both is not sustainable) after the new building is ready for operation. In most cases, such a new construction leads to good flows within the section but to less efficient flows from an entire factory-related perspective (i.e. the factory can be more intertwined from such a perspective; this depends on the factory configuration and current requirements) as the old section was once at its former position for a reason. This is at least valid for relatively new factories, while conveyor bridges can decrease the negative impact on the entire factory efficiency. Normally, the first option with the second building is not chosen due to the requirement for connected and coherent flows throughout production sections of automotive OEM plants; however, it can be an option (e.g. for a press shop). Nevertheless, with this and the second option, displacements within buildings, which can be required when a building is extended (third option), can be avoided. Implementing a new building with connected flows can take place more quickly than extending a building with changing flows, which change in the original part of the building. Nevertheless, further aspects such as required try-out durations must be considered. To construct a new building is thus not always reasonable, (and/)or possible. Which options are possible and reasonable depends on the section type and the circumstances, e.g. the BFPS and the required displacements.

There are buildings which can be extended without the need to change flows in the original part of the building. Nevertheless, extensions of automotive OEM plant sections are normally concerned with changes of flows – particularly production flows (all sections, while specifics differ). Changing flows and other changes require position changes of areas and FOs/FSs, also of fixed ones. Given and new/additional FOs/FSs (e.g. reused ones) are concerned. Changes of flows impact areas and substructures; this is frequently the case, as backed up by the interviewees. In this regard, displacements of FOs/FSs are required, depending on the circumstances, e.g. available and/or occupied areas and spaces. The following 'BMEs' were identified as possible basic elements of capacity-related building extensions which can cause these, as well as additional and other transformation requirements (some BMEs can be reviewed based on figure 45):

BME-I	'new object/structure' (e.g. by reason of additional/new product functions/technologies which, for instance, require new production technologies and/or facilities) (4)
BME-II	'additional (old or new) object/structure' (e.g. a machine by reason of a capacity increase) (3 (2 of 2))
BME-III	'extension' of an object/structure (which happens also through movements, as additional new and/or old objects/structures need to be brought in) (this happens in 2' (in this case, 2 was reused and as a part of 2' finally moved to 2'))
BME-IV	'replacement/exchange' of an object/structure (e.g. remove old (1) and implement new (1'))
BME-V	'change in use' (e.g. a glueing instead of a welding facility) (not depicted) *please consider: a 'change in use' of areas/sections is not a BME, but requires BMEs*
BME-VI	'move/relocation' of given objects/structures for other reasons than collisions/displacements (e.g. centralisations and decentralisations) (not depicted)
BME-VII	'technical modernisation/renewal' (not depicted)
. . .	. . .
BME-n	. . .

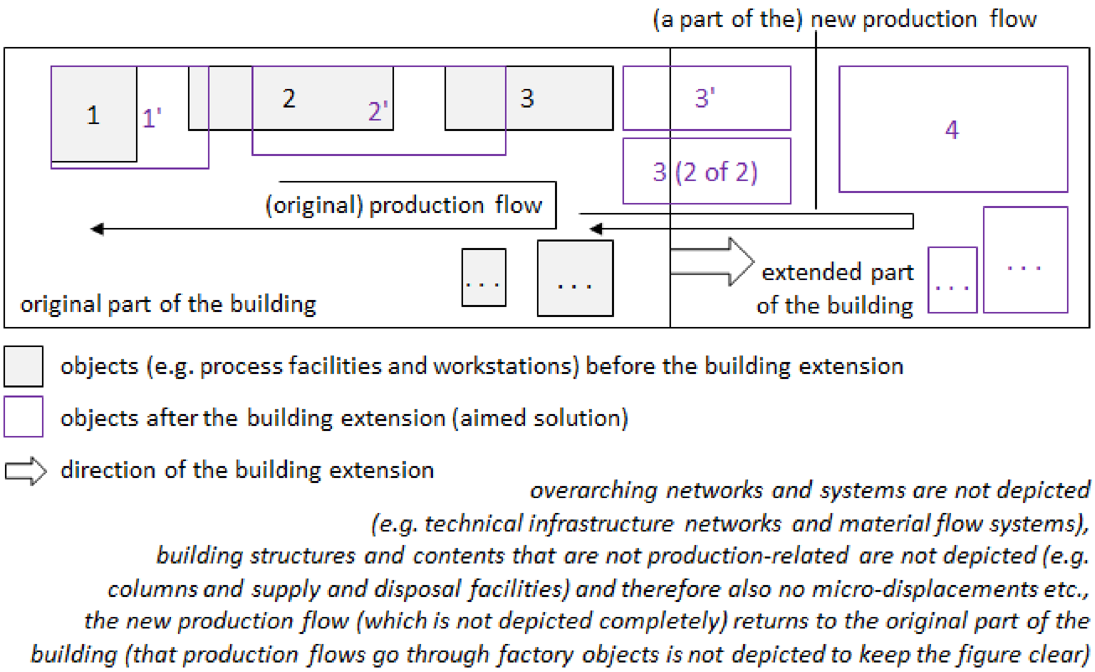


Figure 45: BMEs in the case of a capacity increase-based building extension

These BMEs can occur in all eBFPCs, while each case has specific BMEs. Some BMEs are identically or similarly processed but differ from one another. BMEs can lead to displacements if free areas are not available in appropriate positions. Appropriate positions after the building extension in figure 45 are depicted. The best case from an optimal production flow perspective would be if all depicted objects could be positioned at these positions. This is hardly possible with today's factories. The following are relevant process chain aspects and critical path aspects of figure 45 (without the building extension):

aspect i	the area/substructures at 3' must be finalised before 3 can be moved to 3' (it is displaced by 2');
aspect ii	area/substructure works for 2' at 3 can first take place after 3 is moved (e.g. to 3');
aspect iii	2' can be implemented as soon as 2 and 3 are moved and after required area/substructure works take place;
aspect iv	1' can be implemented as soon as 1 and 2 are moved and after required area/substructure works take place.

Such works can require more time than the foregoing building extension, as several actions depend on one another. Compared to the reality of automotive OEM plants, this is a simple case. To perform a displacement domino of all relevant objects in a row is one extreme to reach an optimal flow which would have an impact on the critical path. Another extreme to reach an optimal flow is to free the original part of the building in order to avoid displacements, which requires internal substitution processes, the pre-production of parts* and/or outsourcing, i.e. external substitution processes. **(When the words 'pre-production of parts', 'pre-produce parts' or 'pre-produced parts' are used, not necessarily and/or not only parts are meant. Systems, subsystems, automobile bodies, assemblies, subassemblies and other objects and structures can be meant. It is also necessary to store pre-produced parts (etc.). These circumstances will not always be mentioned.)* With today's factories, both extremes are disadvantageous. The definition of reasonable measures for such a case depends on the following factors:

factor 1	initial flows
factor 2	target flows
factor 3	the number/amount and positions of inhibitors (mainly fixed points (i.e. RFOs/RFSs)) and their level of inhibition
factor 4	available (extension) areas, available areas within the original part of the building, and available areas for substitution processes and/or the pre-production of parts, and the appropriateness of these areas
factor 5	outsourcing possibilities
factor 6	possibilities with regard to having/performing and reasonableness of substitution processes, the pre-production of parts and/or outsourcing

These factors decide how such cases are dealt with, the number and outreach of direct/primary displacements and/or other difficulty factors, and their indirect impacts (i.e. secondary, tertiary etc. impacts). Thus, these factors are decisive for the duration of such a capacity-related extension and can also be relevant for other eBFPCs. Process chains and critical paths of figure 45 can thus vary. Moreover, substitution and outsourced processes can remain as (quasi-)permanent processes and/or fall out. Further problems are possible.

These circumstances make it difficult to define which of the three abovementioned options is the best. Building extensions with displacement dominos and/or substitution processes etc. can take longer than a new building construction(s) and/or building displacement(s) and vice versa. Subsection 6.1.10 involves further difficulty factors which must be considered in this regard and which make this decision-making problem even more difficult. Furthermore, it is necessary to take into account, particularly with today's factories, that it is rather subjective and partly irrational to define the best solution, e.g. an optimal flow or the fastest transformation, or a trade-off between both. Table 14 recapitulates the eBFPC 'capacity increase' for each section.

Recapitulation of the eBFPC 'capacity increase'	
press shop	In the case of a capacity increase, press shops are less concerned with flow changes. A building extension(s) and/or construction of an additional building(s) can be required, as an additional press shop facility(/ies) and/or additional tools can require a building(s).
paint shop	In the case of paint shops, the solution (as of a certain percentage of a capacity increase) is flow changes, which are normally considered through overcapacities such as reserved areas and spaces. It can be possible to install the final process flow from the start (e.g. with some empty process steps in between). A building extension(s) and/or new construction(s) can be required, as an additional paint shop facility(/ies) requires a building(s). A building with a paint shop facility can be designed in a way that the facility can be extended through the implementation of additional objects and structures at held out and/or reserved areas and spaces in different positions. These areas and spaces can also be seen as overcapacities. It can also be possible to reserve areas and spaces for an additional paint shop facility(/ies).
body shop and assembly shop	Body shops and assembly shops are (as of a certain percentage of a capacity increase) concerned with flow changes. Installed overcapacities and their appropriateness are decisive. If appropriate areas within buildings are available, building extensions and new constructions can be avoided, but impacts of flow changes must be considered. The construction of new buildings in order to replace old ones in (quasi-)exchange areas can be required for both sections, while assembly shops are more concerned with building extensions than body shops (building extensions can also be possible for body shops). The 'product model change'-related information explains the background to this statement. To construct additional buildings for body and assembly shops is rather not appropriate in the case of a capacity increase, as the main production/assembly flows must be connected. However, this can be helpful in the case of a production depth increase, and in the case of a capacity increase.
Please consider that a section can consist of several connected and/or separated buildings (e.g. due to factory developments) and/or that due to different products, several sections of the same type (e.g. several press shops) can be located in one factory. This is valid for all conclusions regarding eBFPCs in this subsection.	

Table 14: Recapitulation of the eBFPC capacity increase

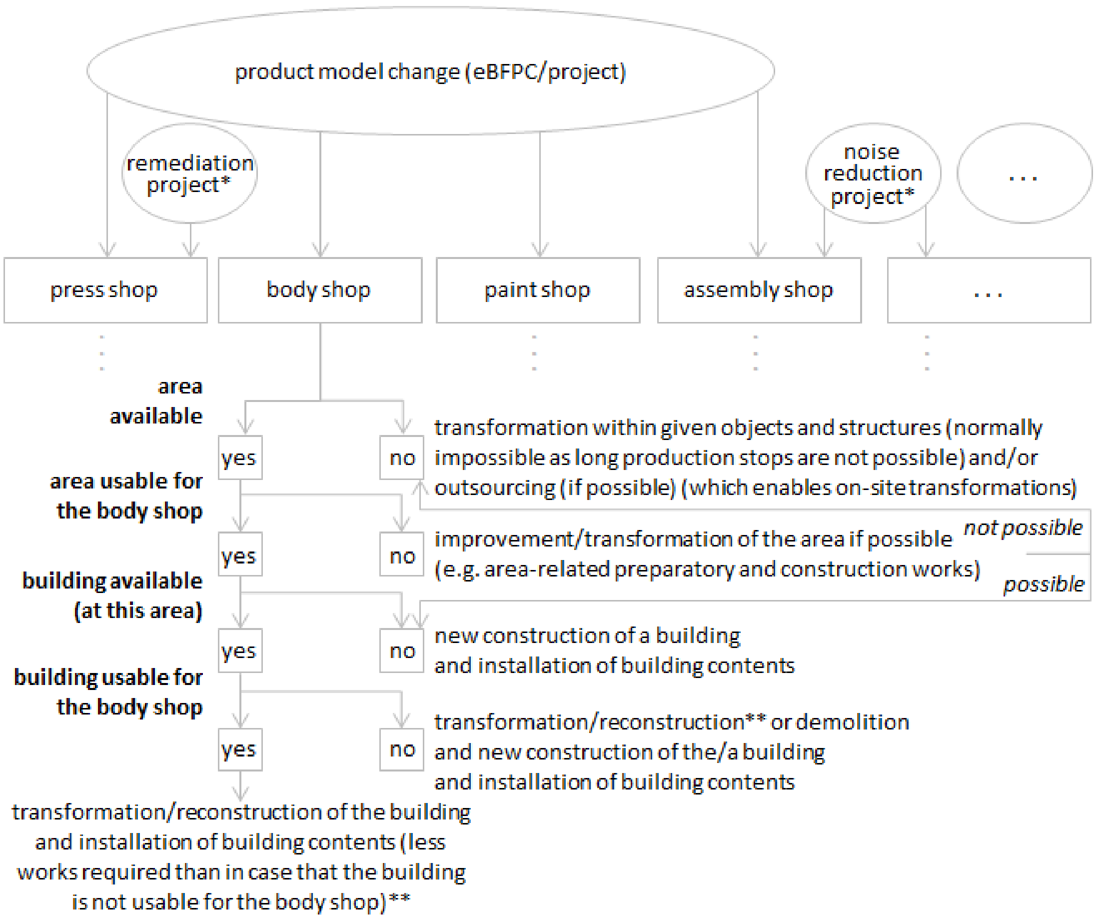
Changing product models, types and/or variants can lead to an area increase. This and the following paragraphs focus on new/changing product models and not on additional ones. Transformation requirements can lead to increasing area demands, even if there is no capacity increase. A **'product model change'** makes areas increase through the changing of products, which is not a special case, as it occurs every six to seven years per model (in plants with several models therefore more frequently) (all interviewees) and requires permanent transformations (IP2, IP3, IP4, IP5, IP6, IP7 and IP8) (see also appendix 6.1.1_03). It emerged from the interviews that the entire body shop requires an exchange area (or building(s)), the assembly shop partly including end-of-line and that the paint shop can require an exchange area which depends on the specific case (e.g. product characteristics, required processes and flows and given production capabilities in terms of processes and flows such as maximum pass-through dimensions).

paint shop-related, assembly shop-related and general statements:		
interview partner (IP)	IP2	Exchange areas can be required for paint shops, as the largest product determines the characteristics of this section.
	IP5	In assembly shops are production lines and single workplaces rearranged. . . . Difficulties occur if no exchange areas are available. This applies to the assembly shop including end-of-line due to the rain test and other fixed points. . . . Product model projects . . . require, as a general rule, new buildings and happen with each model change.
	IP8	If one has no exchange areas, it is necessary to make add-ons, attachments, and patchworks everywhere. . . . The rain test must be transformed with each product model change. The same applies to the marriage and numerous other objects and structures. I invest in the case of a product model change several million (Euro) for the assembly shop.
(continued)		

body shop-related statements:		
interview partner (IP)	IP2	An exchange area for the body shop is in each case required. Even if it is a flexible one, an exchange area will be required as requirements change that cannot be absorbed by new technologies and robots. Possibilities provided by modular robot cells are limited. Modern body shops are therefore not really transformable.
	IP3	In the case of a product model change, different machines and machine arrangements are required in the body shop. Therefore, exchange areas are required. . . . There are several fixed points.
	IP4	We try to avoid substitution processes. This is one reason why we have multiple fields for the body shop. We construct a completely new body shop. Therefore, larger areas are required.
	IP5	In the case of a product model change, the body shop requires a complete change and thus a complete exchange area. Operational sequences, production flows, and logistic flows change. . . . Product sizes increase. Movable robot cells cannot be used in the entire body shop. Several robots and other objects are fixed. This cannot be changed.
	IP8	A body shop requires the implementation of a completely new production system, as steel changes to aluminium and as sheet thicknesses change. Other changes occur. This is a change in use from an area perspective.
Please consider that the designation 'exchange area' can be equivalent to different areas in different positions.		

That the operation (of the production, departments, media flows etc.) must continue is essential for the requirement to have exchange areas. Transformation durations, which find their root in insufficient transformability, lead to the need for these areas. Thus, extension areas are also required for other purposes, and not only for capacity increase-related extensions.

Depending on the circumstances, characteristics of a product model change (and of other cases) can differ and lead to different requirements and FPPs (figure 46).



** A 'remediation project' can be a BFPC-B but can also require prior reductions and/or demolitions (i.e. involve characteristics of, for instance, a BFPC-D) while a 'noise reduction project' can be a BFPC-B but can also require prior reductions and/or demolitions and lead to extensions (and involve therefore characteristics of a BFPC-D and a BFPC-C).*

*** Smaller and/or larger displacements, depending on how appropriate the building which needs to be transformed is, can be required. In case of building (or large) displacements, a new off-site location is required for the current process if the own (on-site) location lacks appropriate areas. Afterwards, building contents need to be dismantled/disassembled, moved out and first then the actual building transformation/ reconstruction or building demolition and new construction can happen which is followed by the installation/setup of building contents (e.g. machines), try-outs, the (re-)SOP and ramp-up. The possibility to have reserved exchange areas within buildings is excluded in this figure. Large exchange areas are required for the body shop in case of a product model change.*

Figure 46: Optional characteristics and requirements of a product model change

This figure shows how complex just a single factory project can be, as it depicts optional circumstances and rough requirements for a body shop in the case of a product model change. With possible impacts on other sections etc. and further projects which can occur simultaneously, the complexity increases significantly. If an appropriate area in the correct position is available, a new building with appropriate building contents can be implemented, which is different to a capacity increase-based building extension, as it does not lead to direct displacements and also not necessarily to a capacity increase. Two large inhibitors, one of which can be demolished or transformed, are the outcome (the same as in the case of a separated building after a capacity increase, where the old building can be demolished or transformed). If areas are not available in appropriate positions or not at all available (BFPS-4), this leads to larger displacements. It emerged from the interviews that building displacements often occur. Other sections require rather fewer and, in sum, smaller exchange areas than a body shop, which normally leads to at least a little growth, even if the capacity remains the same. Figure 46 also indicates that a mix of characteristics of different BFPCs occurs in combination for each case, that different cases can occur together, and that a 'product model change' can be perceived as a programme (not (necessarily) as a 'factory structure recovery programme' (please consider the following text in this subsection)) which sometimes happens in practice. This emerged from the interviews (appendix 6.1.7_01):

interview partner (IP)	IP1	The core grows to the periphery while non-production parts are displaced to the outside of the factory boundary.
	IP2	Displacements take place very often when all areas are occupied. This applies to all factories which have no areas left. It happens in Greenfields that you need to demolish a wall or that lines need to be shifted, but in Brownfields, it comes to numerous moves which require demolitions of floors and foundations, even of buildings. . . . Several buildings were demolished and a new one constructed at the same place.
	IP3	If you have no exchange areas, you are required to displace buildings.
	IP4	It is not that nice if you construct a building for several million (Euro) and realise that its functions, dimensions, and location are not required anymore, as the requirements have changed. This leads to the worst case: You need to demolish the building.
	IP5	These two buildings were demolished for the new body shop. . . . (Building) X and (building) Y were demolished for the new building Z (*X, Y and Z are used instead of the internal designations to protect the interviewee*). . . . This office building . . . has been completely demolished to provide the room for the new one. . . .
(continued)		

interview partner (IP)	IP5	Roads were widened. This required demolitions of . . . buildings. . . . We have bought A which is a very large building complex outside of the factory and we have transformed it to move B (*B stands for an inhouse production which was displaced by a new body shop building*). A much larger area would have been required to keep these contents
	IP6	This building was demolished for the body shop.
	IP7	If I have free areas, I have fewer difficulties compared to the case that all areas are used. Without areas, we must demolish factory objects.
	IP8	The existing production needs to go on. This leads to long transformation durations and to building displacements if exchange areas are not available.
	Please consider that collisions and changes of uses (e.g. of areas) lead to displacements and happen very often from a medium- to long-term perspective. Several subsections (e.g. 6.1.1 and 6.1.10*) involve information about collisions and/or changes of uses. Further displacements are described in other subsections (e.g. 6.1.4* and 6.2.4).*and their appendices*	

appendix 6.1.7_02 explains in detail the reasons why a constant switch between an old and a new body shop building in the case of the subsequent development of new product models (i.e. one can transform and use the old body shop for the next product model and so forth) is hardly possible in today's factories without extensive demolitions and growth. In sum, the reasons for this are the different transformation requirements and factory project cases which occur over time. Table 15 recapitulates the eBFPC 'product model change' for each section.

Recapitulation of the eBFPC 'product model change'	
body shop	In the case of a product model change, body shops require the largest exchange area(s). If the body shop is newly constructed in order to replace the old body shop, this does not lead to flow changes in the old body shop. This is required if no appropriate exchange areas are available within the existing building (consider also the options in the previous figure).
assembly shop	A product model change leads rather to flow changes in assembly shops. Fewer exchange areas are required than in the body shop, but a building extension(s) can be required.
press shop	From an area perspective, press shops are not normally impacted, as new tools and tool changes can normally absorb new/changed requirements. An extension(s) and/or additional building(s) can be required.
(continued)	

Recapitulation of the eBFPC 'product model change'	
paint shop	In the case of paint shops, it can be possible to still use the old building, but a building extension(s) and/or new construction(s) (an additional building and/or one that replaces an old one) can also be required. Due to lost initial investments, the replacement of a paint shop is normally not done, but it can be required if wear and tear are considered and/or if the required transformations are extensive. Parts of the paint shop (and other sections) are anyway changed during its lifecycle.
Please consider that the factory capacity remains the same in this eBFPC. Also consider that a section can consist of several connected and/or separated buildings (e.g. due to factory developments) and/or that due to different products, several sections of the same type (e.g. several press shops) can be located in one factory. This is valid for all conclusions regarding eBFPCs in this subsection.	

Table 15: Recapitulation of the eBFPC product model change

A **'production depth change'** is also common, and can lead to problems in OEM and supplier factories. Helbing (2010, p. 51) argues that factory programme changes (e.g. of cooperations and products) determine direct and indirect areas, and that outsourcing impacts on internal input and output functions. This means that a production depth decrease means not only that requirements are shifted to supplier factories. This case can also lead to position changes of areas and/or FOs/FSs in the own factory. Outsourcing can be an option to eliminate a bottleneck when a factory lacks areas and/or in the case of too excessive transformation durations. (In this case, outsourcing is not necessarily a problem, but the solution to outsource contents can sooner or later lead to problems.) This can make a supplier factory grow and can lead to displacements etc. Areas gained in this way in the own factory can often be used as logistics areas. To use these gained areas to bring internal production flows together is rather difficult (see below). Decreased production depth can also be followed by insourcing. Insourcing and outsourcing occur in alternation for cost reasons (e.g. production, logistics and/or rental costs). Thus, new transformation requirements can occur. Production depth changes are crucial for factory transformations. In the case of decreasing production depth, the gained area can be used for another purpose, but is normally surrounded by processes and is often not in an appropriate position. Thus, it is not perfectly usable, while displacements and other difficulty factors can occur. In the case of a production depth increase, displacements can be larger (particularly if combined production areas respectively connected structures are insourced) and therefore problematic. This emerged from the interviews (appendix 6.1.7_03). Horizontal integration can lead to further changes. Table 16 recapitulates the eBFPC 'production depth change' for each section.

Recapitulation of the eBFPC 'production depth change'	
body shop and assembly shop	A production depth change in body and assembly shops does (rather) not affect main production/assembly flows directly, but rather other connected areas. Building extensions and/or constructions of additional buildings can be required.
press shop	Press shops can handle a production depth increase through additional tools. An additional machine(s) and thus building extension(s) and/or new construction(s) of an additional building(s) can be required (also for the storage of tools).
paint shop	This eBFPC does – in the main – not occur in paint shops. *It must be taken into account that the viewing distance determines about the validity of such statements.*

Table 16: Recapitulation of the eBFPC production depth change

What does all this mean 'in the context of BFPSs' and why do factories develop into 'UHPs'?

A building extension in BFPS-3 without flow changes in the original part of the building can experience displacements (e.g. through domino effects), but in the following paragraph such issues and roads etc. are not considered in order to highlight (basic) direct/primary impacts on buildings.

The construction of a new building with connected flows (options 1 and 2) in BFPS-3 does not lead to direct displacements. The same case in BFPS-4 leads to one or several small and/or large off-site displacements. This can also happen in an unstructured BFPS-3-factory, while here, on-site displacements to the periphery are more likely. In BFPS-3, a building extension without flow changes in the old part of the building does not lead to direct displacements. The same case in BFPS-4 leads to one or several small and/or large off-site displacements. The same can occur in an unstructured BFPS-3-factory, while here on-site displacements to the periphery are more likely. In all of these cases, displacements within buildings are not direct outcomes/consequences; at least old production flows remain the same if these are not impacted by other difficulty factors. For option 2, this is less relevant, as the old building is later demolished or transformed. A building extension with flow changes in BFPS-3 leads to displacements within the original part of the extended building. Such a building extension in BFPS-4 leads to one or several small and/or large off-site displacements and later to displacements within the original part of the extended building. The same can happen in an unstructured BFPS-3-factory, while here on-site displacements to the periphery are more likely. Substitution processes, pre-produced parts and/or outsourcing can generally be helpful in the case of displaced FOs/FSs, but not always.

Displacements can be avoided if appropriate areas are in appropriate positions. Over the years, such areas become rarer. Fewer and fewer areas are available and more and more FOs/FSs are impacted, as buildings and the whole factory become increasingly occupied and intertwined. In addition to small displacements, this leads to large displacements (e.g. when further intertwinings are impossible or obviously not as sensible as displacements), otherwise this would lead to long production stops, which are normally not possible because a factory would therefore not be competitive. Substitution process-related possibilities and possibilities to pre-produce parts decrease, while outsourcing possibilities are limited. It is not possible to generalise about which of the eBFPCs has the worst impacts on a factory, as this depends on the specific case and circumstances. Small displacements occur in BFPS-3, while BFPS-4 is concerned with small and large displacements. Nevertheless, large displacements also occur in BFPS-3, as inner factory structures (the core) are generally built-up/overbuilt/covered (i.e. occupied) and intertwined earlier than the periphery, and as BFPS-3-factories can also lack appropriate areas in appropriate positions. Model exceptions and the dilutive effect between BFPS-3 and BFPS-4 are explained in appendix 6.1.7_04 and also evidenced in appendix 6.2.6_03.

From a flow(s)-related viewpoint, extended and transformed buildings are generally not as efficient as original Greenfield buildings (technological and technical developments are excluded). The same applies to new buildings from an entire factory-related perspective. It must also be considered in all cases that conveyor systems and other FOs/FSs age and must be exchanged sooner or later. Overall, besides initial flows, the degree to which sections and the rest of a factory are intertwined determines the number and positions of small and large inhibitors, the availability and appropriateness of areas and further areas for substitution processes and/or pre-produced parts, outsourcing-possibilities and target flows, and also determines the quantities and sizes of displacements and other difficulty factors (see subsection 6.1.10). In simple terms, occurring cases and existing circumstances determine quantities and sizes of displacements and other difficulty factors, while BMEs must be considered. Intertwinings within buildings and from an entire factory-related perspective are characteristics of UHPs, and lead to a further development of factories into UHPs. If eBFPCs and requirements which can accompany eBFPCs are considered against the backdrop of FO-/FS- and area-related developments of factories throughout the BFPSs, the development of today's factories into UHPs is understandable (with real-world factory projects even more so).

Why can a 'factory structure recovery programme' be required, and why can this eBFPC and other eBFPCs be dangerous?

'Factory structure recovery programmes' can help to return to a more efficient factory. Wide-ranging demolitions of large and/or connected FOs/FSs are required from time to time in order to increase the transformability of today's BFPS-4- and unstructured BFPS-3-factories. Such demolitions could be designated as 're-Greenfield' and are involved in factory structure recovery programmes which are comparable with Helbing's (2010) BFPC-7. Real-world factory layout analyses showed that such cases have taken place several times within aged plants, otherwise, these plants would not be as functional as they are (despite the fact that they are far away from their own theoretically ideal factory statuses). The designation UHP was known by all interviewees prior to the interviews (see appendix 6.1.7_05 which also involves interview data about why factories become UHPs):

interview partner (IP)	IP1	UHPs develop where areas are limited and where continuous transformations occur within building and process facilities.
	IP2	An unstructured development leads to UHPs. A hut is added there, something is demolished there, something is moved there, and this leads finally to a total nesting.
	IP3	The expression UHP exists, as only things were done in the past, which were really required, where numerous different small areas were implemented which the process really wanted. . . . All factories become UHPs.
	IP4	Huts are constructed again and again in several places of a factory. These huts are numerous provisional arrangements which were originally intended for diverse single functions or extensions and which have in different constellations a number of different common functions which have nothing to do with their original function. There are numerous small and nested functions, also indirect ones, which are fixed. The factory is dominated by interfering structures which cannot be relocated due to limited areas. You have an office building right in the middle of the factory which for any reason cannot be removed. . . . a lack of available areas leads to UHPs.
	IP5	Extensions and adaptations are made and little by little turns a factory into the status of a UHP.
	IP6	All factories sooner or later become UHPs. . . . area-scarcity and different factory developments lead to this development, as single sections are extended over time.
	IP7	Transformations lead to this development (the development of factories to UHPs).
	IP8	In the past, small transformations, which were necessary at these points in time, were always planned and carried out. That is the reason why factories became and are becoming UHPs.

The interviews have shown that the contents in the previous paragraph are valid. It emerged from the interviews that the structure of factories and UHPs cannot always be recovered through programmes and seldom entirely, and that such cases often occur. Numerous different cases and FPPs (e.g. redesigns, demolitions, reconstructions and new constructions of large parts of the factory) are, besides smaller and larger displacements and other difficulty factors, required in the case of such programmes, which determine factory developments (appendix 6.1.7_06):

interview partner (IP)	IP1	Programmes are very, very challenging. Changes and overlaps always happen. New projects come up steadily.
	IP2	My former boss said (ten to fifteen years ago) that all seven to ten years the future development of all plants needs to be reflected and planned conceptually for the next ten to twenty years. For these locations, a strategy needs to be developed and is partly developed. . . . It is always a challenge to look into the future. First, how develops the market and production figures?/. How develop the products?/. How develops the production network?/. . . . You cannot look into the future. This leads to delayed decisions . . . It (the factory) can only be transformed in parts and not holistically.
	IP3	The whole organisation (of the programme) is challenging. It (the factory) is meanwhile a UHP with such a status that it should be completely demolished and newly constructed.
	IP4	People in strategy departments think about factory structure recovery programmes. These can but must not necessarily be sensible. . . . Programmes can not always help to restructure a factory as required. Before you complete one task, three new ones come up. . . . Displacements and spatial breathing occur due to organisational changes . . . It is more than just complex.
	IP5	I thank god that I am not involved that much (in this programme). Chaotic. A large number of projects. The coordination is bad. Not only ten people sit together. There are lots more.
	IP6	Demolitions and the development of a new entire structure are required if optimisations are not sufficient . . . There are time delays and increased costs. The demolition of objects has wide impacts on other objects. Production areas and office buildings are impacted . . . either demolitions or a new Greenfield is required.
	IP7	Time, money, project overlaps – one always has overlaps and programmes become always critical. Programmes are a big challenge and a big problem, also from a logistics perspective. Production supply and the transport and removal of construction material and of other things are required. Numerous incoming and outgoing trucks are required and numerous difficulties occur.
	IP8	Far over one billion (one of the world's strongest currencies) are required to bring the factory to a new production system level, not possible at all, in the grown structure, but to make it to some extent survivable. . . . I do not want to say to bring the plant to a new production system, this cannot be done at all within a grown structure – to make it to some degree capable of surviving.

(1) One or several eBFPCs (and/or other factory project cases) can lead to a factory structure recovery programme (i.e. such a programme can be evoked by one or several eBFPCs). Furthermore, (2) a factory structure recovery programme can occur together with one or several eBFPCs. Moreover, (3) one or several eBFPCs can lead to effects/impacts of such a programme which means that one or several eBFPCs can lead to a factory structure recovery, e.g. partly. (If and in which cases a factory structure recovery programme is perceived as such is not reflected.) (4) Further options are possible, the same as (5) combinations of options. Both options and(/or) combinations can occur differently over time. In addition, one or several eBFPCs can belong to a factory structure recovery programme.

In combination with their possible impacts, these eBFPCs (which can involve a mix of different characteristics of different (e)BFPCs) are not covered by current BFPCs; nor are BMEs, difficulty factors and BFPSs considered in current BFPCs. Single or several aspects of the described eBFPCs can also be relevant to other factory project cases, as the impacts of the eBFPCs, which indeed impact differently on different factories and sections, follow similar patterns. In other words, different eBFPCs (and other factory project cases) and thus different transformation requirements occur over time and lead to different impacts but follow similar patterns, i.e. BMEs and difficulty factors. Possible tasks which can accompany BMEs and difficulty factors are explained in more detail in subsection 6.1.10.

Problems in other factories (e.g. supplier factories) can occur with factory project cases, while these cases – each of which can undergo fundamental changes before its completion – occur in a mix with others, rather than in a pure and separated way. This increases their complexity and also increases the complexity of decision-making processes. It is difficult and throughout the BFPSs it becomes increasingly difficult to define what a reasonable course of action is. With today's factories, it can become impossible to make correct decisions (see section 6.2). Other overarching consequences of eBFPCs are heterogeneous transformations and growth, small and large displacements, and other difficulty factors (see subsection 6.1.10).

The information in this subsection is necessary so that readers can understand the research and the subsequent recapitulation and conclusion, and to enable readers to replicate the research. It is not necessary to keep each detail of this subsection in mind.

Table 17 recapitulates and concludes the most important aspects of this subsection and makes sense of them.

Recapitulation of subsection 6.1.7	
recap 1	EBFPCs lead to different impacts for and within each factory section. Nevertheless, these impacts involve similar patterns.
recap 2	EBFPCs lead to small(er) and large(r) displacements once appropriate areas/spaces are unavailable in appropriate positions. The requirement of OEMs to have and maintain connected and efficient flows is crucial in this regard. *Another crucial requirement is to perform rapid transformations, which is considered in subsection 6.1.10.*
recap 3	'recap 2' can already evoke further impacts in the case of a single eBFPC. Besides displacements, other difficulty factors and diverse domino effects can occur (and lead to further displacements and other difficulty factors), which depends on the circumstances. Displacements are crucial, as they lead to different FPPs for each of the developed factory concepts.
recap 4	The number of displacements increases with advanced BFPSs (i.e. BFPS-3 and in particular BFPS-4), as collisions are harder to avoid, the fewer the areas/spaces that are available in appropriate positions. The number of other difficulty factors also increases.
recap 5	It is not knowable 'what' will be required 'where', and 'when'.
recap 6	With advanced BFPSs, these circumstances are hardly manageable and in some cases not at all. More and more complex difficulties occur. Factory structure recovery programmes, for instance, can often hardly or not at all help to recover a factory structure.
(continued)	

Why is it hardly or not at all possible to manage these circumstances? In order to improve the picture of the real-world complexity in factory planning that is required for this research, subsections 6.1.8 and 6.1.10 are required.
Subsection 6.1.8: Real-world factory projects and numerous relevant circumstances occur in a mix and are not as clearly delimitable as the eBFPCs. EBFPCs are only an attempt to break the complexity down into its elements in order to explain the complexity and the elements which lead to this complexity. Thus, these elements do not occur in real-world factory planning in the way that is structured and explained in subsection 6.1.7. Subsection 6.1.8 provides a high-level perspective about the real-world situation and real-world projects. *Subsection 6.1.9 provides a transition to subsection 6.1.10.*
Subsection 6.1.10 takes up the contents of the previous subsections and makes sense of them. This subsection explains the elements which lead to the real-world complexity in factory planning, e.g. project overlaps. These elements are difficulty factors. By means of difficulty factors, the complexity can be explained, as well as why it occurs and why it is often hardly or not manageable.

Table 17: Recapitulation of subsection 6.1.7

These aspects are processed in the following subsections and sections.

6.1.8 Mixed and Off-site Cases

Almost every eBFPC is characterised by different but recurring BMEs and difficulty factors. EBFPCs come close to real-world factory project cases, while these cases correspond rather to a mix of characteristics of different eBFPCs instead of being clearly delimitable. Moreover, different real-world cases can appear in combination. This leads to a mix of cases which can be seen as a mixed case; however, this does not mean that it can be handled in this way. This is in line with Helbing (2010), whose BFPC-8 is a restructuring programme with cooperation changes (e.g. changes of suppliers and/or production depths) and product changes, which is therefore a mixed case. Further mixed cases emerged from the interviews, for example a product model change which is combined with a capacity increase and a production depth change. In another case, a factory structure recovery programme was also involved. Factory planning is engaged with more complex mixed cases, which from a project management perspective are seldom processed as required. This emerged from the interviews. Helbing (2010, p. 123) argues that no task can be formulated definitely and that a project involves numerous tasks. Changing transformation requirements and newly occurring cases make this formulation even more difficult, as these changes and new cases can have an impact on older cases (figure 47).

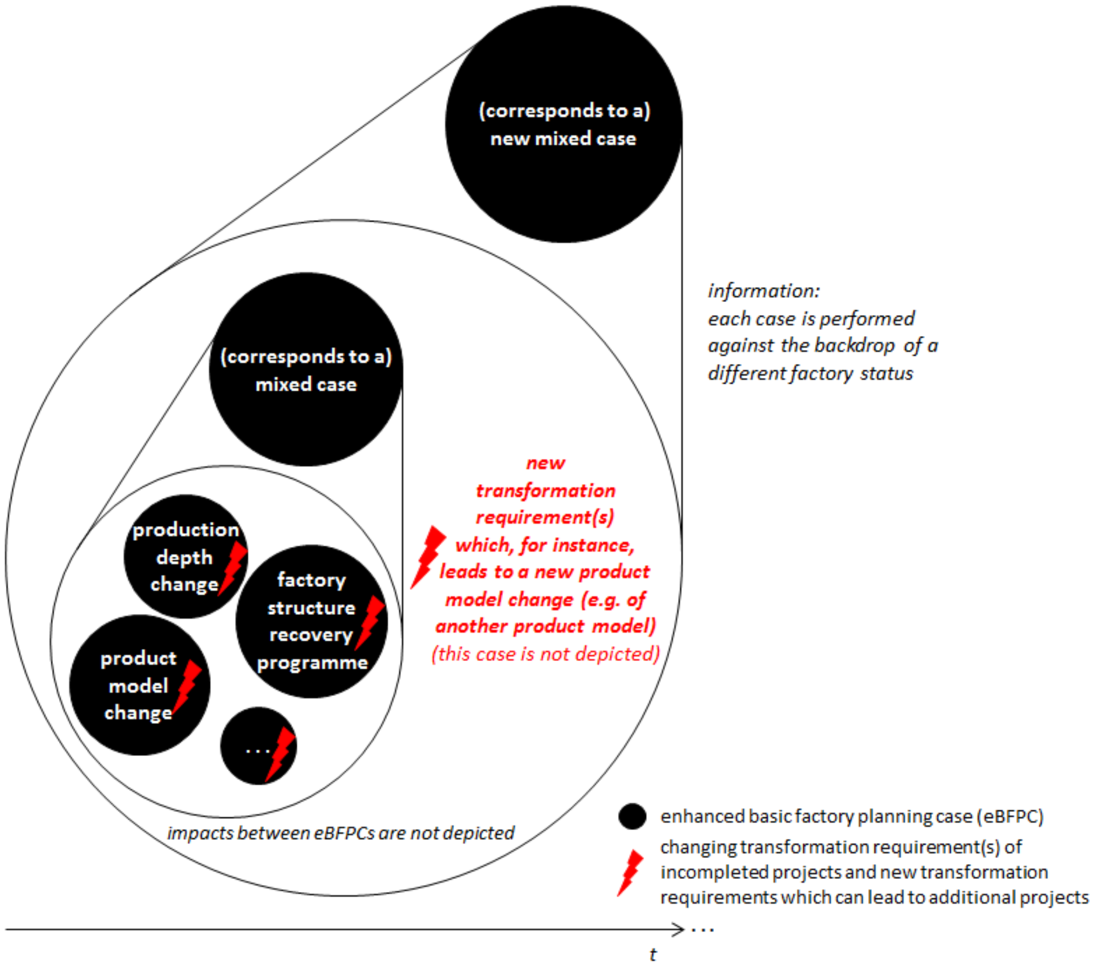
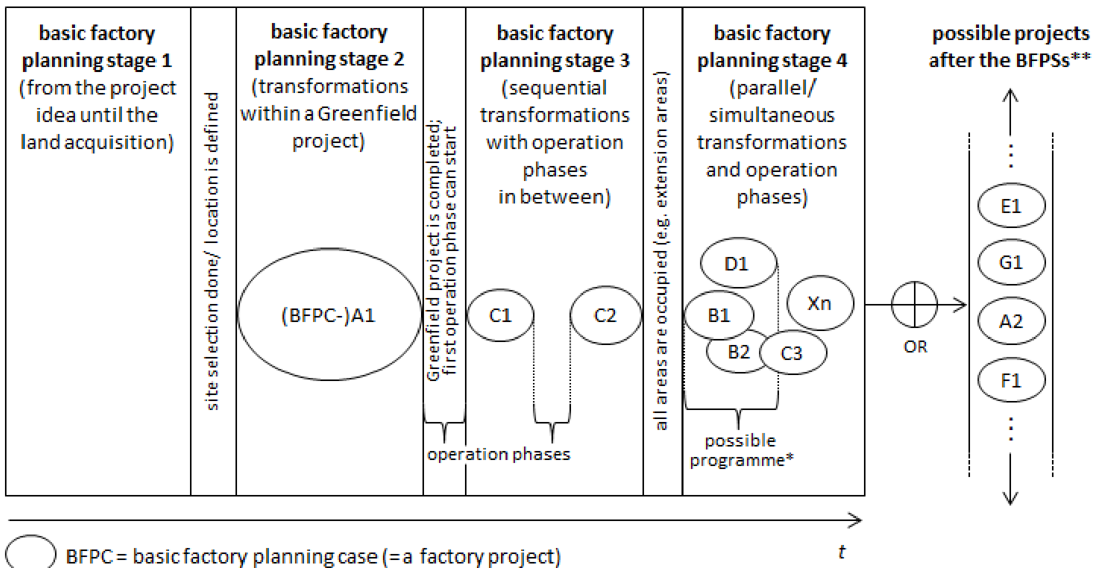


Figure 47: Mixed case

Different factory statuses are not only an outcome when projects are finalised (e.g. in t=1, t=3, t=5 etc.), but also between these statuses, i.e. during a project. The impacts of mixed cases are recognisable in the interview data. Real-world cases in BFPS-3 and particularly in BFPS-4 occur simultaneously. It is therefore hardly possible to comply with the principles of Grundig (2015) and Schenk, Wirth and Müller (2014), who emphasise holistic planning.

Numerous project cases can occur simultaneously, while each case leads to different transformation requirements. These requirements of different cases (or aimed factory statuses) can be mutually exclusive. Furthermore, newly emerging transformation requirements and/or cases can override already performed actions and make them void, while these new factory requirements cannot be handled within the resultant FOs/FSs without demolitions if these FOs/FSs are rigid. All eBFPCs can occur within BFPS-2 (as Greenfield-changes), BFPS-3 and BFPS-4. A problem is the knowledge about 'which' factory project case will occur 'when', and 'which impacts' it will have. The higher a BFPS, the worse the definition of these impacts. A further enhancement of (e)BFPCs is possible. Relevant elements that occur in real-world factory planning are described in subsection 6.1.10.

Cases which lead to mixed cases are shown in figure 48, which provides examples of some cases that can occur in BFPSs 2 to 4, and how these occur.



BFPC = basic factory planning case (= a factory project)
(BFPC-)A1 = (first) Greenfield project (it can be claimed that BFPC-A1 starts already within BFPS-1)
(BFPC-)B = re-engineering project (B1 and B2 are reengineering projects)
(BFPC-)C = extension project (C1, C2 and C3 are extension projects)
(BFPC-)D = reduction project (D1 is a reduction project)
(BFPC-)A2 is a new Greenfield project (as substitute for or in addition to the original/first factory)
(BFPC-)E = revitalisation project (E1 is a revitalisation project)
(BFPC-)F and (BFPC-)G are move projects
programme = multi-project
*must not be confused with a 'factory structure recovery programme'
**these projects can bring a factory into another BFPS while some of these cases can be combined

not all operation phases are depicted,
the dilutive effect between BFPS-3 and BFPS-4 is not considered
(i.e. simultaneous projects/cases are also possible in BFPS-3 while sequential projects/cases also occur in BFPS-4)

Figure 48: BFPSs

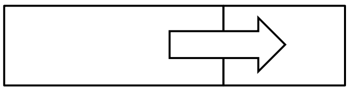
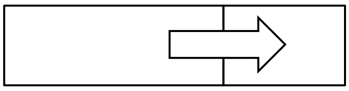
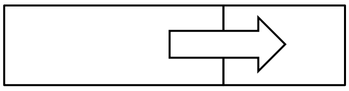
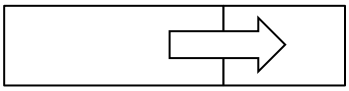
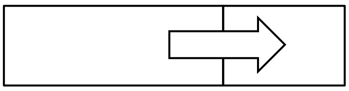
BFPC-C3, for instance, can lead to the requirement to change an already defined programme. Furthermore, off-site cases which require another site are depicted. These cases can be required for several reasons, e.g. when the complexity of a factory is so great that the management of factory projects is hardly possible; this emerged from the interviews. It also emerged from the interviews that not later than at a certain point in BFPS-4 a decision must be made – either to live with a factory, and for example to perform either singly or in combination the following, if it is possible and reasonable: a factory structure recovery programme; outsource contents; purchase adjacent and/or other off-site extension areas in order to use them for FOs/FSs (as a substitute for or in addition to the original factory). Thus, off-site cases can be consequences of further growth and/or other transformation requirements in late BFPSs. This is in line with Helbing (2010), who describes off-site cases in which the importance of movable FOs/FSs is recognisable. The interviews have shown that factory relocations and move projects often occur. Other factories within a related production network can be impacted.

6.1.9 Transition to Difficulty Factors

The answers of the interviewees were analysed and combined (also with further real-world data and data from the literature). This has allowed the development of this transition.

It emerged from the interviews that Brownfields can take longer and, from a project size perspective, can be larger and much more complex than Greenfields, because automotive OEM factories grow and become unstructured over time. Factory structure recovery programmes confirm this statement, as does a large amount of other interview and other real-world data. This statement is also validated through other eBFPCs and more complex mixed cases. The importance of transformability is confirmed by the fact that Brownfields occur much more often than Greenfields.

EBFPCs lead mainly to increasing area demands (except for decreasing production depths, whereas the latter can later lead to increasing area demands).

eBFPC #	name and overarching impact of the case
eBFPC I	‘capacity increase’ 
eBFPC II	‘product model change’ 
a form of eBFPC III	‘production depth increase’ 
eBFPC IV	‘factory structure recovery programme’ 
	= a symbol for the growth of factories (not necessarily a building extension)

Overall, this leads to heterogeneous transformations and growth and, besides other difficulty factors, to small and large displacements.

The sequential occurrence of different eBFPCs and mixed cases

- which occur differently over time (while it is unclear which case occurs, and when) and
- have different impacts (e.g. difficulty factors) on
- heterogeneous FOs/FSs (e.g. different sections and their contents)
- which grow and/or are transformed heterogeneously

leads to factories which grow differently, develop differently and involve different configurations and statuses over time.

It is not only the direct/primary impacts of factory projects that are decisive, but also the indirect impacts (i.e. secondary, tertiary etc. impacts). Therefore, the contents of subsection 6.1.10, which provides details about ‘wider or second level impacts’, must also be considered. The recognition of ‘difficulty factors’ is essential in order to be able to recognise the capabilities and limitations of each developed factory concept against the backdrop of reached BFPSs and required eBFPCs. Displacements, various domino effects, other difficulty factors and further difficulty-increasing events and aspects are described. These are not always obviously detectable and are also currently hardly assessable (particularly as a whole, with all of their interactions etc.); these are two major problems in factory planning. The knowledge of the existence of the contents of subsection 6.1.10 is crucial for sections 6.2 and 6.3, e.g. when (BFPSs and) eBFPCs are considered. These contents also enhance (e)BFPCs.

6.1.10 Difficulty Factors in Factory Planning

It emerged from the interviews that besides the intended effects, displacements, diverse domino effects, back-couplings and/or feedback loops can also occur. Small causes can thus have strong wide-ranging impacts. All of these occurrences are, besides others, combined under the umbrella term 'difficulty factors'. The elements and circumstances that lead to such factors are not sufficiently described in the factory planning literature. This subsection is concerned with their description.

Changes of one flow can impact other flows and the involved FOs/FSs (Schenk, Wirth and Müller, 2014, p. 58). This is in line with Helbing (2010). It has also been recognised that "planning always proceeds from the center (main process) and then in sequence from the first periphery to the second and third." (Schenk, Wirth and Müller, 2010, p. 10). Furthermore, "...production areas [and other area types] ... are calculated both from the approximate to the detailed, as well as inversely through calculation and dimensional design of the layout." (p. 119). Schenk, Wirth and Müller (2010) identify functional area overlaps. These authors emphasise areas and framework conditions in which an overlap is either possible or disabled, and mention different possibilities in between these statuses, such as the use of "easily movable equipment (e.g. rolling containers) ... [and] manual transport elements that can be routed over the floor space elements" (p. 109). Helbing (2010, pp. 572–580) goes a step further and discusses displacements of FOs/FSs, argueing that these can occur depending on the arrangement of elements and their movements. The displaced space is calculated based on the spatial dimensions at the target position. A spatial element cannot be occupied by other spatial elements, but can be extended (p. 577). Displacements occur through system element characteristics (e.g. dimensions and floor depths), extensions, build-ups, and movements of system elements (pp. 578–580). The total calculation of the required system element space is based on the summation of all single spaces, with consideration of overlaps and obstacles. The overall displacement space does not involve overlaps, but impacts on the effective system space (p. 580). Helbing also emphasises replacement demands, e.g. exchanges of old machines through new ones. Dismantlements/disassemblies, demolitions and the possibility that a new object may require more area/space, power etc. are considered (pp. 634–635). In the case of factory projects, he makes clear that a factory must be considered in its entirety. Relationships between tasks, processes and the factory structure must be analysed. The same applies to the number and arrangement of system elements within the factory space, and existing relations between these elements and arrangements. Functions, dimensions, structures, and forms are crucial. Area-related and spatial differences before and after a project (e.g. of all FOs/FSs with regard to their dimensions) must be considered (e.g. p. 152). Project overlaps, structural overlaps, and different impacts between FOs/FSs and projects (e.g. retroactive impacts) are considered (p. 189). Impacts of processes/functions on FOs/FSs and vice versa, impacts of technological systems on infrastructures and vice versa, and their impacts on other structures and projects are also considered (pp. 187–195).

The occurrences described up to this point in this subsection are not sufficiently considered in factory planning. Backgrounds, relations, and impacts of these occurrences are not appropriately described. The following statements exemplify this finding:

Statement of interview partner 2: It is often not possible to handle project complexities as required.
Statement of interview partner 3: During the planning process, one starts roughly, becomes more and more detailed and knows finally what is required and what is there. You cannot know this before. . . .
(continued)

interview partner (IP)	IP3	Demolitions happen where the capacity limit is reached – it is a never-ending story.
	IP4	The complexity in several factories is not manageable. . . . The more projects are performed in a factory, the more difficult it becomes to take decisions at the right time and to define their impacts. The complexity increases extremely and often leads to second-best solutions. . . . How large can the area be at all, so that it can still be managed due to dimensions?/. As there are interactions and mutual impacts . . . There is a maximum factory size that should not be exceeded, otherwise, the factory is not controllable anymore.
	IP5	Cases exist in which the left hand does not know what the right hand is doing . . .
	IP7	Delays of single projects are not foreseeable . . . Product definitions impact on facilities and when changes occur this leads to domino effects. . . . It is known that several overlaps will occur, but this does not mean that these overlaps can be handled.
	IP8	Agile project management (which is not dominated by a reliable planning approach, but rather by ad hoc-decisions) is the only possibility to handle complex circumstances in factory planning. This programme can only lead to chaos, and it can only be handled by means of agile project management, which means only by using real-time decisions and improvisations – there is no other possibility.

This is in line with Burggräf (2012), who repeatedly emphasises the dynamics in factory planning. One example of these dynamics is that bottlenecks in a factory change over time (p. 46). Changing bottlenecks are a problem:

interview partner (IP)	IP6	The bottleneck is the weakest element or link in the overall constellation and crucial for the development of the entire factory and for project durations. Bottlenecks lead to prolonged durations. Depending on where the bottleneck is, other requirements and durations occur, while new changes and new bottlenecks can increase these durations again and again. . . . many other bottlenecks can occur.
	IP4	When a pit must be transformed, it can lead to a domino effect which impacts on the whole factory.
	IP3	The problem, in this case, is that the transformation should be performed much faster, which is not possible at all due to several dominos.
(continued)		

interview partner (IP)	IP3	. . . Unforeseeable chain reactions occur repeatedly.
	IP2	Such a chain of events is not foreseeable.
	IP7	Requirements change and domino effects occur again.

To describe the complexity and dynamic in factory planning holistically and consistently in a structured manner is currently hardly possible, but what makes factory planning complex, dynamic and require ad-hoc decisions can be explained. Difficulty factors, their relations, and impacts have been identified and defined (without raising the claim that these are all of the factors and relations between them).

Statement of interview partner 4:
As soon as a product changes, a transformation within a production facility is required. Depending on the strength of the transformation, the building can be impacted. New additional objects are required and therefore pits and trenches must be changed. This is a chain which impacts the entire location.

The above statement is one out of many which show why it is necessary to generate 'difficulty factors' as generally valid patterns for factory planning.

Just to say that something is complex or that it does not work appropriately and to include some superficial and obvious statements about why this is the case is simple. To provide an in-depth indication of what is actually happening in factory planning and within the developed factory concepts throughout a factory lifecycle, and to provide in-depth reasons as to why this is the case requires the description of relevant elements and their relations. What leads to complexity, why and when? Elements and relations between the elements that lead to diverse domino effects, vicious cycles and unmanageability in factory planning are crucial for the comparison of the developed factory concepts.

Which elements and element relations lead to the complexity in factory planning?

BMEs and displacements can be recognised at micro, meso and macro levels (i.e. from smallest elements to buildings). BMEs can lead to displacements and other difficulty factors such as various domino effects. 'Domino effect(s)', 'domino(s)', 'chain reaction(s)' and 'chaining(s)' are designations which were used by the interviewees and can be used synonymously. The designation 'domino effect', for instance, can be used when a chain reaction consists rather of equal factors, while 'chaining' can be used to indicate that a chain reaction consists rather of unequal factors and to explain the relations of single factors in this regard. This is covered in the following, and completes the picture of the chaos in factory planning. Difficulty factors are shown in table 18.

'difficulty factors'	
single difficulty factor	e.g. a displacement. *Please consider: In combination with changing transformation requirements, the heterogeneity is crucial for displacements.*
domino effect	e.g. a chain of displacements
chaining	e.g. a displacement which evokes a substitution process, while this substitution process evokes a displacement etc.
impacts between projects	e.g. a project overlap
. . .	. . .
Combinations of and overlaps between these factors are possible, while other circumstances must be additionally considered. These are described throughout this subsection.	

Table 18: Difficulty factors

Collisions of objects and/or structures were repeatedly disclosed by all interviewees. Rapid transformations are performed if this is possible. Thus, time-consuming displacements are normally avoided for as long as possible. Today's factories become increasingly occupied and intertwined. Thus, the possibility to perform rapid transformations with today's factories decreases throughout the BFPSs (appendix 6.1.10_01a and appendix 6.1.10_02). With progressing BFPSs, the possibility to avoid collisions through the creation of intertwined structures/

intertwinings decreases more and more. Displacements occur when a collision cannot be avoided. Inhibiting FOs/FSs must be displaced. With advanced BFPSs, fewer areas and spaces are available. Subsection 6.1.7 shows that most eBFPCs generally require additional areas and lead to changing area requirements, which leads to more displacements the higher and later the reached BFPS. The eBFPCs already make it clear that a large number of small and large displacements occur. A factory structure recovery programme often directly impacts several small and large FOs/FSs, e.g. buildings. Project durations increase as 'more numerous' and 'larger' inhibitors, displacements and demolitions occur, while flows become worse and the factory becomes less efficient (today's factories). It emerged from the interviews that in any case, today's factories sooner or later become UHPs if their lifecycles are long enough (appendix 6.1.10_03).

Problem: The probability of avoiding displacements decreases throughout the BFPSs. With progressed BFPSs, 'more numerous' and 'larger' displacements occur, while the dilutive effect must be considered. Differences between different FOs/FSs exist in this regard. To summarise these differences, the larger a displaced FO/FS the more likely it is that demolitions are required; this also depends on the rigidity of this FO/FS and on other circumstances.

Displacements are not the only problem. Displacements can trigger domino effects, which can trigger displacements etc. Capacity-related and capacity-unrelated domino effects can generally be differentiated. All interviewees disclosed several cases of displacements and related domino effects involving buildings and building contents. The information in appendix 6.1.10_04 can be used as a basis for their further analyses. Section 6.2 involves further information about displacements, while not all cases in which displacements occurred can be disclosed (particularly the building displacements). Moreover, in order to protect the interviewees, not all details of the disclosed displacements can be presented.

In addition, chainings which involve many different elements occur. A capacity increase, for instance, can lead to a displacement which can lead to the requirement to implement a substitution process before the displacement can be performed. Real-world projects involve both ‘more numerous’ and ‘more complex’ chainings. These types of domino effects can also be further analysed. Appendix 6.1.10_05 involves examples of chainings that are more detailed. Chainings and other difficulty factors increase project durations.

If one reconsiders the building extension in subsection 6.1.7 or imagines a building displacement, it is possible to conceive the complexity that can result. Substitution processes, the pre-production of parts and outsourcing can be required for numerous different functions, and are often unavoidable if one wishes to perform a transformation with today’s factories (particularly displacements). This illustrates their importance. Substitution processes, the pre-production of parts and outsourcing can be perceived as difficulty factors. However, this is not always the case, as they can help to perform transformations and also because they do not always lead to great difficulties.

In addition, other/new projects and/or changing/new transformation requirements can impact FOs/FSs in a similar manner, making transformations even more difficult and also increasing project durations. Changing/new transformation requirements and/or late specifications of the product and/or process planning can lead to different difficulty factors. Changes, project overlaps and other impacts between projects occur. Basics for further analyses are provided in appendix 6.1.10_06.

Displacements, domino effects, chainings, impacts between projects and other difficulty factors can occur together. With advanced BFPSs the situation becomes worse, and further circumstances must be considered. Not only do substructures impact superstructures and vice versa; transformation requirements and/or difficulty factors can have impacts on subordinated, identical and/or superordinated factory structure levels, i.e. macro-on-meso-on-micro and/or micro-on-meso-on-macro impacts. An additional duct, for instance, might lead to a move of a larger object, while an additional machine might lead to a building extension etc. Back-couplings of one and the same project are also possible. A worst case is thus hardly definable. Difficulty factors are not always completely delimitable and can overlap. Further in-depth analyses must be done in other research projects (table 19). The perspective and the depth of analyses can decide whether or not a domino effect is perceived as a chaining.

'possible starting points/relevant aspects for further analyses'	
I.	difficulty factors (all in this subsection)
II.	heterogeneous FOs/FSs (e.g. different sections and their contents)
III.	heterogeneous transformations and growth
IV.	cross-structural impacts, i.e. micro-meso-macro and macro-meso-micro
. . .	. . .
These and other issues must be considered and analysed – in combination.	

Table 19: Possible starting points for further analyses

It emerged from the interviews that displacements and other difficulty factors happen more often and have larger and more negative impacts the higher and later the reached BFPS. It also emerged from the interviews that today's factories sooner or later reach an unstructured status in BFPS-3 or BFPS-4. Displacements and other difficulty factors have particularly negative impacts when one of these two statuses is reached, because displacements are often accompanied by demolitions (today's factories). Smaller displacements happen in many factory projects. With progressed BFPSs, 'more numerous' and 'larger' displacements occur, while the dilutive effect must be considered. Thus, negative impacts increase. This validates the proposition that the other difficulty factors also occur more often throughout the BFPSs, and that the complexity increases exponentially.

The question is how and at what point it is possible to identify which areas, objects and/or structures are impacted through a transformation requirement, as well as when and how this requirement and its impacts can be processed; the identification of this point(s) is usually delayed. The recognition of the transformation requirement itself is already delayed and is not as precise, not to mention the impacts. The more nature-related, physical/chemical and/or human-related processes are involved, the less these impacts are perceptible/identifiable and operationalisable. More and more FOs/FSs, which become increasingly intertwined, are involved throughout the BFPSs. These FOs/FSs, difficulty factors, domino effects, chainings and further difficulty-increasing events and aspects make it increasingly difficult to define projects and to delimit them from one another.

The circumstances in this subsection make the circumstances described in the previous subsections worse. Factory planning can be highly complex; if production networks are considered, complexity increases substantially. It emerged from the interviews that the circumstances that apply to physical FPPs also apply in a similar manner to several non-material FFPs. Non-material processes can also have impacts on physical solutions. When changes appear, these can lead to delays or restarts of processes.

“Geometry, load, interference, supply and disposal parameters all have an influence of the [building] floor space and room...” (Schenk, Wirth and Müller, 2010, p. 119). The importance of this statement is recognisable if the contents of the previous subsections and this subsection are combined.

Displacements and impacts between different projects are discussed in the literature. Nevertheless, in previous research these factors have not always been won from real-world data, and particularly not combined with other real-world factors in order to make sense of them and to explain relevant circumstances, occurrences and difficulties in factory planning; this has been accomplished in this research project.

Required actions cannot always be completely defined. This can be recognised even more if one makes a deep-dive into the appendices of this subsection, which is only recommended if one wishes to analyse factory planning relations in-depth.

In order to further process the circumstances which lead to the complexity in factory planning, the definition and use of ‘difficulty levels’ is required. ‘Difficulty factors’, their relations and further difficulty-increasing events and aspects can in combination be associated with ‘difficulty levels’, which will be represented by the letters ‘a’ to ‘z’: ‘a’ represents the simplest/lowest and ‘z’ the worst/highest difficulty level. These difficulty levels will be allocated to the BFPSs of today’s factories in order to indicate the difficulties and complexity that this factory concept faces within each BFPS (see subsection 6.2.5). The difficulty levels of TFCs are examined in subsection 6.3.5. Difficulty levels can involve several difficulty factors and their combinations. Part of the problem in factory planning is that required actions (i.e. difficulty factors in combination and resulting FPPs) cannot be completely defined. This applies particularly to BFPS-4-factories and to unstructured BFPS-3-factories, depending on the specific case. Another 'tragic circumstance in factory planning' is that a requirement that seems to be easily achievable can have larger impacts on a factory than, for instance, a large displacement.

Factory planners must not only manage complex factories, but must also manage chaotic and disordered ones. A factory develops throughout the BFPSs through these domains. In addition, complex projects and programmes take place. Not only does the complexity of factories increase, but also the complexity of projects and programmes and their management. This explains why factory planning reaches chaotic and even disordered domains. Therefore, a basic knowledge of factory- and factory planning-related relationships and effect mechanisms is important. Even if the latter are not completely definable, it is recognisable that transformation velocity must be increased, and thus transformability must be increased, as transformability impacts on FPP-capabilities and transformation velocity. Projects which are performed with today's factories require longer durations and lead to higher difficulty levels due to the limited capabilities of these factories. This is recognisable in section 6.2. Section 6.3 explains why TFCs can better handle factory projects. The importance of fundamental enablers and accelerators can be understood if difficulties in factory planning are recognised, e.g. heterogeneity in combination with transformation requirements.

A large number of changing transformation requirements, different area extension and (ex)change requirements, and the heterogeneity in factory planning are more tangible through the eBFPCs and difficulty factors. Through the eBFPCs and this subsection, it is shown that displacements can occur in almost each project. Not only do eBFPCs and diverse difficulty factors (e.g. chainings) etc. determine the number and sizes of displacements, but also specifically the reached BFPS. Displacements are representative of other difficulty factors. Furthermore, diverse difficulty factors can be evoked by displacements, and vice versa. Therefore, the focus in subsections 6.2.5 and 6.3.5 lies more on displacements than on other difficulty factors. In addition in these subsections, eBFPCs are used to support the study of the developed factory concepts based on the impacts of eBFPCs on factories, which differ for every BFPS and factory concept. The developed factory concepts can deal with eBFPCs and upcoming difficulty factors in a different manner. The reasons for butterfly effects and vicious cycles are explained in more detail throughout section 6.2. These occurrences are considered in the light of TFCs throughout section 6.3. Difficulty levels are used in sections 6.2 and 6.3 to enable the consideration of the complexity in factory planning, which changes throughout the BFPSs.

The lower the transformability and transformation velocity, the higher the risk that complexity cannot be handled, as more effort and time are required to perform a transformation. The lower the transformability of areas, the more difficult the situation becomes. The problem with today's factories is that the fewer areas that are available, the lower the transformability and transformation velocity, and the more effortful and time-consuming the required FPPs. The larger the impacted immobile area/space that is displaced and must be (quasi-)moved/relocated, the more FOs/FSs are impacted and the more complex, effortful and time-consuming the transformations, and the more important the advantageous fundamental enablers (e.g. the MAS and transformable area and substructure characteristics), which enable the mobility of areas together with their sub- and superstructures and/or their transformation. The larger the areas and FOs/FSs that are mobile and the higher their transformability, the higher the transformability and the better and the faster transformations can be performed, which decreases complexity. This indicates the importance of fundamental enablers.

One of the most important aspects to understand is that the developed factory concepts lead to different fundamental enablers. These fundamental enablers have an impact on the possible complexity management, which differs for every factory concept.

6.1.11 Summary and Conclusion

Section 6.1 made clear the reasons why numerous transformation-related FPPs are required and what makes factory planning complex and factory projects hardly manageable (e.g. hardly or indefinable 'to be'-factory statuses), particularly if (area-)transformability is low. Reductions were hardly or not at all identified by the interviewees. Factories grow and breathe in many different ways, rather than being reduced. In combination with heterogeneity, these transformations are disastrous if areas are not transformable; this is not recognised in the factory planning literature. This can be said about the contents of this chapter up to and including subsection 6.1.6.

The complexity in factory planning could then be explained more deeply and at the same time combined to form analysable data units and patterns. This was possible because the interviewees provided numerous real-world factory projects and impacts, and because it was possible to deeply probe these and to track, backtrack, identify and analyse cause-and-effect relationships. The identified patterns were ordered and arranged throughout subsections 6.1.7 to 6.1.10. It was therefore possible to describe when and which area and substructure works are required and in which cases. EBFPCs and their consequences are also not recognisable in the literature, particularly when these patterns are combined with BFPSs.

Overall, section 6.1 provides a new basis for further analyses in sections 6.2 and 6.3, as important elements of the model and further concepts could be developed. RO1 could be partly achieved. The application of the model and associated concepts in sections 6.2 and 6.3 will lead to the complete achievement of RO1.

As a result of the interviews, it can be concluded that area and substructure transformations play an important and significant role for factories. It is also obvious that the importance and significance of the transformability of areas and substructures is currently underestimated, and that this is much more important than indicated in the factory planning literature. Area- and substructure-transformability are relevant for all BFPSs, and particularly for BFPS-4. (E)BFPCs, which occur in a mix, are related to BMEs and displacements of FOs/FSs. Entire buildings are even displaced, while further difficulty factors occur. This requires area, substructure and other works, and leads to complexity.

The frequency of area transformations is high, and this increases with late BFPSs. It will be shown that more transformation-related FPPs are required with today's factories than with TFCs. The described amount of area and substructure works and related difficulties are therefore especially relevant for today's factories, as TFCs decrease these works and further negative impacts, and make them more easily solvable.

Furthermore, relocations of huge, complex and firmly anchored factories would be sensible, and not only relocations of those which produce simple products and/or can be relocated by means of containers etc. Even if factory relocations are ignored, transformations lead to changing flows and positions of numerous FOs/FSs, many of which exceed container dimensions and/or are difficult or impossible to move/relocate. In order to simplify FPPs, factory-related dynamics in combination with the required heterogeneity require a higher transformability and transformation velocity than is achievable with today's factories. The developed concepts and model and the difficulty levels will be used to verify this statement and to indicate what is possible with TFCs. The importance of these concepts (particularly of fundamental enablers) and of area-transformability is already recognisable and will become even more so. Intertwinings are initially possible, but small and large displacements are later required. Displacements in particular are considered in the following sections, while eBFPCs are taken into account in order to support the analyses and the assessment of the developed factory concepts. The following section will also confirm that factory planning can be chaotic and even disordered. The same applies to the fact that factories become UHPs if their lifecycles are long enough and their area-transformability limited, and that project complexities, project durations and factory complexities increase the risk of this development.

Table 20 summarises how the interviewees viewed the most important topics and concepts, which along with the following data also shows that the developed transitions and further research results are valid and reliable.

		views of the interviewees							
		IP1	IP2	IP3	IP4	IP5	IP6	IP7	IP8
described topic/concept(s)	changes and transformation requirements	●	●	●	●	●	●	●	●
	inoperativeness of scenario techniques	●	●	●	●	●	●	●	●
	factory growth compulsion (during a factory lifecycle)*	●	●	●	●	●	●	●	●
	types of factory growth and transformations	●	●	●	●	●	●	●**	●
	heterogeneity in factory planning	●	●	●	●	●	●	●	●
	BFPSs 1 to 4	●	●	●	●	●	●	●	●
	eBFPCs, mixed and off-site cases	●	●	●	●	●	●	●	●
	impacts of eBFPCs (nuances differed)	●	●	●	●	●	●	●	●
	difficulty factors (particularly displacements)***	●	●	●	●	●	●	●	●

● emerged completely from the interview and/or has/have been fully validated

*Reductions and (quasi-)exceptional cases were described. Nevertheless, the interview data of these experts showed clearly that it is a general rule that factories grow throughout their lifecycle.

**The knowledge of IP7 about exchange areas was mainly implicit/tacit.

***The described circumstances need to be considered.

This table does not differentiate explicit and implicit/tacit knowledge.

All these topics and concepts are furthermore validated throughout the following sections (e.g. through the interview data that can be found in these sections).

Table 20: Expert views section 6.1

6.2 Results Relevant for Today's Factories

This section is concerned with today's factories.

Subsection 6.2.1 demonstrates that terrestrial areas and today's factories are largely fixed. In subsection 6.2.2, transformation and fundamental enablers are applied in order to specify the transformability-related capabilities and limitations of today's factories. In subsection 6.2.3, accelerators and fundamental enablers are applied to specify FFP-related capabilities and limitations of today's factories. Under consideration of the contents of section 6.1 and subsection 6.2.1, the application of these concepts results in FPP-related information that is specific to today's factories. Thus, subsection 6.2.4 summarises the contents of the previous subsections and provides a transition to subsection 6.2.5, in which the model is applied to today's factories. First, the development of the transformability of today's factories throughout the BFPSs is examined and explained, and then the development of difficulty levels (i.e. complexity) throughout the BFPSs is considered. It is then clear which difficulty factors and levels are specific to today's factories for each BFPS, and how these can be handled within each BFPS. Subsection 6.2.6 describes the consequences for today's factories, while subsection 6.2.7 summarises and concludes section 6.2.

This section involves real-world interview data about the BFPSs of today's factories, and about real-world factory project cases in BFPSs. EBFPCs are reflected against the backdrop of BFPSs, as each eBFPC occurs in a specific BFPS. These data show the importance of BMEs, accelerators and fundamental enablers. The resulting consequences in terms of today's factories' characteristics and capabilities throughout the BFPSs are crucial. These consequences are at the same time reasons for the increasing complexity in factory planning; the less this is able to be managed, the higher the BFPS.

6.2.1 Limited Transformability of the General Structure

Most objects and structures in the ground are either fixed in the soil or additionally encased in concrete. The dimensions of an FO/FS and how deep it is positioned in the ground co-determine its rigidity. Basements, tunnels, media ducts and other fixed spaces in the ground can enable transformations, but only within their inner dimensions and fixed positions/locations. Over time, they become inhibitors (appendix 6.2.1_01):

interview partner (IP)	IP1	Objects and structures are firmly anchored within terrestrial areas. . . . Canals can absolutely inhibit transformations. . . . Buildings are constructed on solid ground with solid foundations. They cannot be moved.
	IP2	Objects and structures in the area can hardly be transformed non-destructively and should be located where one does not plan to build a building. Machines exist which one cannot and does not want to relocate, especially if they go deep into the ground. . . . Everything that one brings into the area should be assembled or buried in a way that does not inhibit future transformations.
	IP3	The more is overbuilt or the more an object or structure is overbuilt, the lower the transformability of factories.
	IP4	It considerably limits the transformability if an object is positioned in the area.
	IP5	The transformability of objects and structures in the ground is limited and demolitions are normally required in the case of their transformation. . . . Canals within areas are not transformable. . . . Tunnels and ducts inhibit transformations quite often.
	IP6	Pipe-systems that are buried in the area are always fixed.
	IP7	A foundation remains as it is and a reuse is rather difficult.
	IP8	It is restrictive if an object is positioned in the ground.

Thus, terrestrial areas have negative impacts on the transformability of FOs/FSs and on FPPs. Furthermore, the possibilities of today’s factories with regard to the transformability of substructures can only temporarily lead to advantages.

Factories, rigid buildings, many building contents, outdoor FOs/FSs, technical infrastructures, their connecting points and other FOs/FSs are fixed. Areas and consequently substructures are the main problem, not superstructures (appendix 6.2.1_02):

interview partner (IP)	IP1	Press shops and paint shops cannot be relocated.
	IP2	Buildings stand solidly on the ground and on foundations. Sometimes on 20 m deep poles. They cannot be moved. . . . In buildings are naturally also facilities which cannot be relocated – especially if they are deep in the ground. . . . Objects exist that one does not want to move at all due to a huge effort. The A (an object) in B (a real-world factory) is over 120 m long, 12 m high and requires 8 m deep pits. . . . The X (an object) in Y (a building in a real-world factory) disturbs transformations and prevents efficient flows since decades.
	IP3	If a press or a paint shop is implemented in a Greenfield, it is fixed. . . . If locations for such objects have been defined, they should remain there, especially if tanks are positioned in the ground.
	IP4	Fixed points are canteens, factory fire brigade departments, gas, and combined heat and power stations. . . . The energy centre is often located beside the paint shop. This is a further fixed point.
	IP7	Objects that are encased in concrete are rigid . . . Objects and structures are statically arranged. The presence of a large number of these objects and structures will inhibit transformations when a production flow changes.
	IP8	All production sections are fixed today.
	Other examples of fixed building contents are: body shop robots (not all of them are movable) (IP2, IP3, IP4, IP5 and IP8); measurement labratories and equipment which require specific foundations (IP3); measuring rooms and geo stations (IP4); marriage (engine/chassis/ body) (IP4 and IP3); rain test (IP3, IP4 and IP5); filling and other process facilities (IP2); automobile test stands (IP2 and IP4); floor extraction/ exhaust systems (e.g. end-of-line) (IP4); conveyor technologies which require foundations and pits (all interviewees); logistics areas with high loads (e.g. movable racks) (IP2 and IP4); other heavy-duty areas; high-rise objects and special processes such as galvanisation (consider approval processes) (IP1, IP6 and IP7). *see appendix 6.2.1_02 for further information and details*	

Today's factories are largely static, and once defined, their locations are fixed.

The general structure of today's factories is largely fixed once a factory is implemented, and can only be changed with huge effort and wasteful processes, e.g. demolitions. The older that current factories become, the more extensive these wastes. The transformability of the general structure is particularly important for long-term factory developments.

Throughout long factory lifecycles, terrestrial areas are relevant for multiple transformations of the general structure. These areas have direct negative impacts on the transformability of (1) the general structure, (2) transportation infrastructure, (3) s&d infrastructure, (4) outdoor FOs/FSs and (5) user-specific factory buildings (including building contents). Points (2) to (5) have a further negative influence on the transformability of the general structure, which involves furthermore green and other areas (figure 49).

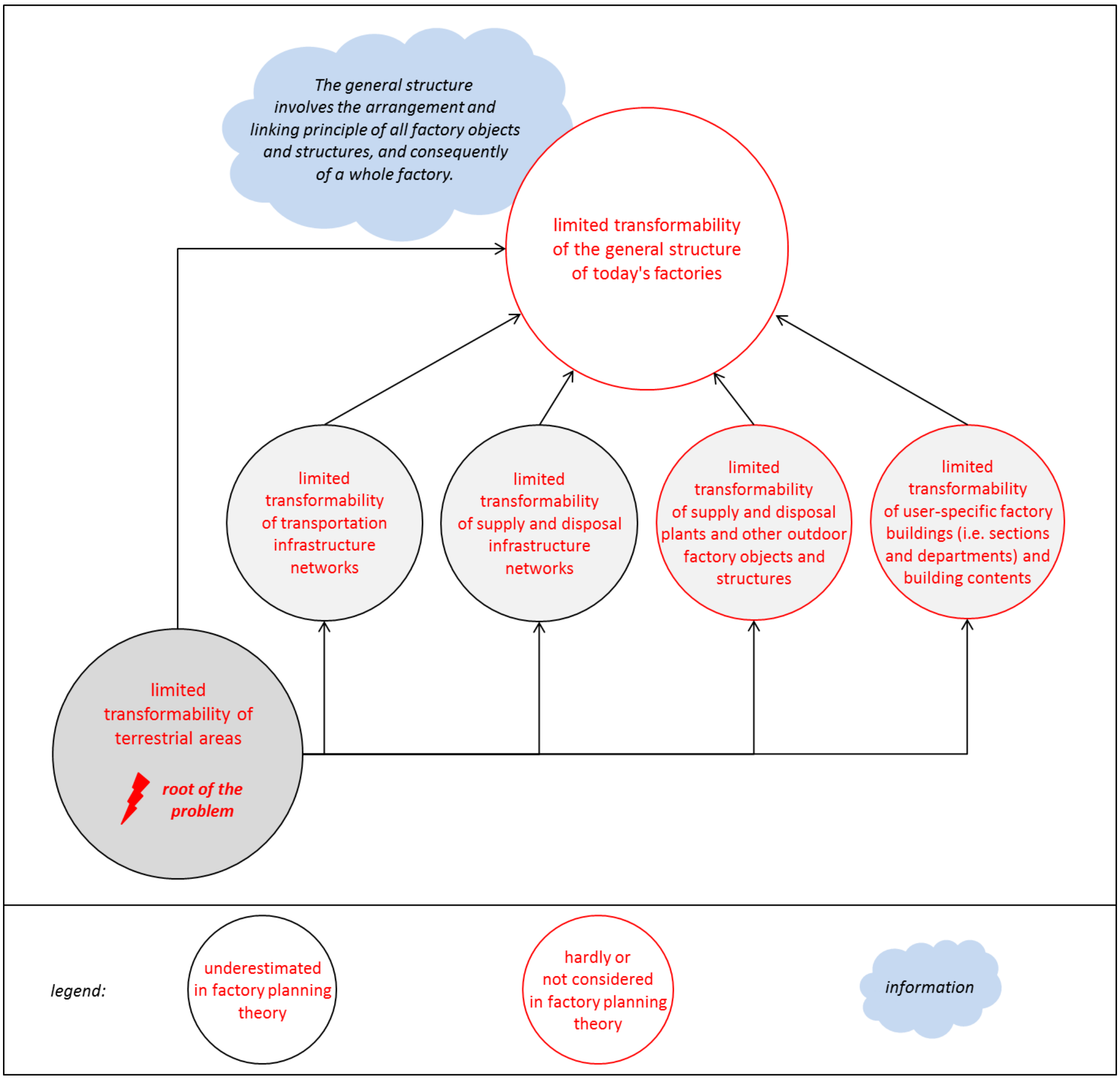


Figure 49: Terrestrial areas – the root cause of the limited and decreasing transformability of today's factories

If the influencing arrows in figure 49 are reversed, it is recognisable that terrestrial areas are the root of the problem. Layout positions of RFOs/RFSs are determined once they are defined. Furthermore, RFOs/RFSs limit the transformability potential of TFOs/TFSs. Moreover, TFOs/TFSs can be fixed through/under soil, stones, concrete and the like.

Thus, the area determines all factory structure levels and the general structure. The limited transformability of today's factories is caused by the insufficient transformability of terrestrial areas. This has not been stressed in the current literature.

Numerous small and large FOs/FSs require movement/relocation (and/or other transformation) from time to time. The general structure changes at micro, meso and macro levels. This is undesirable if areas and substructures are fixed. If the area-mobility and MAS (including sub- and superstructures) are disabled, other transformation units, acceleration units and fundamental enablers can enable transformations. However, these are limited by terrestrial areas and today's factory structures (except fixed spaces in the ground which enable transformations for a limited time and later become inhibitors). Area characteristics limit today's factories. Extensive earthworks are often required for Greenfields and Brownfields. It emerged from the interviews that today's factories are fixed, limitedly transformable and surrounded (appendix 6.2.1_03) (figure 50).

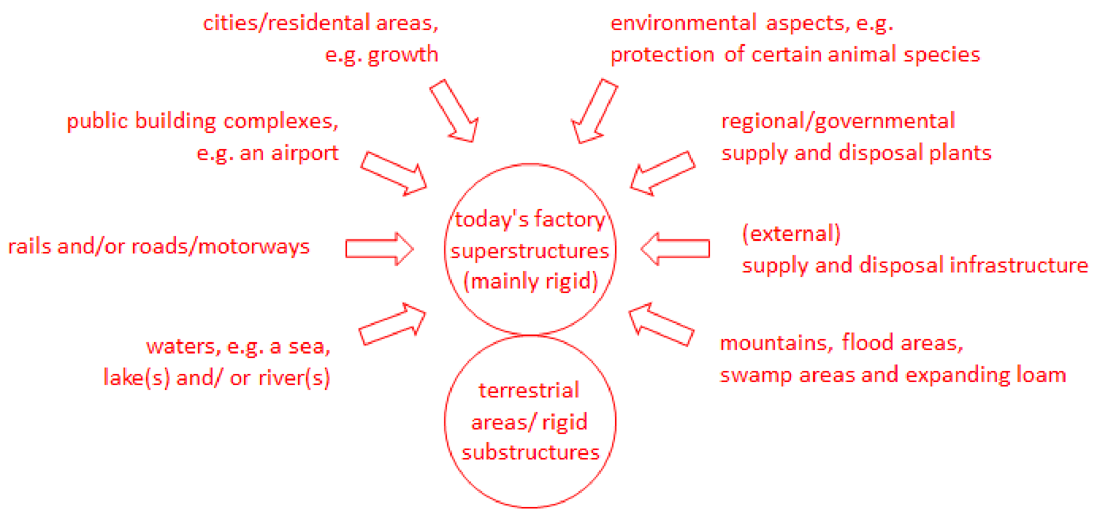


Figure 50: The surrounded factory

Modular and mobile container factories (e.g. Fox, 2015) are therefore limited, not only in terms of their possible production scope. These factories can also require RFOs/RFSs (of which all cannot be taken along in the case of a relocation), are surrounded, and face similar difficulties, which are partly less disadvantageous, and are therefore not as transformable and advantageous as presented.

6.2.2 Application of Transformation and Fundamental Enablers

The mobility and pluggability and thus (active) scalability and linking ability of areas are disabled. Modules and their mobility are therefore limited to a maximum dimension of container sizes. This impacts negatively on all transformation enablers/units of today's factories, which are mainly superstructure-related (e.g. building superstructures and building contents) and not area-/substructure-related, and are also inhibited through fixed heterogeneous substructures and other inhibitors.

The fundamental enablers of today's factories are depicted in figure 51.

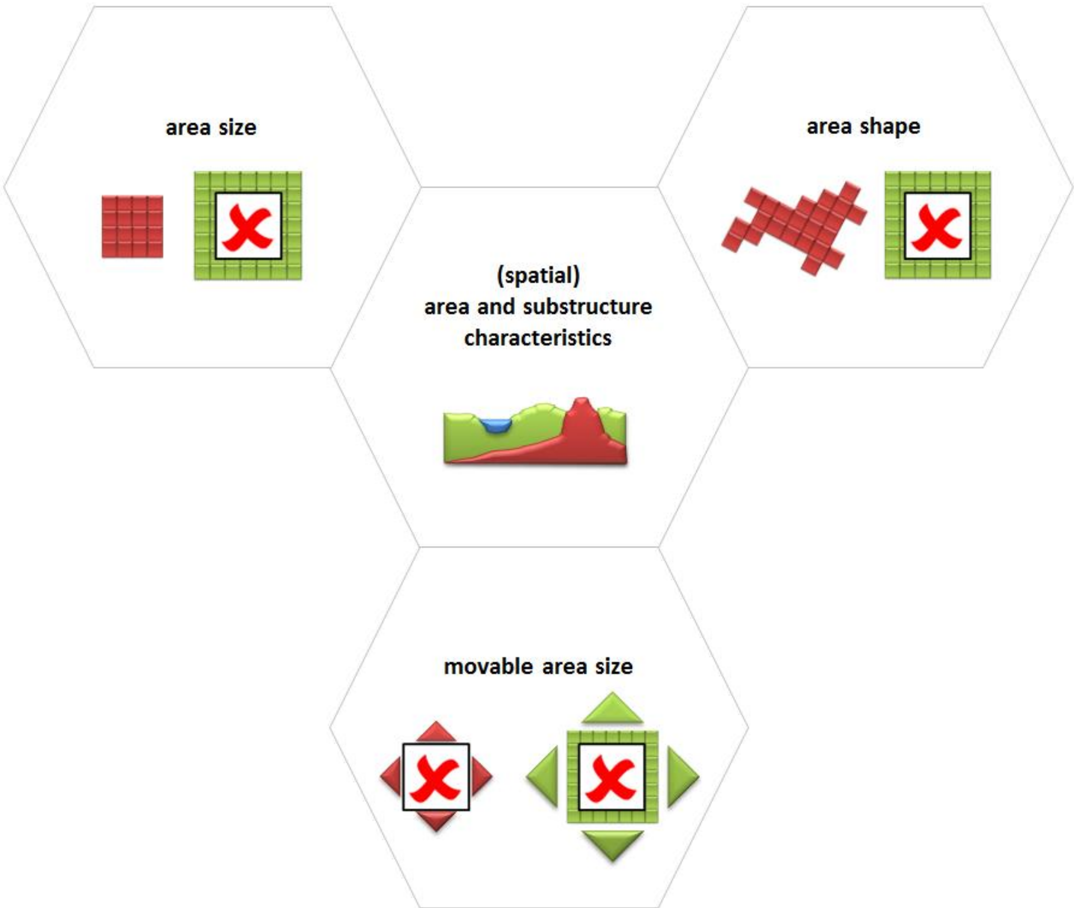


Figure 51: Fundamental enablers of today's factories

The area shape is seldom the favoured rectangular shape, and the area size is often limited. To find a site with adequate size, good shape and suitable area characteristics is highly difficult. Appropriate sites are rare and are becoming rarer. Furthermore, appropriate free areas in suitable positions within factories become rarer throughout the BFPSs. Terrestrial areas are natural, and involve inhibitors. Soil conditions are also largely unclear, even after test drillings. It is normal to perform land levelling and to remove soil and inhibitors. It emerged from the interviews that the soil condition/area quality is often not good enough, and requires additional efforts, e.g. reinforcement. With the construction of sub- and superstructures the situation becomes worse, as area and substructure requirements more often become inappropriate and inhibit transformations (together with other FOs/FSs) the higher the BFPS. The MAS of today's factories is zero/disabled, as the area-mobility is disabled. Movable object size is limited to container sizes. Micro- and meso-mobility of TFOs/TFSs is possible, but no macro-mobility. With increasing BFPSs it becomes increasingly difficult to find area and substructure characteristics that fit (unplanned) new/changing requirements (consider BMEs), while the number and extent of inhibiting FOs/FSs increase. This is especially problematic in BFPS-4.

Areas (often amorhous/unshaped) with a limited area size become increasingly built-up/overbuilt/covered, area and substructure characteristics determined, and possible mobility-advantages increasingly inhibited throughout the BFPSs. Thus, today's heterogeneous factories become increasingly fixed. This is particularly problematic against the backdrop of required transformations. Furthermore, the transformation velocity decreases. This emerged from the interviews. All in all, terrestrial areas impact negatively on sub- and superstructures (figure 52).

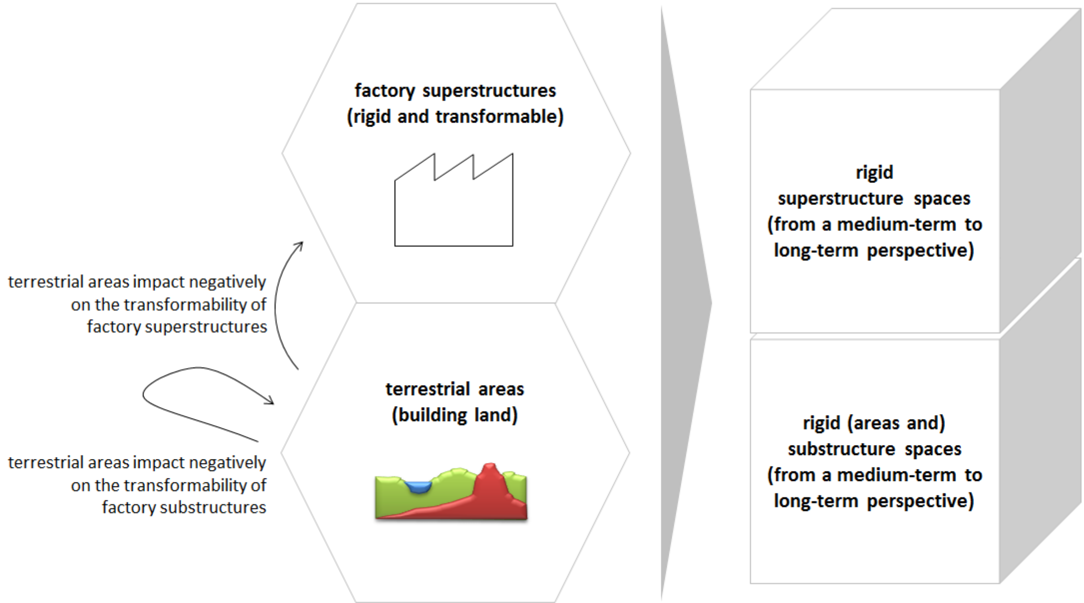


Figure 52: Negative impacts of terrestrial areas

These areas are also surrounded by natural and man-made inhibitors.

The modern factory can, compared to the traditional factory, be significantly advantageous for simple building extensions and transformations in which areas and substructures are not impacted. When an FO (e.g. a TFO) is moved/relocated, an appropriate floor load capacity, area size, and area shape are required, the same as sufficient free spaces/rooms within sub- and/or superstructures at the new destination, besides numerous other requirements. In almost all cases in which the area is impacted because of building extensions, new constructions and/or reconstructions, approval processes, earthworks and construction works for substructures are required. TBSs and TFOs/TFSs can lead to advantages with regard to the transformability and transformation velocity of factories, but these advantages are only minor when areas and substructures must be transformed. In sum, even a modern factory is not transformable if areas are impacted (figure 53).

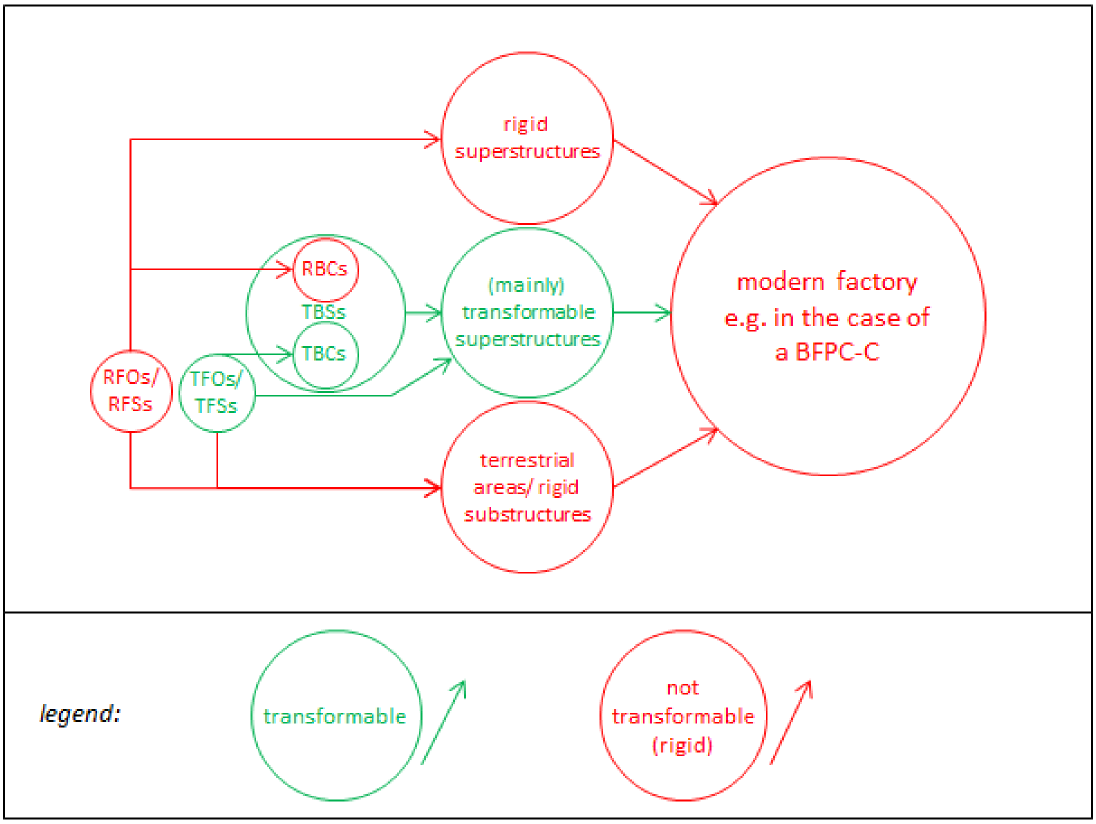


Figure 53: The rigid modern factory

Transformability-related advantages of TFOs/TFSs are limited by terrestrial areas. The time gain through a TBS in comparison to a building construction is marginal in the light of required FPPs. Other TFOs/TFSs do not lead to considerable advantages over time due to numerous fixed points, other inhibitors and transformation requirements which also impact these FOs/FSs. Figure 53 is thus rather idealised with regard to transformable superstructures.

From this point onwards the traditional factory is no longer considered, as the thesis focuses mainly on area and substructure transformations (as these dominate factory planning). The designation 'today's factory/ies' is used further.

Industry 4.0-developments cannot lead to significant advantages in this regard, as:

- Industry 4.0 and other current and modern solutions cannot be used for all process requirements, and many of these solutions also require their own RFOs/RFSs (appendix 6.2.2).

- There are many heterogeneous fixed points and other inhibitors (mainly RFOs/RFSs). Heterogeneous area and substructure requirements are crucial for numerous FOs/FSs, especially if they must be moved/relocated. To retain single RFOs/RFSs and use them as a reference does not lead to advantages, as there are too many of them which cannot be replaced or substituted by modern solutions. Most RFOs/RFSs are faded out in Industry 4.0-related publications. The same applies to changes of these RFOs/RFSs, which significantly impact areas and substructures.
- Transformations that impact only TFOs/TFSs/TBCs and/or only superstructures without impacting other structures/objects (e.g. areas, substructures, buildings/TBSs and/or other large objects) are rare.

It emerged from the interviews that TFOs/TFSs (including TBSs) and TBCs cannot meet all factory transformation requirements because areas and substructures are, in most cases, already significantly impacted in a pure BFPC-B, e.g. a reconstruction. The contents of section 6.1 are relevant in this regard. Increased efforts, difficulties and problems will occur together with transformations as long as superstructures require and involve heterogeneous areas and substructures without the capability of being movable/relocatable. Thus, relevant physical requirements and restrictions (especially those given by areas and substructures) cannot be bypassed with Industry 4.0-developments, e.g. floor loads, floor depths and other area-, sub- and superstructure-related requirements. Without TASs, many transformations take too long.

Figure 54 depicts one reality of industrial substructures. Such substructures must provide the space for FOs/FSs and to perform transformations, particularly when not all FOs/FSs can be positioned above ground level. Huge difficulties and efforts (e.g. demolitions) are involved when rigid areas, substructures and/or RFOs/RFSs must be (quasi-)relocated/moved.

Figure 54: Modular ventilation shaft in a rigid basement (used by permission of Rauschenberger GmbH)

Industry 4.0-developments can be used with both today's factories and TFCs. The information to this point is necessary in order to understand the limitations of Industry 4.0 when used in combination with today's factories, new versions of which will not be capable of absorbing all transformation requirements, and will become as dusty and rusted as the depicted structures.

The fixed heterogeneity of today's factories combined with real-world area and substructure transformation requirements puts today's factories in a very bad light. That areas limit the transformability of today's factories (factory sub- and superstructures) which decreases further throughout the BFPSs has not been described in the factory planning literature. The importance of the fact that the configurations/statuses of a current factory exclude one another has also not been discussed as required. The same applies to real-world transformation requirements which determine the importance of fundamental enablers. Inner and outer mobility are limited, and the same applies to transformability, which can also be subdivided into inner and outer parts. For example, when an FO is moved and plugged within a factory, the inner transformability is involved. When an FO is unplugged and relocated from one factory to another and must then be plugged there, both the inner and outer transformability are involved.

6.2.3 Application of Accelerators and Fundamental Enablers

Non-existent MASs and other limited fundamental enablers impact on transformability and FPPs, and thus on implementation and transformation velocity, which in the case of today's factories is low. Acceleration units do not comprise areas and are limited to container sizes if moves/relocations are involved. The move/relocation of larger FOs/FSs, if at all possible, requires in any case larger efforts. In the case of Brownfields this is even more so due to inhibitors. Besides the other fundamental enablers, the non-existent MAS(s) mainly limits the creation of acceleration units. Terrestrial area and substructure characteristics also restrict rapid transformations.

Areas and numerous substructures are not pre-producible and their reuse is limited and/or accompanied by great effort. Pre-producibility, pre-testability and reusability of production lines for example is possible if these are dismantled/disassembled and (re)assembled at the target location, but all area-related requirements must be appropriate. Thus, pre-producibility and pre-testability are limited to container sizes if an FO/FS is not directly implemented (entirely or in parts) at a target location or if FOs/FSs were not pre-produced and pre-tested at another location and afterwards dismantled/disassembled to transportable sizes. The implementation and transformation velocity therefore involves further potential that cannot be gained by today's factories.

6.2.4 Resulting Factory Planning Processes

The limited and furthermore decreasing transformability of today's factories impacts negatively on FPPs. More and more laborious works are required throughout the BFPSs. Furthermore, today's factories are dominated by sequential (particularly physical) processes. Earthworks, area and substructure works are essential in this regard. Nature-related, physical/chemical and human-related processes dominate today's factories. RFOs/RFSs require area and/or substructure works in the case of moves/relocations. Approval processes, the dismantling and/or demolition and removal of inhibitors, new construction and/or remake of areas and/or substructures, change of interfaces, and mainly manual disconnections/ connections and installations are largely required in order to fit new/changed requirements (consider displacements in this regard) (see appendix 6.2.4 for a practice-oriented explanation of relevant approval processes). It is possible to disconnect, move and connect TFOs/TFSs if target areas and substructures are available and appropriate. If not, the abovementioned works can be required.

It emerged from the interviews that Greenfields require a minimum of 33 months (2.75 years) to complete, and that the average time taken is 44 months (3.67 years). This is without site selection and processes that are required before site selection can take place. The interviews also showed that a duration of less than 30 months is hardly feasible for an automotive OEM plant which involves all sections, even if processes are performed in parallel and if TBSs are used. Brownfields often last longer than Greenfields, and numerous Brownfield cases that took 5 years or more were cited by the interviewees (particularly building displacements).

interview partner (IP)	IP1	Changes appear for sure within the three years that are required for a Greenfield. . . . An energy and media canal is the aorta of a plant. If it is disconnected, parts of the factory do not work anymore. Thus, a substitution process is required. One year is required to construct a new energy and media canal. Only then one can start with the actual work – to implement a new building (on top of the old canal). . . . The core grows to the periphery while non-production parts are displaced to the outside of the factory boundary.
(continued)		

interview partner (IP)	IP2	Many hundreds of thousands of truckloads and tours were required over a period of one year. . . . Minimum three steps are required: First, one requires a substitution process which means one constructs and installs what needs to be demolished. Second, the infrastructure needs to be installed and connected. Third, the old structures need to be demolished. Only then one can do what she/he wanted to do – for instance, to extend an assembly line. If one does it in a different way, it leads to a production stop. . . . Displacements take place very often when all areas are occupied. This applies to all factories which have no areas left. It happens in Greenfields that you need to demolish a wall or that lines need to be shifted, but in Brownfields, numerous moves take place which require demolitions of floors and foundations, even of buildings. . . . Several buildings were demolished and a new one constructed at the same place.
	IP3	Two years at least are required for the re-engineering of this press shop. New machines and new foundations will be integrated, and conveyors for the sheet cut and scrap. The problem, in this case, is that the transformation should be performed much faster, which is not possible at all due to several dominos . . . You cannot disconnect it just like that. First, the production must be ensured. I do not know yet if this can be done in our factory . . . This is a relatively simple case.
	IP4	. . . not required anymore as the requirements have changed. This leads to the worst case: You need to demolish the building.
	IP5	Five to six years are required to transform a factory for a new model. . . . These two buildings were demolished for the new body shop
	IP6	This Greenfield project has required almost four years (SME factory). . . . This building was demolished for the body shop.
	IP7	If I have free areas, I have fewer difficulties compared to the case that all areas are used. Without areas, we must demolish factory objects.
	IP8	The existing production needs to go on. This leads to long transformation durations and to building displacements if exchange areas are not available.

Numerous cases with displacements were revealed. Such cases belong to the daily business of factory planning for BFPS-4-factories and several BFPS-3-factories (the dilutive effect between BFPS-3 and BFPS-4 must be considered). Examples of 28 different real-world cases with extensive displacements (mainly building displacements) and different chainings were described, 3 of which are described next:

interview partner (IP)	IP3	real-world case in a BFPS-4-factory: It was required to demolish an on-site building (A) in which two departments (I and II) were located to enable a new construction of a building (C). This led to a domino effect with numerous displacements and moves. Following steps were required (simplified representation): 1a. construct a new off-site building for department I 1b. transform another off-site building (BFPC-E) to enable an off-site move of a third department 2a. move department I to the new off-site building 2b. move third department to the transformed off-site building to free the on-site building B 3. transform building B 4. move department II into building B 5. demolish building A 6. construct the new building C in the area of building A *Many more and further moves and displacements were required.* *Further details are not provided to protect the interviewee.* *Some elements were removed to protect the interviewee.*
	IP4	real-world case of a building displacement in a BFPS-4-factory: 1. one year master planning (plant development/general structure planning) 2. two years for the building and approval planning, and the building (new) construction (partly in parallel with 1.). 3. almost one year interior construction, installations/set-up (partly in parallel with 2.) 4. move-out (from the old into the new building) 5. demolition* of the old building (one year) 6. IP4: only then we could start the actually required work: to construct a new building (the planning and approval processes were done before in parallel) In sum: minimum 5 years *further processes are required
	IP5	real-world case of a building displacement in a BFPS-4-factory: This area was required for better things . . . We said that we demolish the procurement building and the production will be extended. . . . This, of course, led to a chain reaction of processes. . . . Before employees can move, one needs to construct a new building . . . which required two years. Afterwards, one can perform moves and demolish the old building and construct the new building. . . . This means a total duration of four to five years.

Building displacements have required approximately 4 years on average for their full completion; several cases have required 5 to 6 years. Some cases were so complex that a planning of up to 18 months was required before FPPs could be initiated. Displacements of smaller RFOs have required 4 months and of larger RFOs (e.g. middle-size presses) 6 months (average times without chainings etc.). If chainings etc. are considered, these durations are longer. Chainings also make it understandable why some Brownfields take more than 5 years to complete.

In combination with today's transformation requirements, heterogeneity is problematic for today's factories. This is because substructures, superstructures and 'sub- and superstructures' differ, while area and substructure characteristics are decisive for and have an impact on both transformability and FPPs. The same applies to the other fundamental enablers. In the case of today's factories, because there is no MAS(s) and because the mobility is limited to container sizes, the area size is significantly important; it is simpler to transform free areas than built-up/ overbuilt/covered areas. The transformability of inappropriate built-up/overbuilt/ covered areas is generally lower than that of free areas due to the presence of additional interfering inhibitors. Inhibitors impact negatively on transformability and FPPs. Long chains of sequential processes are crucial in this regard, and lead to extensive project durations and difficulty factors etc. IP8 argued that the transformability of areas is not sufficient and repeated this statement, adding that it can be seen in the living object (i.e. the factory) that this is the case and that there is no absolute flexibility and transformability today.

It is recognisable in the literature that area and substructure characteristics are important. The same applies partly to area shape and area size. It emerged from the interviews that the most important fundamental enablers are area and substructure characteristics, area size and the MAS. The following statements exemplify this finding, which is also validated through collisions, changes of uses and displacements:

		fundamental enabler 'area size'
interview partner (IP)	IP2	Free extension and exchange areas should be located between buildings. However, such areas also lead to problems such as longer distances and ways. . . . Areas should be as large as possible, but they should not be built too large due to cost and risk reasons.
	IP3	If you have no exchange areas, you are required to displace buildings. . . . An optimal factory is a factory in which one has huge areas and alternative or, in other words, exchange areas. . . . Doubling areas are very sensible. A Brownfield without exchange areas is problematic, as transformations must be performed within UHPs which must be demolished first.
	IP4	The area should be levelled and large without a river, mountain or tree. . . . Exchange areas are often required in the case of transformations. . . . One should have areas – healthy free areas to be able to rotate, to breathe. Which extension- and exchange-possibilities do I still have; limitations in both regards exist.
	IP5	A new construction at an exchange area is preferred in factory planning . . . It is not simple to find large areas. . . . If you do not have large areas, it is required to perform transformations within given structures and this is always bad. . . . It would be desirable to always have areas in the required amount, or to have a new factory. . . . Doubling areas are very important to enable an outstretching of the factory. . . . Difficulties occur if no exchange areas are available. This applies to the assembly shop including end-of-line due to the rain test and other fixed points. . . . Transformations within buildings are required if exchange areas are not available. This makes transformations difficult, if these are possible at all.
	IP7	Available extension areas, exchange areas, and building volumes are very sensible, as one can bypass many problems.
	IP8	Free areas are a desire.
		Please also consider the interview statements and information in subsection 6.3.1 and its appendices.

		fundamental enabler 'area and substructure characteristics'
interview partner (IP)	IP1	Objects and structures are firmly anchored within terrestrial areas. . . . The question is whether the building shell, substructures and the energy and media supply are appropriate if an object is moved. . . . You must dig up areas in order to change infrastructures.
	IP2	It is normal to change substructures. . . . One can excavate and relocate almost everything, but it cannot be planned because one never knows what will happen. If I have empty conduits, pipes or canals, I can of course include something, but I must have them in the right positions with the right characteristics. . . . Objects and structures in the area can hardly be transformed non-destructively. Machines exist which one cannot and does not want to relocate, especially if they go deep into the ground. . . . Everything that one brings into the area should be assembled or buried in a way that does not inhibit future transformations.
	IP3	The more is overbuilt or the more an object or structure is overbuilt, the lower the transformability of factories.
	IP4	Transformations naturally lead to infrastructure transformations. . . . A certain object can require more energy and another one less. This shows the requirement to have a transformable infrastructure. . . . Movable production cells can be shifted, but these objects also require s&d infrastructure connections and appropriate floor load capacities. . . . It considerably limits the transformability if an object is positioned in the area.
	IP5	The transformability of objects and structures in the ground is limited and demolitions are normally required in the case of their transformation. . . . Canals within areas are not transformable. . . . It was required to bring conveyors and media ducts into the floor. This led to displacements and new foundations were also required. There was no other option. The roof structure could not be used. To open the area and remove concrete structures was very laborious and expensive.
	IP6	Roads are constructed and not even six months later these roads are opened to include s&d infrastructures. . . . The soil bearing capacity for this building extension was insufficient. . . . Coupled lines and pipes in the ground can be used to a certain limit and grow afterwards stepwise. . . . Pipe-systems that are buried in the area are always fixed.
(continued)		

		fundamental enabler 'area and substructure characteristics'
interview partner (IP)	IP7	A foundation remains as it is and a reuse is rather difficult.
	IP8	Infrastructures do not fit anymore. . . . Substructures are, as a rule, not appropriate at the location of (e.g. machine) installation. . . . It would be beneficial if structures could be flexibly integrated into the substructure . . . Normally, we leave it where it is and include new pipes. Nevertheless, cases exist in which we need to remove large parts of the infrastructure.
	Please also consider the interview statements and information in subsection 6.3.1 and its appendices (and in subsection 6.2.1 and its appendices (e.g. about inhibitors and fixed points/RFOs/RFSs)). Contamination, archaeological finds, problems with groundwater etc. must also be considered.	

		fundamental enabler 'movable area size (MAS)'
interview partner (IP)	IP1	Buildings are constructed on solid ground with solid foundations. They cannot be moved.
	IP2	Almost everything is larger than containers. If one wants to move a building, she/he also needs to move the contents of this building. Today, this is not possible.
	IP3	It would be very sensible if objects that are larger than containers were movable. . . . The mobility of factory objects is very important, but limited today. . . . If you have no exchange areas, you are required to displace buildings. . . . In the case of a product model change, different machines and machine arrangements are required in the body shop. Therefore, exchange areas are required.
	IP4	It is not that nice if you construct a building for several million (Euro) and realise that its functions, dimensions, and location are not required anymore, as the requirements have changed. . . . One should have areas – healthy free areas to be able to rotate, to breathe. . . . The relocatability of objects and structures is desirable. Indirect functions should be close, but if more areas are required, they should be movable so that they can be shifted away. Other objects and structures must be close. Canteens must be reached within a certain timeframe and must therefore be located within a certain radius; the same applies to factory fire brigades. . . . Exchange areas are often required in the case of transformations.
(continued)		

		fundamental enabler 'movable area size (MAS)'
interview partner (IP)	IP5	Roads were widened. This required the demolition of adjacent garages and other buildings. . . . It would be sensible if buildings and building contents were movable. . . . It would be very good if buildings could be moved together with all their robots and other machines . . .
	IP6	It would be best if I could make a real area exchange, but on land – on the fixed floor – this is hardly possible.
	IP7	It would be sensible if factory objects and structures that are larger than containers were movable, especially as different departments and sections change. . . . It would be sensible if entire buildings were movable.
	IP8	Numerous free areas were heavily built-up with diverse objects and structures which were afterwards demolished to construct something new.
	Please also consider the interview statements and information in subsection 6.3.1 and its appendices (and in subsection 6.2.1 and its appendices e.g. about inhibitors and fixed points/RFOs/RFSs)). Furthermore, changes of uses (of areas), collisions and displacements must also be considered.	

Today's factories have limited transformability, implementation velocity and transformation velocity. The required FPPs appear to be outdated, particularly in the light of Industry 4.0-developments. As areas and substructures are not transformable, subsequent problems occur in any case. The following subsection demonstrates and validates the proposal that the capabilities (e.g. the transformability) of today's factories decrease throughout the BFPSs, whereas their complexity and the complexity of factory projects increase.

6.2.5 Application and Validation of the Model

Site selection is a form of site determination. Changing premises and conditions can thus lead to problems, while fundamental enablers are largely determined after BFPS-1. Factory relocations are thus not sustainable and lead to a high level of difficulties, efforts and wastes, because numerous FOs/FSs cannot be relocated (building substructures and s&d plants, for instance, are lost), while it is extremely difficult to find an appropriate location. The selected site and each factory configuration in BFPS-2, BFPS-3 and BFPS-4 determine the future transformability and transformation potential. Different sites involve different characteristics. Thus, possible factory configurations depend strongly on the location, site, and on decisions. Friese (2008) and other authors indicate that decisions are relevant to the transformability of factories; nevertheless, these authors do not consider BFPSs. The more a factory is built up and thus inhibited, the lower the transformability and the higher the risk of displacements etc.

Transformability is high at the beginning of a Greenfield project. Soft and hard key milestones decrease the transformability of terrestrial areas. With each milestone, a further restriction level is entered. Anticipations are replaced by reality-related data. The more a project progresses, the fewer the possibilities to implement this data without significant disadvantages in terms of costs, time, effort and resources; this is especially relevant for today's factories. The decrease of the transformability of today's factories is an effect that accompanies factory development (figure 55).

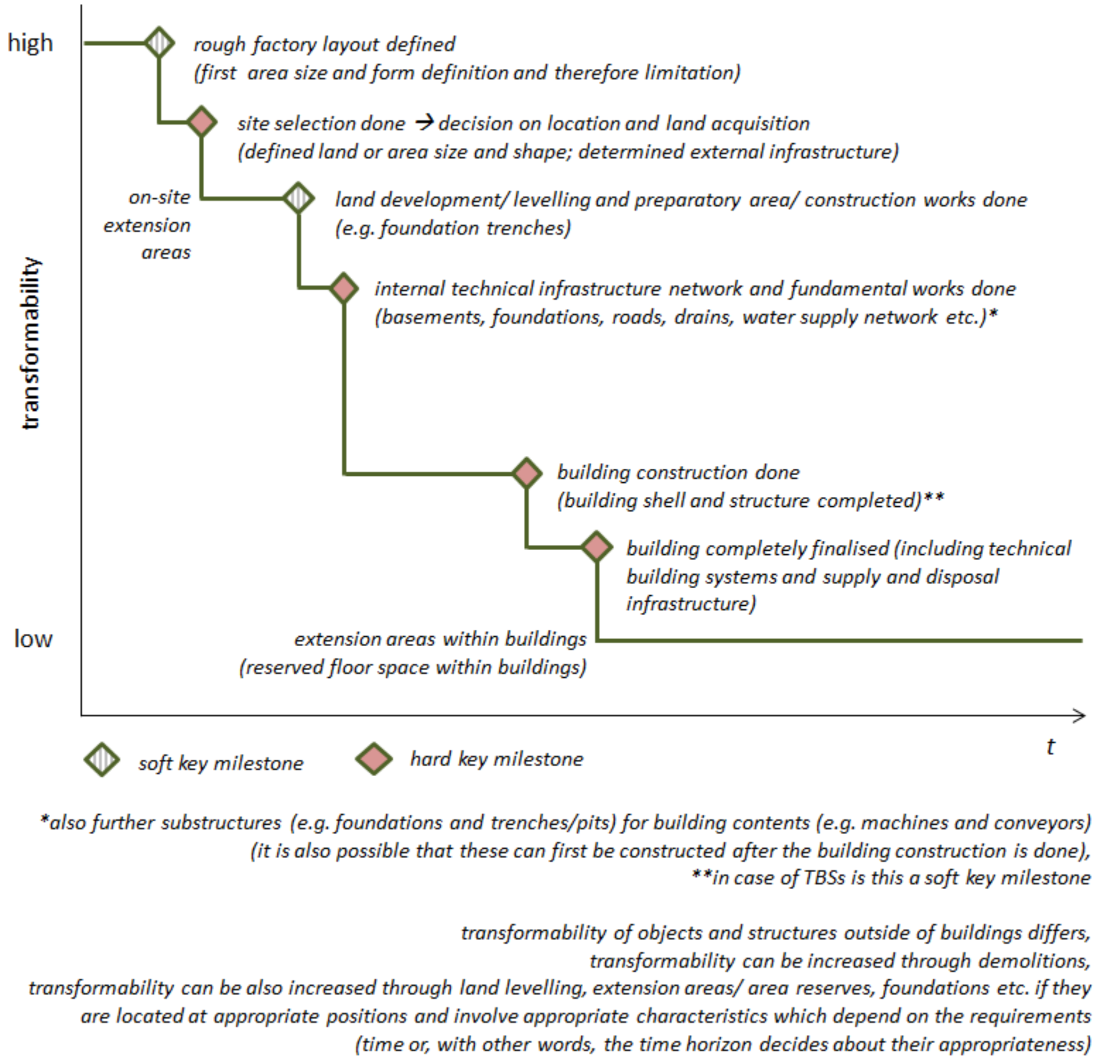


Figure 55: Decreasing transformability of today's factories (BFPS-1 and BFPS-2)

Over time, there is increased clarity about what is required to be done. New/changing transformation requirements and (quasi-)exceptional cases can determine this clarity. Unfortunately, the transformability of today's factories decreases with project progressions (at least from a medium- to long-term perspective). A finalised Greenfield configuration is hardly revocable.

Transformability decreases further with each construction (figure 56).

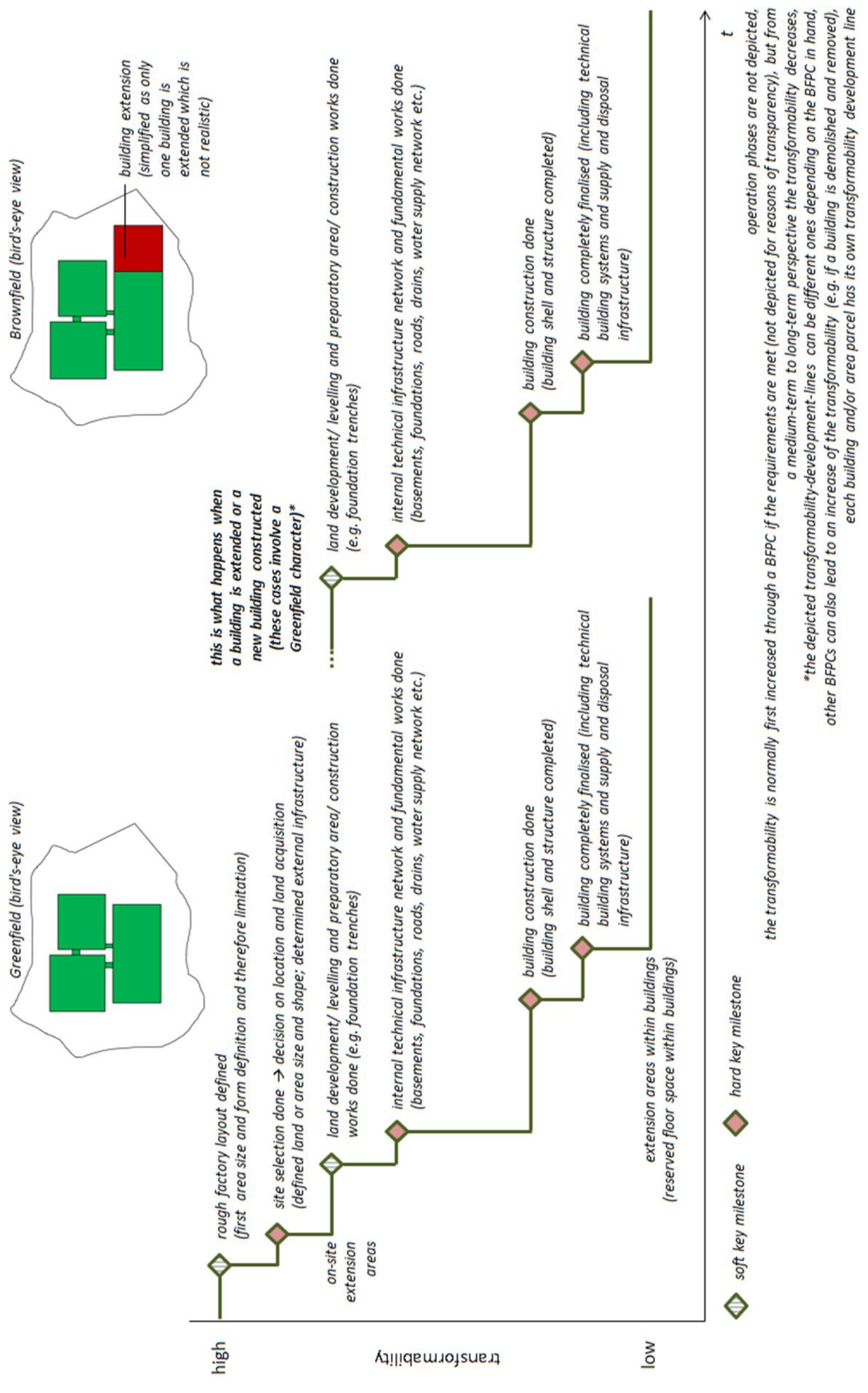


Figure 56: Decreasing transformability of today's factories (BFPS-3)

Other processes (e.g. non-material processes) follow these development lines, although in a different form. Premises and conditions can change (e.g. product requirements) after the initiation of purchasing processes or the completion of contracts. An often larger problem here is if incorrect FOs/FSs are implemented and/or if the area size becomes too small. Unfortunately, major factory configurations must be defined as early as possible in order to keep to project timelines. It is particularly problematic in late BFPSs that demolitions are often required to neutralise inhibitors and increase transformability (figure 57).

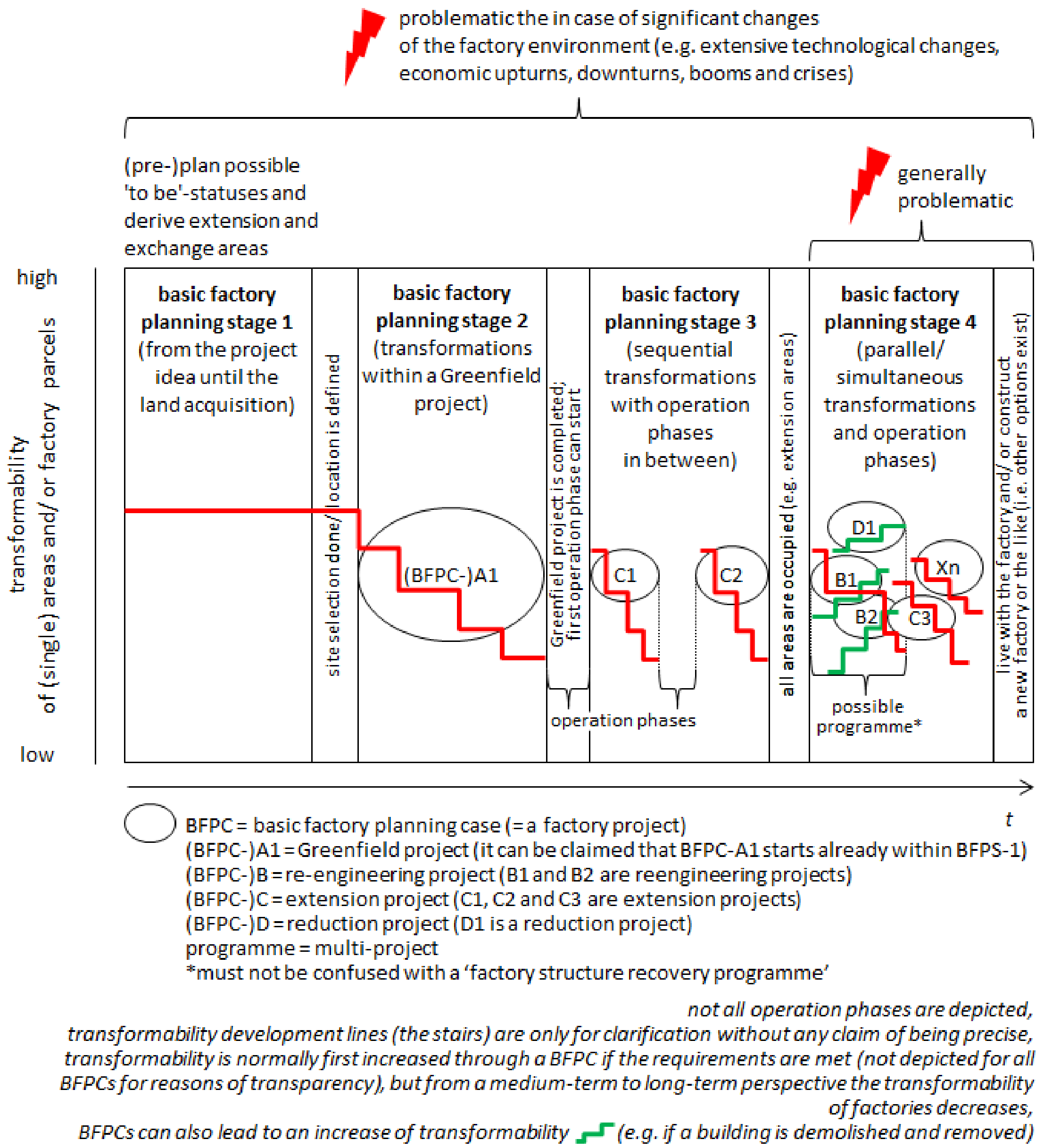


Figure 57: Decreasing transformability of today's factories (all BFPSs)

Overall, the transformability and transformation velocity of today's factories are low and decrease further throughout the BFPSs. This also leads to more and more factory structures and inhibitors, and today's factories become increasingly intertwined and encrusted to the point of total blockage (UHPs). Finally, the general structure is encrusted and transformational inability is reached. What is essential in this context is that earlier decisions and factory configurations are decisive for future ones. The following statements exemplify and validate the transformability-development throughout the BFPSs:

		transformability-development-related statements – BFPS-1
interview partner (IP)	IP1	A new factory should be implemented where the lowest labour and raw material costs are, and where the highest subventions and incentives can be received.
	IP3	It would be desirable that a factory always has an optimal location close to the market, and close to a motorway, railway, harbour, and airport.
	IP5	A Greenfield requires connections to rails, roads, electricity, and water, and needs to be close to a city as workers are required and as their ways to the factory need to be short.
	IP2	Site selection is one of the most important managerial decisions, as a factory cannot be relocated completely once implemented at a wrong location. . . . One goes there where as much supplier industry as possible is located, where as many people as possible live so that one has the required workforce, but simultaneously one wants to have a large free area, that cannot be found in such regions. This leads to the problem that one wants both but cannot find both. You can find one of these factors, but not the other factors.
	IP6	Site selection is decisive for the development of a factory. . . . If a factory is done and the market changes, a factory closure can be the consequence if the total costs are too high. *Information: This was said in the context of a real-world case.*
	Please consider the number of fixed points (i.e. RFOs/RFSs) and changes/changing transformation requirements.	

		transformability-development-related statements – BFPS-2
interview partner (IP)	IP2	You start with a white piece of paper, your Greenfield, with ideal processes, and then you build your adapted buildings over these processes . . . Displacements take place very often when all areas are occupied. This applies to all factories which have no areas left. It happens in Greenfields that you need to demolish a wall or that lines need to be shifted, but in Brownfields, it comes to numerous moves which require demolitions of floors and foundations, even of buildings.
	IP4	Project overlaps can be generally more easily solved if you have areas, compared to a factory in which all areas are occupied.
	IP6	If one excludes authority-related processes, such as approval processes, and area-related restrictions, it would be basically possible to achieve an optimal factory in a Greenfield. . . . Given building structures restrict you and predetermine possibilities.
	Please consider the number of fixed points (i.e. RFOs/RFSs) and changes/changing transformation requirements.	

		transformability-development-related statements – BFPS-3
interview partner (IP)	IP3	Exchange areas increase the transformability of factories. . . . A Brownfield without exchange areas means that transformations must be done within given structures which make transformations more difficult and partly not possible. If exchange areas are available one can implement a new production and demolish afterwards the old one.
	IP4	Exchange areas are often required in the case of transformations.
	IP5	Doubling areas are very important to enable an outstretching of the factory. . . . Transformations within buildings are required if exchange areas are not available. This makes transformations difficult, if these are possible at all. . . . A new construction at an exchange area is preferred in factory planning . . .
	IP6	Exchange areas are very important, as they lead to transformability and enable transformations which without these areas are not possible at all.
	Please consider the number of fixed points (i.e. RFOs/RFSs) and changes/changing transformation requirements. *Please consider furthermore what the interviewees said about areas in the context of the transformability of factories.*	

		transformability-development-related statements – BFPS-4
interview partner (IP)	IP1	Transformability is limited where areas are limited and where through permanent transformations within buildings and facilities the development went towards UHPs so that one is only able to perform future transformations through exorbitant costs. . . . The transformability of factories decreases when all areas are occupied. Everything becomes more static.
	IP2	When a factory has reached its capacity and area limitations, there is little remaining transformability. . . . When all areas are occupied, there is no capability to breathe and no optimal arrangement of areas is possible anymore, as no exchange areas are available to restructure areas. This thing (the factory) languishes. It can only be transformed in parts and not holistically.
	IP3	. . . the more one builds up, the worse becomes the transformability. . . . First, one must demolish something before a new construction can be done. . . . A Brownfield without exchange areas is problematic, as transformations must be performed within UHPs which must be demolished first.
	IP5	When all areas are occupied, this leads definitely to a UHP . . . (and to) massive changes and demolitions.
	IP6	Transformations can be disabled without exchange areas. . . . When all areas become occupied, either demolitions or a new Greenfield will be required.
	IP7	It is required to perform constructions around inhibitors . . . Demolitions are one option. Demolitions can be the simplest possibility if it is possible at all to perform demolitions . . . On the main axis, we have demolished X (two buildings) to extend Y (another building) and to construct Z (a new building) . . . Complex, as numerous outsourcings were required . . . will take long.
	IP8	. . . Then (when all extension areas are occupied) we talk about UHPs. Transformation possibilities are very limited in such a case. Transformations can be partly only done through demolitions before one can build something new. . . . These (BFPS-4-)factories are not viable.
	Please consider the number of fixed points (i.e. RFOs/RFSs) and changes/changing transformation requirements. Please consider furthermore what the interviewees said about areas in the context of the transformability of factories. Please consider that the number of complex real-world factory project cases and circumstances has increased together with the BFPSs.	

Following this transformability-development-related perspective, a complexity- and difficulty level-development-related perspective will be provided.

If there were no transformation requirements and/or if everything was homogenous, there would be no or very few problems with today's factories. Because most FOs/FSs are heterogeneous and because vast area and substructure transformation requirements occur, problems are pre-programmed. In the real world: (a) all possible difficulty factors occur; (b) domino effects/chainings and other difficulty-increasing events occur more frequently; (c) requirements of single incompleted projects change more often; and (d) the number of simultaneous projects and operation phases which impact one another and can also change increases together with the BFPSs (see subsection 6.2.6 for further details and evidence). The difficulties that real-world cases can lead to can be imagined by reconsidering mixed cases.

Today's factories' FPP-limitations lead to increasing difficulty levels throughout today's factories' BFPSs (figure 58). This indicates the impact and outreach of the 'limited and furthermore decreasing transformability (and transformation velocity) of today's factories' on FPPs.

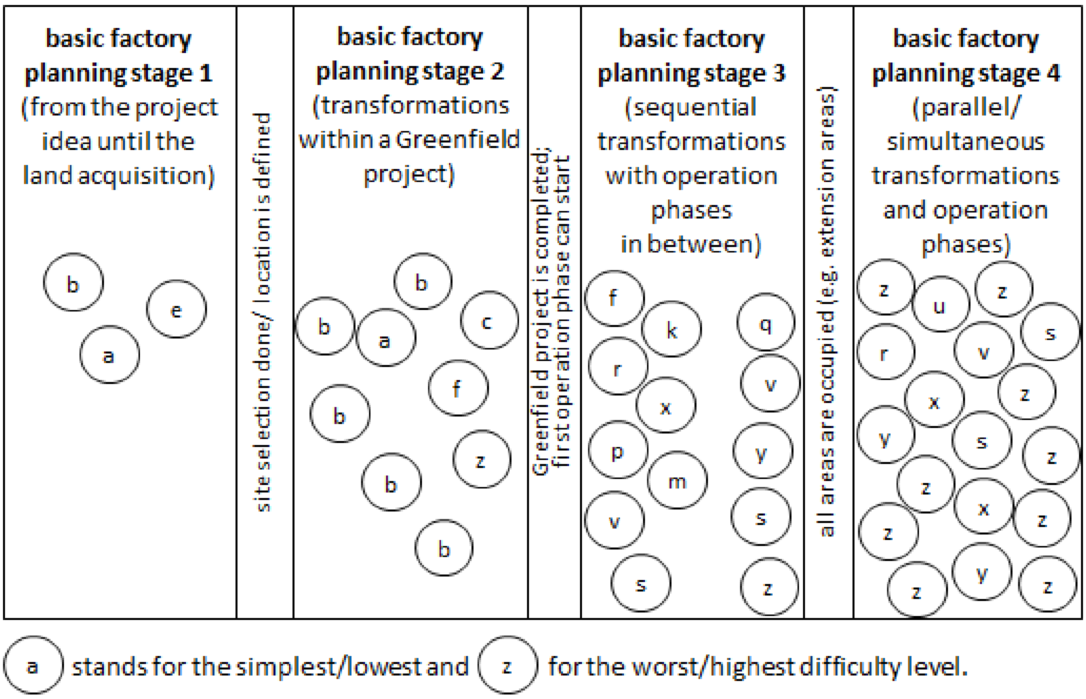


Figure 58: Difficulty levels of today's factories for each BFPS

BFPS-1 and BFPS-2 involve fewer difficulty factors and lower difficulty levels, but are decisive, while BFPS-3 and BFPS-4 lead to more difficulty factors and higher difficulty levels. Through the dilutive effect, difficulty levels in BFPC-3 can be as high as in BFPS-4. It can also occur that in BFPS-4, these are lower than in BFPS-3. Nevertheless, the dilutive effect is generally not involved in normal development.

Capacity increases, product model changes, production depth increases and factory structure recovery programmes require additional areas, and can lead to far-reaching difficulty factors and levels; these depend on the BFPS, e.g. only small or additional large displacements. Domino effects/chainings and other difficulty-increasing events can occur. If appropriate areas are in appropriate positions, this is not as problematic as when areas and FOs/FSs in BFPS-3 or FOs/FSs in BFPS-4 are not appropriate. The situations that mixed cases can lead to are already recognisable in the 'chaining examples' (appendix 6.1.10_05).

The evidence to this point validates the proposal that the location can be changed during BFPS-1 (and afterwards in any case) and that new requirements/changes can, as a general rule, be more simply implemented within Greenfields than within Brownfields. The following statements exemplify and validate the complexity- and difficulty-level-development throughout BFPS-3 and BFPS-4:

		complexity- & difficulty level-development-related statements – BFPS-3
interview partner (IP)	IP2	We still have areas and can extend the press shop. . . . Some demolitions will be required. A wall here and there.
	IP3	The older a factory building, the higher the roof and floor loads, as more contents are integrated.
	IP5	Transformations within buildings are required if exchange areas are not available. This makes transformations difficult, if these are possible at all. . . . Brownfields are the most challenging project types. These projects are much more challenging than Greenfields. King's class.
	IP6	This can be done. It would look different if there were no areas left.
	Please consider that the number of complex real-world factory project cases and circumstances has increased together with the BFPSs.	

		complexity- & difficulty level-development-related statements – BFPS-4
interview partner (IP)	IP1	The core grows to the periphery while non-production parts are displaced to the outside of the factory boundary.
	IP2	Displacements take place very often when all areas are occupied. This applies to all factories which have no areas left. . . . Efforts increase over time. These efforts depend on the factory structure. When the factory is completely covered, it becomes more and more complex to do a restructuring, particularly if no exchange areas are available. Then even for 200 m² you need a whole planning team. . . . The complexity of a factory generally increases when it grows.
	IP3	If you have no exchange areas, you are required to displace buildings. . . . The older a factory becomes, the more difficult become transformations, as divisions and especially departments need to move, as their areas are required for production purposes.
	IP4	Which transformation (in BFPS-4) is not problematic?/. . . . There are scattered functions, scattered functional areas and a lot of conveyors and interfaces when all areas are occupied. A factory is dominated by long distances which are spread all around.
	IP5	It is more difficult to perform transformations within given structures than with exchange areas. . . . When all areas are occupied, this leads definitely to a UHP.
	IP6	Several demolitions and new constructions would be required. The only sensible option is to find a new location with a larger area.
	IP7	If I have free areas, I have fewer difficulties compared to the case that all areas are used. Without areas, we must demolish factory objects. Projects in factories which have no areas left are always problematic.
	IP8	You recognise first during the project that you need to extend or supplement infrastructures. . . . Exchange areas increase the transformability of factories and if one does not have them, she/he needs to do a patchwork and extend single separated areas as required. . . . If one has no exchange areas, it is necessary to make add-ons, attachments, and patchworks everywhere. . . . It is clearly more complex to perform projects if there are no free areas. . . . There are permanent transformations. You just need to drive through this (BFPS-4-)factory – it is a disaster.
	Please consider that the number of complex real-world factory project cases and circumstances has increased together with the BFPSs.	

Complexity increases throughout the BFPSs. An increasing number of displacements occurs, as fewer free areas are available (all interviewees). Furthermore, displacements become larger (all interviewees). Other difficulty factors also validate this complexity increase. FPPs become more complex throughout the BFPSs.

In sum, the capabilities of today's factories decrease throughout the BFPSs, whereas their complexity and the complexity of factory projects increase. Decreasing transformability also affects complexity. This could be demonstrated through the model application.

It must therefore be well thought out if complex wide-ranging projects and programmes should be done at all, as these can lead not only to challenges and/or struggles, but also to chaos and/or disorder (appendix 6.2.5). In this context it must be considered that longer planning (including implementation/transformation) can possibly increase but generally decreases the clarity about 'what is required (what must be done)'. This is because an increased project duration increases the risk of new/changing requirements, and factory planners can lose themselves due to various reasons, which are explained further in subsection 6.2.6. Late BFPSs are dominated by so many different and unknown impacts (e.g. indefinable chainings) that several projects are currently either hardly plannable or not at all plannable and manageable. Furthermore, from a certain point in BFPS and factory status, it is not at all possible to define 'what is required (what must be done)', particularly in the case of complex wide-ranging projects, nor is the total effect/impact of these projects knowable. This makes such projects processible only step by step. Why this is the case is explained in subsection 6.2.6.

The contents of this and the previous subsections are also validated through the following subsection and its appendices.

6.2.6 Consequences

In addition to the data provided to this point in sections 6.1 and 6.2 (including their appendices), the interview data in this subsection and in the appendices of this subsection validates the identified consequences for today's factories.

All interviewees stated that site selection is essential for a factory and its future development. Burggräf (2012, pp. 46–47) acknowledges that decisions are crucial for the future of a factory. He mentions the dynamics of the factory environment, and indicates the location as well as FOs/FSs in this regard. IP8 argued that for site selection, the following requirements, besides others, must be completely appropriate:

- site characteristics
- external and internal technical infrastructures and s&d plants/systems
- time-related risks for approval processes
- the political situation/stability

A good location is also characterised by a low risk of natural disasters, low costs (e.g. for construction, production, logistics and labour), the availability of raw materials, proximity to appropriate suppliers, product and labour markets, appropriate fiscal framework conditions and the possibility of receiving high subventions and incentives.

The interviews provide evidence that it is difficult to find a good location. The requirements that cannot be met also change continuously. Thus, the best possible location changes over time, which demonstrates the importance of the outer mobility and transformability of factories and large FOs/FSs (appendix 6.2.6_01). It also emerged from the interviews that the acquisition of a huge site/area at an appropriate location very often leads to difficulties, even though a huge area is required and important (appendix 6.2.6_02).

Initial and previous factory configurations strongly determine possible future configurations, while all configurations are also determined by the selected site. Thus, future configurations are predetermined by BFPS-1 and BFPS-2 etc. The interviews showed that Greenfield changes also occur during the implementation phase, which can lead to demolitions, reconstructions and new constructions. Factory planning must begin long before the process is defined and before it can be implemented. Process planners are still in the concept phase when construction already takes place, without having all of the required data from the product and process (IP2, IP3, IP4, IP5 and IP8; the data of IP1, IP6 and IP7 also validates this). IP4 named several real-world cases and argued that Greenfield transformations are normal, which was validated by all other interviewees. IP3, for instance, mentioned column shifts and wall and ceiling breakthroughs in this regard. In order to appropriately synchronise factory and process planners, several processes must happen more rapidly, and transformability must be increased. Furthermore, (quasi-)exceptional cases occur, e.g. shortly after a Greenfield completion a total plant-reconstruction is required, as the market changes dramatically (IP7). Several comparable cases were provided by all interviewees.

FOs/FSs (including areas) must be in correct positions that have appropriate characteristics. It was clear from the interviews that the infrastructure can only be sensibly pre-defined to a certain extent, and this applies similarly to areas, buildings and other FOs/FSs. A maximum of two planned successive transformations (e.g. extensions) can be done without larger efforts and problems, and only if the market develops as forecasted, which is rather unlikely. After the transformations at the latest, larger efforts and problems occur. It also emerged from the interviews that more and more inhibitors arise throughout the BFPSs, and these lead to larger efforts and longer project durations. Furthermore, factories can become unstructured despite available areas, while displacements and project overlaps etc. also occur in these BFPS-3-factories (appendix 6.2.6_03).

IP8 stated that the available area size is a restriction, that they are permanently searching for areas in almost all factories, and that there are no remaining areas. The characteristics of BFPS-4-factories are poor (appendix 6.2.6_04). Thus, substitution processes and the pre-production and storage of parts are often not possible. It emerged from all interviews that building displacements are performed when today's OEM plants have reached BFPS-4, and that this also occurs in BFPS-3 (in BFPS-3 not always). Non-production buildings are displaced to the periphery (if possible and sensible) and/or outside the factory. IP8, for instance, argued that displacements are the normal case and claimed that one permanently thinks about outsourcing, while IP6 asserted that profit maximisation determines which processes are the most favoured ones. Production buildings are also displaced. Transformations in BFPS-3 and particularly in BFPS-4 can consequently be very challenging, while cases exist in which neither outsourcing nor displacements are possible, the same for substitution processes and the pre-production and storage of parts (appendix 6.2.6_05). It also emerged from the interviews that today's factories develop into UHPs if their lifecycles are long enough* (appendix 6.2.6_06) and that a Greenfield can at the soonest reach an ideal factory status, but even then not, and after the Greenfield not at all** (appendix 6.2.6_07).

* interview partner (IP)	IP2	This (BFPS-4-factory) is such a hut. If I take a look at these plans (factory layouts) at the wall I see only huts and a hut with some yellow streets in between. . . . There are already all these sheds and all these small huts which were constructed during the Greenfield for different purposes. This plant is already a UHP and will turn even more into one. . . . No areas are left and nothing at all can be done, as the structures are intertwined.
	IP3	All factories become UHPs.
	IP5	This is a chaotic plant (BFPS-4-factory). There is no exchange area, no area to stretch the factory out.
	IP6	UHPs can often be found. . . . All factories sooner or later become UHPs. Extensions play one role and transformability another role.
	IP8	This factory became a UHP as only reactions to current requirements took place. The factory was extended and transformed . . . The extension steps were too small to justify a factory doubling or a new factory. . . . Market changes and so forth make it impossible for automotive OEMs to plan in development steps. . . . All factories are meanwhile UHPs. Even some new factories are unstructured.
	Please also consider the other data that is provided throughout this document.	

** interview partner (IP)	IP2	The ideal factory is the best compromise. There is no 100%-solution but only compromises, as there are so many influencing factors and interests that one can never reach 100% but only compromises. We have an optimal factory when 80% of all single factors of our assessment system are fulfilled. We then have 100%. . . . You start with a white piece of paper, your Greenfield, with ideal processes, and then you build your adapted buildings over these processes. No, you cannot (have ideal processes). . . . You always deviate from the ideal process and somehow use the existing building structures, areas and sizes, and you adopt them. Thus, one is away from what is ideal.
	IP6	If one excludes authority-related processes, such as approval processes, and area-related restrictions, it would be basically possible to achieve an optimal factory in a Greenfield. . . . Given building structures restrict you and predetermine possibilities.
	IP7	A historically grown factory cannot be an ideal factory.
	IP8	Transformability is limited wherever spatially and historically grown structures are. Everything leads to UHPs. The factory gets larger and more unstructured and thus more complex.
	Please also consider the other data that is provided throughout this document.	

Next, development lines of the most important aspects are considered for each BFPS. The structure of today's factories is (usually) initially well-ordered and transparent. An effective arrangement and linking of FOs/FSs enables an efficient and green factory. The transformability of today's factories is enabled mainly through extension areas. Of particular importance is the transformability of the general structure. This has a special relevance with regard to multiple factory transformations, but decreases throughout the BFPSs (together with the transformability of areas). Consequently, the general structure becomes more and more stuck, becomes encrusted and finally reaches a state of a total blockage. Over the decades the general structure becomes almost deadlocked from a transformability perspective, and the mismatch between the real and the ideal factory becomes larger, i.e. the structure of today's factories becomes more and more disordered and non-transparent throughout the BFPSs. From an overarching viewpoint, this transformational inability of today's factories can only be resolved through demolitions (reconstructions and new constructions). However, with certain factory characteristics, even demolitions cannot help to avoid this status. In current times this is particularly bad due to an enormous complexity and constant changes of the factory environment, which lead to a complexity maze within today's factories that increases together with the BFPSs. Factories are always complex if analysed in detail, but this complexity is initially structured and involves well-ordered process flows. Therefore, factories are understandable and assessable, or relatively simple. The complexity of factories increases with the BFPSs, and reaches chaotic and disordered domains in which FOs/FSs are enormously convoluted.

The factory planning effort increases with the BFPSs, while the plannability decreases. Brownfield projects are more difficult to plan and carry out the higher the BFPS and the higher the unstructuredness, size and thus complexity of a factory; this also depends on other characteristics. Due to 'more numerous' and 'more complex' FOs/FSs, the definability of the 'to be'-factory status becomes increasingly difficult, while the reliability of anticipations is anyway low. The number and extent of conflicts and collisions between FOs, FSs, and FOs/FSs increases throughout the BFPSs, which leads to an increasing number of displacements. This also involves the FOs/FSs which must be implemented. Conflicts and collisions are also possible between projects and/or projects and FOs/FSs. The number of different inhibitors and the extent of intertwined structures (which are partly widespread inhibitors) increase together with the BFPSs. As 'more numerous' and 'larger' inhibitors are comprised by a factory over its BFPSs, 'more numerous' and 'larger' displacements and demolitions are required, while smaller displacements and other difficulty factors can also have extreme impacts due to domino effects/chainings etc. Thus, the transformation intensity and project durations increase, and both also increase due to an increasing number of simultaneous projects and operation phases. Simultaneous projects impact given FOs/FSs, and can impact on one another, while given FOs/FSs also impact these projects. Operation phases can also negatively impact transformations (and/or FOs/FSs), as operations can inhibit transformations and increase their duration and/or be negatively impacted by them (and/or by FOs/FSs). This can lead to inefficient processes and/or required operation halts and/or substitution processes etc. Transformations which last longer can also increase the ongoing (old) operation phase(s). If no substitution processes, pre-produced parts and/or outsourcing are available/possible but are required, a longer transformation can lead to longer (old) operation stops and shorter (new) operations, as the start of these is delayed. Impacts between operation phases and impacts between transformations can also occur. This reinforces why the factors described in subsection 6.1.10 can impact dramatically on factories. It becomes increasingly difficult to define projects and to delimit them from one another (e.g. as 'more numerous' and 'more complex' FOs/FSs are involved throughout the BFPSs), and thus to define programmes.

In parallel to these developments, transformability decreases and together with this the possibility of achieving an efficient and green factory also decreases. Figure 59 summarises developments and effects which come up throughout today's factories' BFPSs.

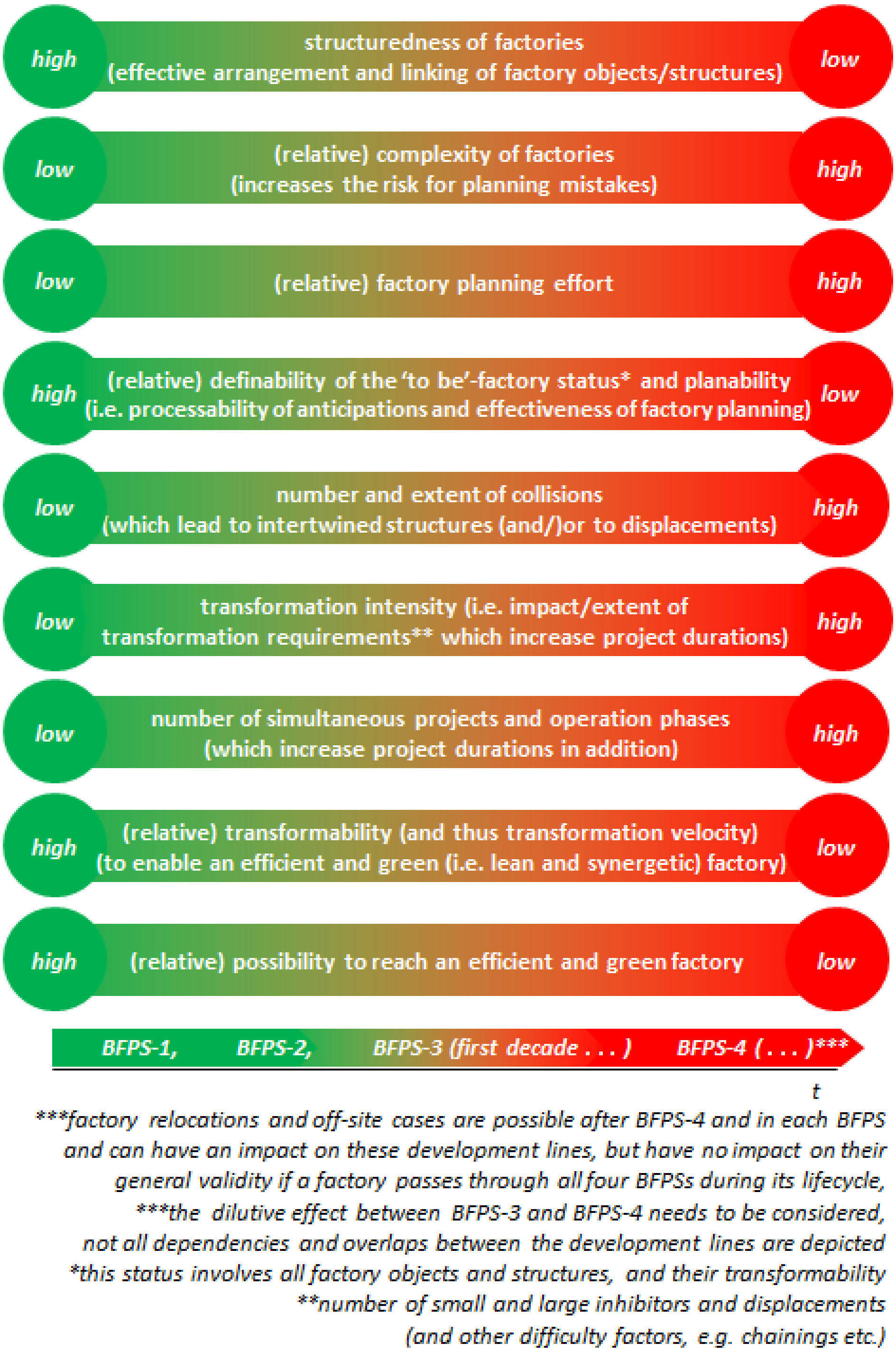
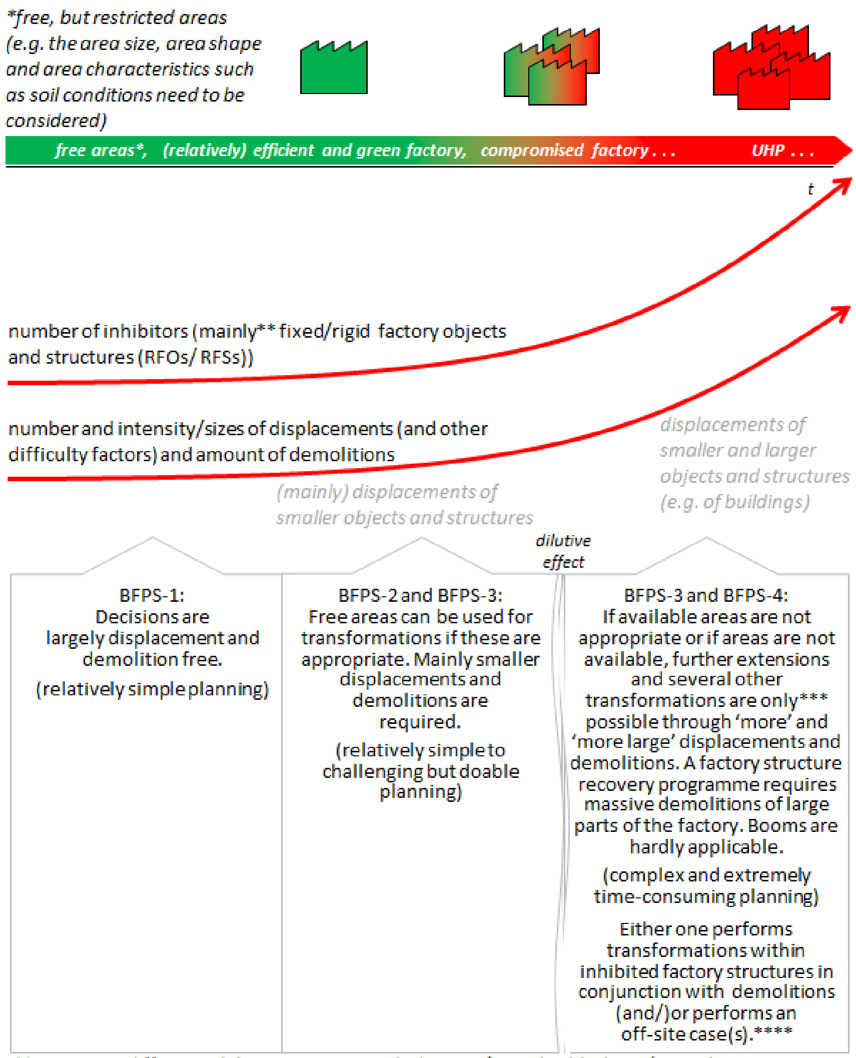


Figure 59: Development lines of today's factories and aspects relevant for factory planning

Furthermore, negative impacts (e.g. demolitions) of mutually exclusive but required factory configurations/statuses increase together with the BFPSs, i.e. a required quasi-ideal factory in t=1 inhibits required factories in t=3, t=5 ... t=n. In sum, this leads to vast demolitions.

This development of today's factories is mainly caused by immobile RFOs/RFSs. The root cause of this situation are terrestrial areas. Inhibitors increase together with the BFPSs. The entire factory, which is fixed from the start, turns little by little into a huge encrusted inhibitor – the UHP (figure 60).



***Numerous different inhibitors exist. Not only do RFOs/RFSs disable direct/immediate implementations and/or transformations. Other inhibitors exist (e.g. laws and regulations). TFOs/TFSs can not only be inhibited (e.g. through or in RFOs/RFSs or through or under soil, stones and the like); TFOs/TFSs can inhibit transformations too if they need to be implemented or moved/ relocated and no appropriate area(s) is available to enable such an implementation or move (or another transformation). When a RFO/RFS is located inside of a TBS or any other TFO/TFS, the transformability of the latter can decrease and make it inhibit transformations.*
Extension/exchange areas (i.e. areas which need to be kept free) are also inhibitors when it is desirable to use them and they cannot be used as they are reserved for another purpose(s). Such areas can lead to the circumstance that a factory is not as efficient before an extension or another transformation as it would be if these areas could be used (i.e. if FOs/FSs could be arranged more appropriately which means if there would not be the need to consider future transformations when placing them).
Whole buildings and even whole factories can become inhibitors. In such a case, several FPPs are required to perform a transformation. These objects and structures are consequently not non-destructively transformable once constructed. Furthermore, transformations can lead to a vicious cycle(s). It can happen that the 'as is'-status of a factory cannot be defined.
****but not always*
*****When a plant cannot be closed, one needs to live with it. When a new plant is constructed to replace an old one, old factory structures remain and cannot be used completely for a new purpose. New factories pass furthermore through the BFPSs and the same cycle starts again.*

Figure 60: Development of today's factories into UHPs

The more numerous the FOs/FSs (particularly RFOs/RFSs) and the worse the inhibitors (e.g. their dimensions), the more transformability decreases and the worse the situation becomes for today's factories and factory planners.

Thus, transformability decreases along with the increase of inhibitors. There are many inhibitors (e.g. foundations, s&d plants and other RFOs/RFSs) and these are also the results of FPPs. The number of small and large inhibitors, displacements and other difficulty factors such as chainings leads to high transformation intensity. Project durations increase. Through increased durations, the risk for changes and new additional projects and operation phases increases. These impact on given FOs/FSs, and can impact on old projects and operation phases and vice versa (consider simultaneous projects and operation phases). Transformation intensity and durations increase further, as does the risk of changes and additional new projects. This sequence continues and corresponds to a vicious cycle (figure 61).

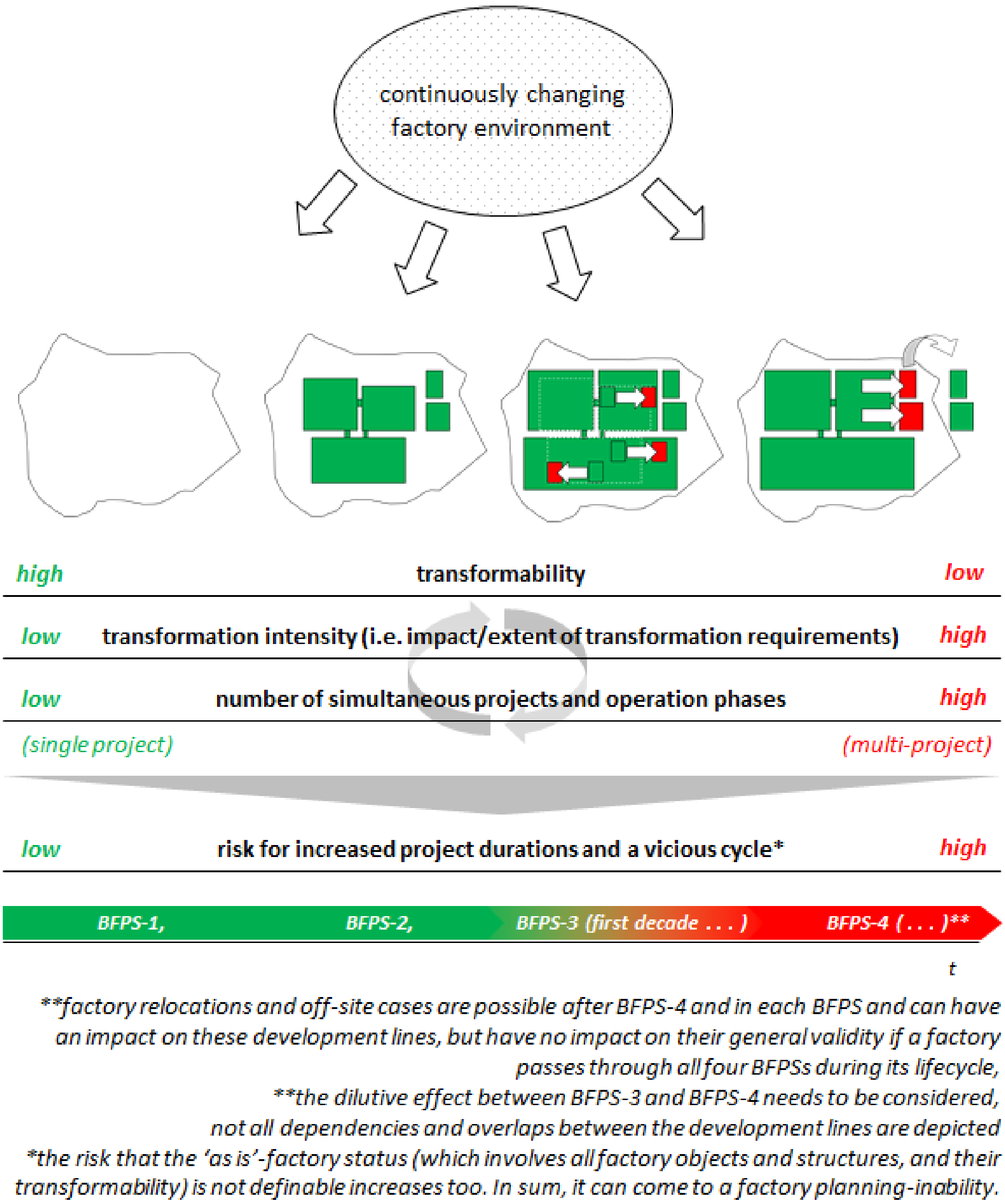


Figure 61: Planning inability with today's factories

Bottlenecks change continuously and are hardly tangible. Furthermore, there is a dilemma, particularly in late BFPSs: On the one hand, the requirement to plan in detail increases throughout the BFPSs. On the other hand, the necessity to quickly plan also increases, as physical works require more time and as it is more and more necessary to rapidly finalise projects due to the vicious cycle(s) and/or the circumstances which lead to it. Thus, longer planning increases the risk of changes, planning restarts, and vicious cycles, whereas shorter superficial planning increases the risk of planning mistakes and inhibitors. To begin transformations as early as possible in order to keep to the schedule can therefore be problematic, the same as when planning takes too long (or if a time schedule is prolonged, e.g. when the implementation of a necessary transformation requirement is postponed). Which of these options is more problematic depends on the specific case. Nevertheless, that the risk of planning mistakes can decrease with longer planning disappears more and more with increasing BFPSs.

As of a certain factory complexity, factory planners cannot have knowledge about which actions result in which consequences, while earlier initiated actions can impact negatively on new/changing transformation requirements. This leads to unclear and/or unknown impacts of new projects/FPPs and earlier started projects/ FPPs (e.g. in t=now and later; due to unmanageable complexity). When new transformation requirements occur before projects/FPPs have been completed, these can still impact the 'as is'-factory status. This means that there is then a risk that not even the 'as is'-factory status (or parts of it) is definable, which also decreases the ability to plan and also increases the risk of planning mistakes (as the ability to plan decreases and as the risk for planning mistakes increases anyway throughout the BFPSs). It is difficult, and it becomes more difficult to define the 'as is'-status and rather doubtful whether the 'to be'-status can at all be defined, which makes the delta between these statuses hardly definable or not definable. If a factory has reached a state in which not even the 'as is'-status can be defined, one is caught and stabs in the dark. This can also be the case if the 'as is'-status is clear, as the 'to be'-status is required in order to define the delta. This can lead to a situation where factory planners are unclear about which actions are required. This leads to 'planning inability' or 'hand-to-mouth planning'. 'Hand-to-mouth planning' is sometimes called 'agile project management' in factory planning, e.g. by IP8. The following points summarise why it can occur that not even the 'as is'-status of a factory can be defined:

a.	complexity of a factory (i.e. a factory's FOs/FSs) that is hardly or not tangible and therefore hardly or not definable*
b.	complexity of the transformability of a factory (i.e. the transformability a factory's FOs/FSs) that is hardly or not tangible and therefore hardly or not definable*
c.	impacts(/effects) of the own project which are partly undefinable
d.	impacts(/effects) of other projects which are partly undefinable
e.	changes/changing requirements which are unknown and cannot be known upfront
f.	the occurrence of a vicious cycle(s) and its impacts
. . .	. . .
Information: Both the desired 'to be' -status of a factory (or all impacted FOs/FSs) that needs to be implemented (and/)or transformed and the corresponding status of the transformability of this factory (or all impacted FOs/FSs) have to be anticipated, assessed and planned. This means that besides the 'as is' -transformability(-status) also the 'to be'-transformability(-status) needs to be assessed and planned in addition to the corresponding factory statuses. Please consider that it is hardly possible to impossible to define 'to be' -statuses of a factory.	

This can lead to a change of project leaders and to a planning change, which can in turn lead to great(er) chaos or disorder. Wrong actions can be initiated and can lead to system collapse. To return to a structured factory (throughout its structure levels) through a programme can therefore be hardly possible (consider also vicious cycles and nature-related, physical/chemical and human-related processes). A state of permanent transformation can hardly be ended without an off-site case(s). Nevertheless, transformability and outer mobility and transformability are very limited, which increases the difficulty of off-site cases.

It is not always true that a factory can be kept efficient through permanent demolitions, reconstructions and new constructions, e.g. due to project durations. BFPS-3 or BFPS-4 with an unstructured and complex factory is reached sooner or later. Factory characteristics can become so bad that projects cannot be appropriately managed and processed. BFPS-4 in particular is a black box from a project manageability perspective, which is undesirable as it encompasses permanent transformations (even if not necessarily in the same area). Furthermore, the risk of vicious cycles and the inability to define the 'as is'-factory status(es) are increased in late BFPSs. Besides the following interview data, the interview data in appendix 6.2.6_08 reinforces the statements in the above paragraphs.

In addition to the previously provided data, the following statements exemplify and validate the BFPSs, and their plausibility and rationality:

interview partner (IP)	IP1	Factories become stopgap solutions after several Brownfield projects. . . . Transformations within a factory in which the inner structure is covered through buildings are difficult. If one can keep the arrangement and order of production sections and still have areas, the factory could at least not become too worse. If factory structures are dense and narrow, the factory becomes worse. . . . Transformability is limited where areas are limited and where through permanent transformations within buildings and facilities the development went towards UHPs so that one is only able to perform future transformations through exorbitant costs.
	IP2	In an older factory, even small areas can be a problem and lead to further problems. Parallel projects lead to problems and substitution processes. . . . Efforts increase over time. These efforts depend on the factory structure. When the factory is completely covered, it becomes more and more complex to do a restructuring, particularly if no exchange areas are available. . . . The complexity of a factory generally increases when it grows. . . . Transformations become increasingly difficult as you do not have exchange areas. . . . To restructure the factory becomes increasingly difficult as you do not have an exchange area.
	IP3	The older a factory becomes, the more difficult become transformations, as divisions and especially departments need to move, as their areas are required for production purposes. . . . the more one builds up, the worse becomes transformability.
	IP4	Overlaps and collisions occur in Greenfields and the more the Brownfield, the stronger they become. . . . In an ideal case, when everything happens as assumed, the initial product and possibly also the successor product can be implemented, but afterwards, latest with the third product generation, it becomes difficult, even if one considers it upfront. Changes destroy the nice idea which means that other buildings are placed in between or that, due to cost reasons, interfering structures are constructed into the planned structures. If one takes a look at our factories, she/he realises that they are . . . cluttered up. After several years, one reaches area-related limitations or the product requirements change significantly. Thus, one starts to make compromises.
(continued)		

interview partner (IP)	IP5	The area gets narrower and narrower. . . . Factories become more and more built-up and inhibited. . . . Brownfields are the most challenging project types. These projects are much more challenging than Greenfields. King's class. . . . To perform transformations within given structures is more difficult than with exchange areas.
	IP6	Over time we had less and less space in this factory. . . . The required time increases through interdependencies. The more products and functions, which can compete, a factory involves, the larger the factory size and the more transformation requirements occur. Results are increasingly fixed conditions and restrictions within buildings. . . . The more a production capacity in a factory increases, the more are the limitations of the infrastructure hit. S&d networks in the ground are a big topic.
	IP7	Influencing factors increase throughout a factory life cycle.
	IP8	The number of projects and investment requirements increase over time. One must always accept compromises, outsource processes, rearrange objects and rebuild structures. It is always the same. . . . Transformability is limited wherever spatially and historically grown structures are. Everything leads to UHPs. The factory gets larger and more unstructured and thus more complex.
	Please also consider the other data that is provided throughout this document.	

Besides the previously provided data, the following statements exemplify and validate that the complexity in factory planning is not always manageable:

interview partner (IP)	IP2	It is often not possible to handle project complexities as required.
	IP3	During the planning process, one starts roughly, becomes more and more detailed and knows finally what is required and what is there. You cannot know this before. . . . Demolitions happen where the capacity limit is reached – it is a never-ending story.
(continued)		

interview partner (IP)	IP4	The complexity in several factories is not manageable. . . . The more projects are performed in a factory, the more difficult it becomes to take decisions at the right time and to define their impacts. The complexity increases extremely and often leads to second-best solutions. . . . To make this process lean is first possible during operation. You cannot know all influencing factors upfront. . . . How large can the area be at all, so that it can still be managed due to dimensions?/. As there are interactions and mutual impacts . . . There is a maximum factory size that should not be exceeded, otherwise, the factory is not controllable anymore.
	IP5	Cases exist in which the left hand does not know what the right hand is doing . . .
	IP7	Delays of single projects are not foreseeable . . . Product definitions impact on facilities and when changes occur this leads to domino effects. . . . It is known that several overlaps will occur, but this does not mean that these overlaps can be handled.
	IP8	There are numerous systems that show first during operation that they must be changed. . . . One experiences during a project that other dimensions and functions (than the planned ones) must be extended. . . . Agile project management (which is not dominated by a reliable planning approach, but rather by ad hoc-decisions) is the only possibility to handle complex circumstances in factory planning. This programme can only lead to chaos, and it can only be handled by means of agile project management, which means only by using real-time decisions and improvisations – there is no other possibility.
	Please also consider the other data that is provided throughout this document.	

Factory and transformation requirements can hardly be identified and defined. Required transformations/FPPs and their impacts (e.g. chainings) are rather unassessable, indefinable and unprocessible. These depend on the ‘as is’- and ‘to be’-factory status(es), and on decisions which are made against the backdrop of numerous influencing factors, of which not all are depicted in figure 62. The total benefit is already lost at the point where the decisions are made. Furthermore, human minds cannot sufficiently consider the revealed relevant aspects (e.g. in section 6.1), even if all of them are explicitly known. To use algorithms is not sufficient due to (a) the required amount of data and its complexity (e.g. complex and partly indefinable interconnections), and (b) nature-related, physical/chemical and human-related framework conditions and processes (consider also what has been said about parameters). Factory planning is also dominated by subjective and partly irrational decisions and human-controlled processes. This leads to hand-to-mouth planning, and explains why projects are hardly manageable. The recognition of factory implementation and transformation requirements (i.e. the relevant points in time and required implementation and transformation scopes) is also questionable. The question is, who brings these requirements in, when, and how.

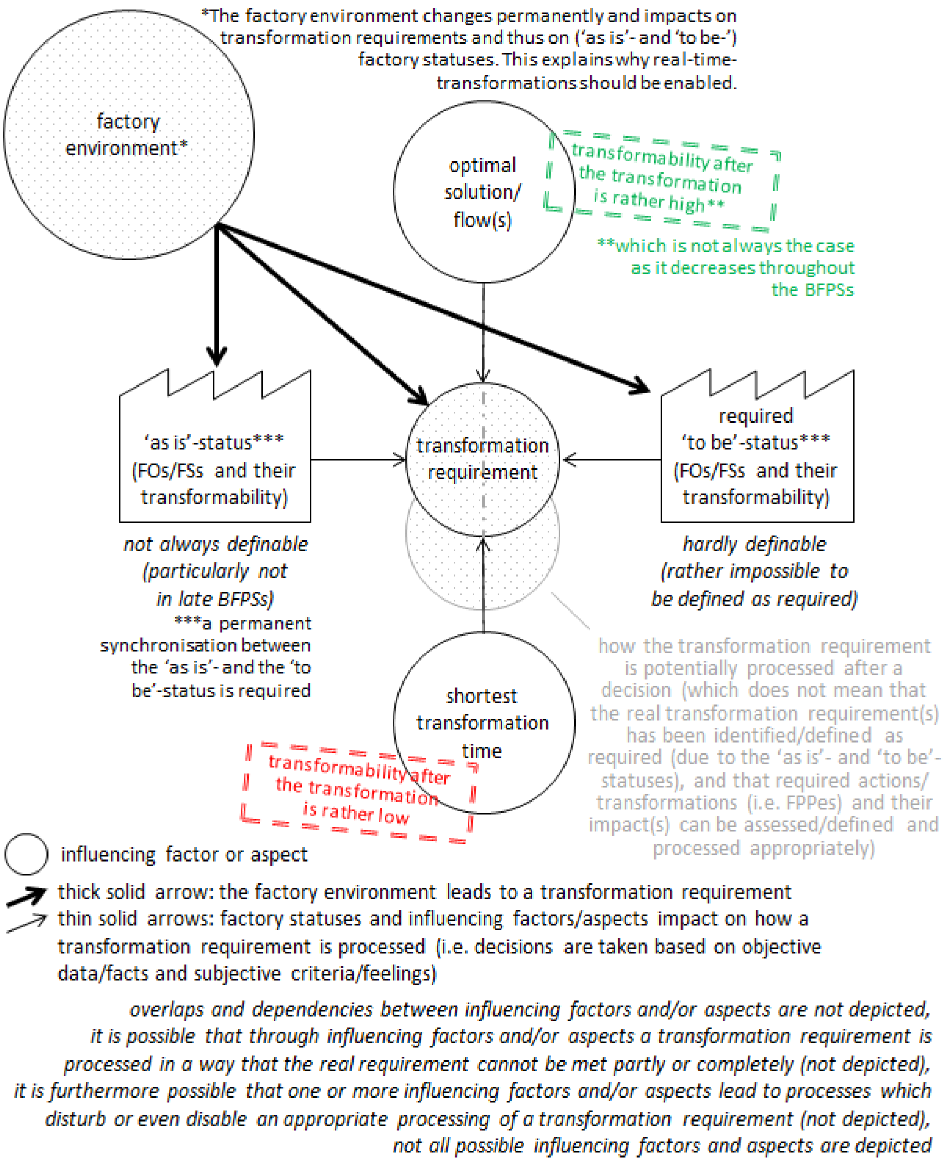


Figure 62: The pain of choice

An optimal solution/flows in late BFPSs can only be achieved if one stays largely with what was planned. Transformability can increase at this very moment, but decreases with the next transformation requirement that cannot be absorbed. At the beginning of a factory lifecycle when areas are still available, one can either choose between an optimal solution/flows and a fast transformation or something between these two which meets the reality soonest, or even reach both targets at the same time, e.g. through a building new construction in a free area. The ability to reach optimal solutions decreases together with the transformability throughout the BFPSs, while project durations increase. Finally, optimal solutions can neither be reached nor fast transformations performed.

BFPS-1 is decisive for today's factories, while transformability and other factory capabilities and characteristics become negative throughout the BFPSs. Unreliable forecasts dominate decisions and are decisive for the development of today's factories. Decisions that are made are also relevant to their transformability, particularly because of the limited transformability of areas.

Today's factories are furthermore dominated by:

- less efficient processes and flows (compared to TFCs)
- unexploited potential for synergies
- low flexibility and transformability, which decreases over time, while factory configurations exclude one another (at least to a certain extent)
- low definability of real factory requirements and required FPPs
- investments which are mainly bound
- unsustainable structures which experience huge demolitions, reconstructions and new constructions

The danger of vicious cycles and situations in which not even 'as is'-factory statuses can be defined make the unacceptability of today's factories complete.

The importance of operational planning for short-term transformations has been described by Kirchner, Winkler and Westkämper (2003). The full benefit of such operational planning can be gained if short-term transformations of factory structures are enabled. Today, terrestrial areas disable short-term transformations. Moves/relocations of RFOs/RFSs are not possible without demolitions, while TFOs/TFSs provide only minor advantages within today’s factories. An alternating and breathing factory is not possible because the active transformability of terrestrial areas is impossible. Thus, the transformability of today’s factories is largely disabled.

The limited and furthermore decreasing transformability of today’s factories is mainly caused by the insufficient transformability of terrestrial areas, which is the root cause of this and for the advancement of the other development lines. Moreover, knowledge about the future would not lead to considerable advantages, at least not from a perspective that involves FOs/FSs (consider that different factory configurations exclude one another). This has not been considered to the required extent.

Unknown future transformations of ever growing factories which increase in complexity against the backdrop of ‘lifecycles greater than 10 years’ and ‘steadily decreasing transformation cycles’ (i.e. the number and frequency of transformation requirements and transformations increase from an entire factory-related perspective) cannot be handled adequately, as areas and substructures are often impacted. This shows the limitations of today’s factories and the limitations of factory planning theories and Industry 4.0.

Today’s factories only partly meet changing transformation requirements, and only at some points in time (different transformation requirements occur over time, and these can change). These circumstances lead to considerable efforts, delays and costs that are hardly or not at all plannable, as well as to changes of already implemented FOs/FSs, and to suboptimal planning and factory solutions. The presented development lines explain why projects are often delayed and overrun their budget. The consequences of the use of today’s factories are decreasing lifecycles of FOs/FSs. Demolitions, reconstructions and new constructions make today’s factories unsustainable. Transformation requirements and changes are implemented against the backdrop of what is possible and reasonable at that particular point in time, because black box factory planning cannot be completely illuminated (particularly not with today's factories) and because of human behaviours. The more inhibitors there are in a factory and the worse these are, and the fewer areas that are available, the worse the impacts of the continuous changes in the factory environment. Area (and space) limitations are a problem for forthcoming transformation requirements. Difficulty levels increase throughout the BFPSs, while the possibility of implementing transformation requirements decreases.

The importance and significance of areas and area requirements are far too underestimated in the factory planning literature. In late BFPSs, area requirements cannot be fulfilled with terrestrial areas as required. Areas and substructures and their characteristics are considered in factory planning, but their importance and significance and particularly the requirement for transformable areas have not been recognised. Terrestrial areas limit the transformability and implementation and transformation velocity of factories, which was demonstrated through transformation enablers/units, accelerators/acceleration units and fundamental enablers. The impacts of the limited and furthermore decreasing transformability and transformation velocity of today's factories within each BFPS emerged from the interviews, and this has also been demonstrated through the application of the model and the concepts. Transformation intensities and difficulty levels increase further and further, and factories finally reach a transformational inability. Why today's factories develop into UHPs has been explained, as well as the factors which lead to chaos and disorder.

In BFPS-1 and BFPS-2, transformability is relatively high and decisions can largely be freely made. Transformability decreases throughout BFPS-3 and BFPS-4, which is problematic as displacements and chainings etc. occur more often. BFPS-4-factories are almost always problematic, and also BFPS-3-factories if they are huge and unstructured and thus involve a certain complexity which is also influenced by other factors. The perception of all interviewees that transformations always occur in some BFPS-3-factories and almost all BFPS-4-factories is consequently understandable. The same applies to the idea that the importance of transformation enablers/units, accelerators/acceleration units and fundamental enablers increases throughout the BFPSs if the importance of these concepts for factory implementations is excluded (figure 63).

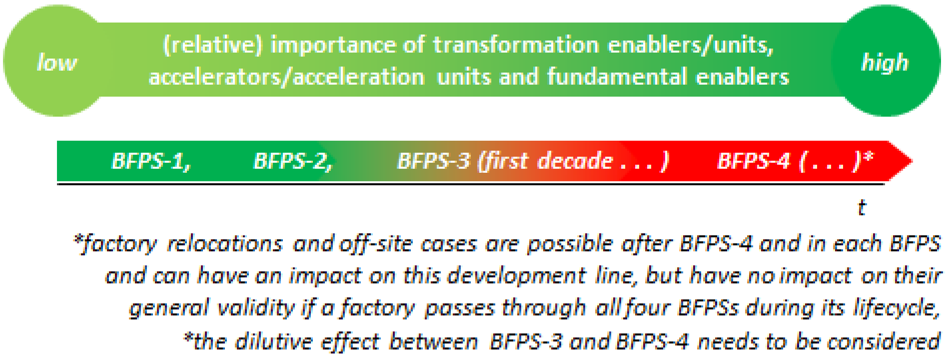


Figure 63: Importance of applied concepts throughout the BFPSs

Transformability and implementation and transformation velocity requirements remain unfulfilled. Fast market (re-)entries are important, but the probability of having them is low, and this decreases throughout the BFPSs. Transformability decreases throughout the BFPSs and factories become less efficient and green. What is most important is that it is neither sustainable to use today's factories with suboptimal flows nor to perform demolitions, reconstructions and new constructions. A part of 'black box factory planning' may have been unveiled in this work, and this makes today's factories shine in a very bad light.

6.2.7 Summary and Conclusion

The results of section 6.2 are particularly substantiated through the interviews and the application of the developed model and concepts (which were themselves developed mainly based on the interviews).

The importance and functionality of the model and associated concepts were validated through their application and through the interview data. The capabilities and limitations of today's factories were researched and assessed. Thus, RO2 was achieved. RO1 will be fully achieved when the model and associated concepts were applied to TFCs.

This section shows that the limited transformability and other capabilities of today's factories decrease throughout the BFPSs (i.e. when areas are built-up/overbuilt/covered), while the complexity of today's factories and factory projects increase. The number of transformations increases. Chains of sequential processes become more difficult, effortful, time-consuming and expensive throughout the BFPSs, which increase(s) project durations and the unsustainability of today's factories, also as more and more demolitions, reconstructions and new constructions are required. Transformations that occur more often and have additional and larger impacts throughout the BFPSs call for a substantial change in factory planning, especially if transformability- and complexity-development are taken into account. This is because quantities and sizes of displacements increase for instance, as does the number and impacts of chainings etc., while transformability decreases.

This section demonstrates even more that the benefits of scenarios in factory planning are overrated, and that their functionality is highly questionable. Scenario planning, factory planning theories and Industry 4.0 require a rethink. Today's factories are not at all sustainable and environmentally friendly when their (structural) lifecycle (e.g. greater than 20 years) is considered. Lifecycles of different factory structure levels and FOs/FSs (including areas) must be synchronised in order to avoid major destruction. This can only happen if areas are made transformable, as transformation cycles disrupt their lifecycles and the lifecycles of other FOs/FSs.

Table 21 summarises how the interviewees viewed the most important topics and concepts. Along with the data in the following sections, this also shows that the developed transitions and further research results are valid and reliable.

described topic/concept(s)		views of the interviewees							
		IP1	IP2	IP3	IP4	IP5	IP6	IP7	IP8
	transformability of today's factories	●	●	●	●	●	●	●	●
	transformation enablers and units*	●	●	●	●	●	●	●	●
	accelerators and acceleration units*	●	●	●	●	●	●	●	●
	fundamental enablers*	●	●	●	●	●	●	●	●
	resulting factory planning processes (FPPs)	●	●	●	●	●	●	●	●
	transformability-development throughout the BFPSs	●	●	●	●	●	●	●	●
	complexity-development throughout the BFPSs	●	●	●	●	●	●	●	●
	further developments and changing impacts of projects	●	●	●	●	●	●	●	●
	cases in which complexity was hardly or not manageable	●	●	●	●	●	●	●	●
	requirements and desires (see particularly section 6.3)	●	●	●	●	●	●	●	●

● emerged completely from the interview and/or has/have been fully validated

*Not all enablers, accelerators and units were considered to the same extent in each interview. Nevertheless, the description/explanation of related and other data provided sufficient evidence that ensures the validity and reliability of these table contents.

This table does not differentiate explicit and implicit/tacit knowledge.
All these topics and concepts are furthermore validated throughout the following section.

Table 21: Expert views sections 6.2 and 6.3

In the light of this background, it is reasonable to ask why we still use today's factories when better solutions are possible.

"We build but to tear down. Most of our work and resource is squandered. Our onward march is marked by devastation. Everywhere there is an appalling loss of time, effort and life. A cheerless view, but true."

Nikola Tesla

The limited transformability of terrestrial areas has been identified as the root of the main problems in factory planning; this is not acknowledged in the factory planning literature. One of these problems is the limited transformability of today's factories, and this transformability decreases throughout the BFPSs. Different factory configurations exclude one another, and movements (position changes) of FOs/FSs are required over time, while location changes can be required. Demolitions, reconstructions and new constructions are outcomes of these occurrences, which is undesirable.

The importance and significance of the transformability of areas and of fast implementations and transformations was substantiated in this section. Industry 4.0-developments lead to advantages, but what we also require is transformable areas. This is verified in the following section.

6.3 Results Relevant for TFCs

This section is concerned with TFCs.

Subsection 6.3.1 is concerned with the TAS-requirement profile. In subsection 6.3.2, transformation and fundamental enablers are applied in order to specify transformability-related capabilities and limitations of TFCs. Accelerators and fundamental enablers are applied in subsection 6.3.3 in order to specify FFP-related capabilities and limitations of TFCs. Under consideration of the contents of section 6.1 and subsection 6.3.1, the application of these concepts results in FPP-related information that is specific to TFCs. Thus, subsection 6.3.4 summarises the contents of the previous subsections and provides a transition to subsection 6.3.5, in which the model is applied to TFCs. First, the development of the transformability of TFCs throughout the BFPSs is considered and explained, and followed by examination of the development of difficulty levels throughout the BFPSs. It is then clear which difficulty factors and levels are specific to TFCs for each BFPS, and how these can be handled within each BFPS. Subsection 6.3.6 describes the consequences for TFCs, while subsection 6.3.7 summarises and concludes section 6.3.

This section involves real-world interview data about desired and required factory characteristics and capabilities. These data especially demonstrate the importance of fundamental enablers, and thus which TFC-capabilities are advantageous and required. The resulting consequences in terms of TFCs' characteristics and capabilities throughout the BFPSs are crucial. These consequences show that the complexity in factory planning can be better managed and also decreased with TFCs.

6.3.1 TAS-Requirement Profile

The interview statements at the end of this subsection exemplify the most important contents of the appendices to section 6.3, and exemplify and validate the importance of fundamental enablers in addition to the previously provided data.

This subsection shows what TASs must be capable of. It emerged from the interviews that all FOs/FSs should be modular and mobile/movable. Moves/ relocations of small and large FOs/FSs are required, e.g. small and large areas and substructures, buildings etc. To move/relocate superstructures together with their substructures and areas must be enabled. TAS-elements must be pluggable with one another and enable a coupling with building structures, building contents and other FOs/FSs (appendix 6.3.1_01). This enables a transformable layout/general structure which is scalable and linkable.

Further capabilities of TASs/TFCs are required. If no substructure-spaces are available, more interfering contours in superstructure-spaces are the consequence (at least very often). TASs must provide additional spaces and have at least one functional layer for substructures. Thus, interfering contours can be distributed through the '(transformable) area content integratability', which enables the transformation of substructures as required. Structures of TAS-elements can be optionally and additionally transformable (e.g. exchangeable floor plates with or without openings/pits and/or different thicknesses for different loads, and walls in which elements with openings can be exchanged), which is not necessarily required due to MASs. It is anyway possible to construct TAS-elements with large openings (e.g. in walls), which enables a certain flexibility. TAS-elements are consequently universally usable and their inside/inner contents transformable without prior structural TAS-element transformations/customisations, which does not necessarily mean that these contents must be oversized and/or lead to less efficient processes. Structural transformations/customisations of TAS-elements are also possible. Both standardisability and transformability/customisability are not separated but are combined in one system, which unlocks the possibility to comprehensively implement ‘transformable standardisations’. It emerged from the interviews that areas and numerous substructures should be accessible and walkable by people (this will be less required in future if one considers, for instance, robot capabilities and their developments), and that it would be advantageous to integrate as many tier-1 suppliers as possible in one location if the area was to be transformable (appendix 6.3.1_02).

Overall, TAS-elements must be a ‘transformable substitute’ for terrestrial areas, substructures (e.g. foundations and pits) and transportation infrastructures, and also comprise different substructures if required, e.g. supply lines. Inner transformability is required to a certain extent, and this is possible. The formation of large areas and their mobility/movability are required. Moreover, a consistent and known area quality is desired by the interviewees, which is possible as area and substructure characteristics are largely definable. To have different TAS-element sizes in X and Y is advantageous but is not necessarily required. This requires further analyses with regard to different parameters such as masses, dimensions, moments of inertia etc. The X- and Y-sizes of single TAS-elements can be different, but should be based on a common factor (the largest TAS-element should be a multiple of the smallest). Different sized TAS-elements can be plugged and unplugged many times as required, which enables free configurations. Free areas on the site and in buildings are required in order to enable movements of single and combined TAS-/ TFC-modules. To submerge marTASs can lead to advantages in this regard. In the case of terTFCs, a certain area should be kept free for larger transformations, e.g. building moves. MarTFCs also require free open areas for the water ecosystem (consider light), and environmental risks must be prevented (this applies to all TASs/ TFCs). TASs/TFCs support the maintenance of heterogeneity and thus the efficiency of factories, as the arrangement and linking of all FOs/FSs can take place as desired/required, but which can lead to the requirement to change a TAS-element(s) and/or combinations of TAS-elements which carry FOs/FSs.

Factories are long-term investments and must be of high quality and transformable (IP6 and IP7). IP3 emphasised the use of recyclable materials for FOs/FSs. The reuse of FOs/FSs is rather possible and more likely if these are transformable and of high quality, as new/changed characteristics/elements and/or functions/technologies can be more easily integrated and exchanged. Reusability increases sustainability; thus, transformability increases sustainability. FOs/FSs and consequently factories must be sustainable and thus be of high quality, transformable (at least mobile/movable and usable in another position/location), reusable and preferably produced out of recyclable material. The same applies to TASs. In the case of today's factories, these requirements are not actually pursued, except for some available TFOs/TFSs. IP1 argued that the sustainable development of factories is important in the light of global resource consumption, but also stated that quick profits are in the foreground. IP6 talked about a short return on investment, IP8 said that the return on investment is one and a half years and IP7 that there is no long-term thinking today, as it is not in the interest of companies. Today's transformations are mainly unsustainable. Because one cannot forecast what will be required when and where, and because the capabilities provided by available TFOs/TFSs are marginal compared to other unavoidable works, attempts are made to keep the costs of expensive factory solutions as low as possible (this refers primarily to initial investments). Transformable, reusable and recyclable high-quality long-term investments therefore hardly have a chance. This is understandable, as they do not provide a panacea (not without TASs). Furthermore, the importance of transformable areas has not been recognised, despite practice-related knowledge and experience. This knowledge is recognisable in numerous interview statements such as the statement of IP6, who claimed that relocations of FOs/FSs are part of the daily business.

A key that can unlock the widespread use of sustainable solutions is the use of TASs. TASs provide a modular area that is combined out of single TAS-elements instead of solid ground, foundations etc. Compared to terrestrial areas and terrestrial area-based FOs/FSs, significantly increased area-, sub- and superstructure-transformability can be achieved. Autonomous movements are possible, and the possibility for a self-sufficient operation is increased. RFOs/RFSs are immediately transformable (at least movable/mobile), which increases sustainability. The requirements in this subsection can be met with area systems. This is particularly the case when their advantageous capabilities and those of other systems, which can be combined with area systems, are considered in their further development. Thus, terTFCs and marTFCs can be made possible. Nevertheless, TASs – particularly terTASs – must be further developed and specified. Ground levels, for instance, must have the same levels and there should be no levelling- and height-problems with TAS-elements inside and outside of sections. Information about terTAS design options, terTASs beside waters and TAS hybrids, which lead to a dilutive effect between terTASs(/TFCs) and marTASs(/TFCs), are provided in appendix 6.3.1_03. TAS-substructures provide the bases for TAS-elements, which are relevant for all terTASs/terTFCs. Generally, one TAS-substructure can be provided for several sections, while it is also possible to separate them and to provide one or more TAS-substructures per section. The following subsections and sections consider terTFCs, terTFCs beside waters (terTFCs_bw) and marTFCs.

The following tables are concerned with area and substructure characteristics, MASs and the importance of MASs, as sufficient information about the area size and shape has already been provided.

		fundamental enabler 'area and substructure characteristics'
interview partner (IP)	IP1	Buildings, facilities, and infrastructures must be more transformable. Furthermore, simpler changes of uses and a more flexible use of buildings are desirable.
	IP2	It would be good if it were possible to retrofit or implement additional s&d infrastructures.
	IP3	Areas should not be contaminated. Furthermore, areas should be levelled and have a sufficient floor load . . .
	IP4	The supply of production cells with energy and media is often provided over the roof structure, which is not as ideal as if it would be possible to go through a transformable ground. If I go over the roof, I must first get to the roof. I hit directly diverse roof structures. There are often collisions with structures that are already integrated there, e.g. with the conveyor technology. To go over the roof leads to interfering contours for cranes, conveyors and different . . . supplies. . . . The area should be levelled and large without a river, mountain or tree.
	IP5	It would be good if . . . it would not be required to first neutralise inhibitors in order to transform infrastructures. . . . Optimal positions of objects change and with these objects also the infrastructure.
	IP6	A second installation layer would be rather beneficial if it is a flexibly connectable solution with an integrated infrastructure to enable the rerouting of given cables and the integration of new ones. This would make it possible to bring a structured cabling to each workplace. . . . It is not foreseeable and not pre-plannable what will be required and where. Therefore, a modular and flexible infrastructure is required and not a fixed one. . . . A modular and scalable infrastructure would be desirable. . . . Substructures should be transformable due to continuous changes. . . . Not only the transformability of superstructure networks, but also of substructure networks is required. . . . A pipe system is required that can be transformed more easily. This, for instance, is required if one must include fibre optic cables. . . . It would make sense to integrate escape routes within substructures. Substructures are furthermore usable for underground car parks and material supplies.
(continued)		

		fundamental enabler 'area and substructure characteristics'
interview partner (IP)	IP7	It would be very good if the technical infrastructure was modularly adaptable. . . . Inclusion of additional pipes must be enabled, because this is required to transform supply infrastructures.
	IP8	The given infrastructures no longer fit the new capacity requirements. You recognise that you need to exchange them or you include additional ones. . . . One permanently reaches limits with regard to technical infrastructures and tries to find new possible solutions.

		fundamental enabler 'movable area size (MAS)'
interview partner (IP)	IP1	(If buildings were movable) One could shift a building to the periphery, and instead, put more important ones in the middle. . . . If I have new requirements in the body shop, a new product model with three parts . . . and I could bring them together, I would have completely new possibilities and would not be as static as today.
	IP2	The infrastructure should be located where one will not construct a building later, but this is hardly possible. The problem is that infrastructure requirements change over time, and consequently infrastructure dimensions and positions. . . . The position of this facility was once reasonable. This facility inhibited lean processes, and transformations were done around it. . . . Free extension and exchange areas should be located between buildings. However, such areas also lead to problems such as longer distances and ways. . . . It would be desirable if several buildings could be moved. . . . It would be good if buildings were movable.
	IP3	It would be awesome if we could move buildings with all their contents, or even better if the contents could be moved just like that. . . . It would be desirable that a factory always has an optimal location close to the market, and close to a motorway, railway, harbour, and airport.
	IP5	It would be great if it could be enabled to shift s&d plants. . . . When buildings are extended, roads and s&d infrastructures must be shifted, while topographical differences must be aligned. Areas around buildings should therefore be movable, the same as buildings.
(continued)		

		fundamental enabler 'movable area size (MAS)'
interview partner (IP)	IP6	It would be very good if machines with their areas could be rearranged as required. . . . Buildings must be . . . interchangeable. It would be best if I could make a real area exchange, but on land – on the fixed floor – this is hardly possible. . . . Extension areas for the future should also be available in the inner of a factory, as the inner factory structure is also changing. . . . Infrastructures should not only be scalable, but also movable, particularly large-scale infrastructures.
	IP7	If buildings were movable, entire buildings – this would be sensible. . . . It would be advantageous if free areas in the middle of the factory could be generated. . . . It would be sensible if factory objects and structures that are larger than containers were movable, especially as different departments and sections change. Consequently, it would be nice if we could generate free areas in the middle (of the factory). . . . Such production plants should be movable, but they are fixed. . . . It would be great if production elements could be plugged to one another as required, e.g. a whole building or parts of it, or if this building could be segmented in order to unplug and re-plug areas. Factory solutions should be sophisticated, and unproblematically pluggable and unpluggable.

		(importance of the) fundamental enabler 'movable area size (MAS)'
interview partner (IP)	IP1	It would, of course, be sensible if factory objects that are larger than containers were movable, because then a completely new dimension of transformability would be achieved. Buildings could be moved. This is required as building displacements take place. . . . One could shift a building to the periphery and instead, put more important ones in the middle. . . . The area . . . needs to be flexible and movable to enable area-transformability. This would be advantageous, as one could then move and relocate single elements where they make more sense and where they are more reasonable from an economic perspective. Furthermore, shorter planning and implementation times could be reached. We would be faster. Moreover, we could shift parts of the body shop together. This is not possible today. Static.
(continued)		

		(importance of the) fundamental enabler 'movable area size (MAS)'
interview partner (IP)	IP2	If a line is extended, drive and tensioning stations (conveyor system) could be shifted if the area was transformable. To do this, it would be required to shift area elements back and forth, like a piece of a puzzle.
	IP3	It would be very sensible if objects that are larger than containers were movable.
	IP4	Transformation durations would decrease and objects could be optimally moved if the area would be transformable. These durations would decrease, as dismantlements, demolitions and multiple moves could be avoided. . . . What is required on a small scale with production cells is also required on a large scale which means that it is required to move buildings and to reconfigure buildings as required. A reconfiguration or change of areas enables one to free areas, remove inhibitors that can be moved somewhere else, and to bring afterwards the free areas together to win again a larger free area – this would be a nice to have. . . . A shifting of areas is desirable.
	IP5	Power and wastewater treatment plants should be movable. Furthermore, it would be advantageous and sensible to move objects to be able to implement other ones instead. . . . Body shop units could be brought together and more easily exchanged if the area would be transformable. . . . It would be sensible if buildings and building contents were movable.
	IP6	The mobility of machines is important, and it would be sensible if entire buildings were movable.
	IP7	Mobile areas, which can be flexibly combined, would lead to advantages. . . . Fewer transformations would be required if the area was transformable. I would only transform single elements and not the whole system or large parts of the system as today.
	IP8	It would be advantageous if an entire body shop could be moved. . . . The production structure would be independent of the production system if areas were transformable. Independently of what I want to produce, it is producible. This would be an evolutionary step compared to the current status, as today we intervene in the entire system to make a change. If areas were transformable, I would only impact parts of the system.

6.3.2 Application of Transformation and Fundamental Enablers

TASs enable all area-, general structure-, transportation infrastructure- and s&d infrastructure-related transformation enablers/units. Other substructures (e.g. floors, foundations and pits) are also transformable. In addition, capabilities of existing transformation enablers/units (i.e. transformation units of today's factories) are enhanced. TASs can almost completely be described using transformation enablers/units, which is ironic because these concepts are neither capable of indicating the importance of fundamental enablers nor of accelerators, and because fundamental enablers impact transformation enablers/units.

TASs/TFCs increase the possibilities of fundamental enablers and accelerators in comparison to those of today's factories. TFCs' fundamental enablers therefore lead to advanced capabilities of factories in terms of transformation and acceleration units. TFCs' transformation enablers/units are not only superstructure-related but also area- and substructure-related, which leads to enhanced and new dimensions of transformability and new opportunities. However, the importance of area-transformability is recognisable more fully through real-world factory requirements and fundamental enablers (also in terms of implementation and transformation velocity).

Figure 64 depicts the fundamental enablers of TFCs.

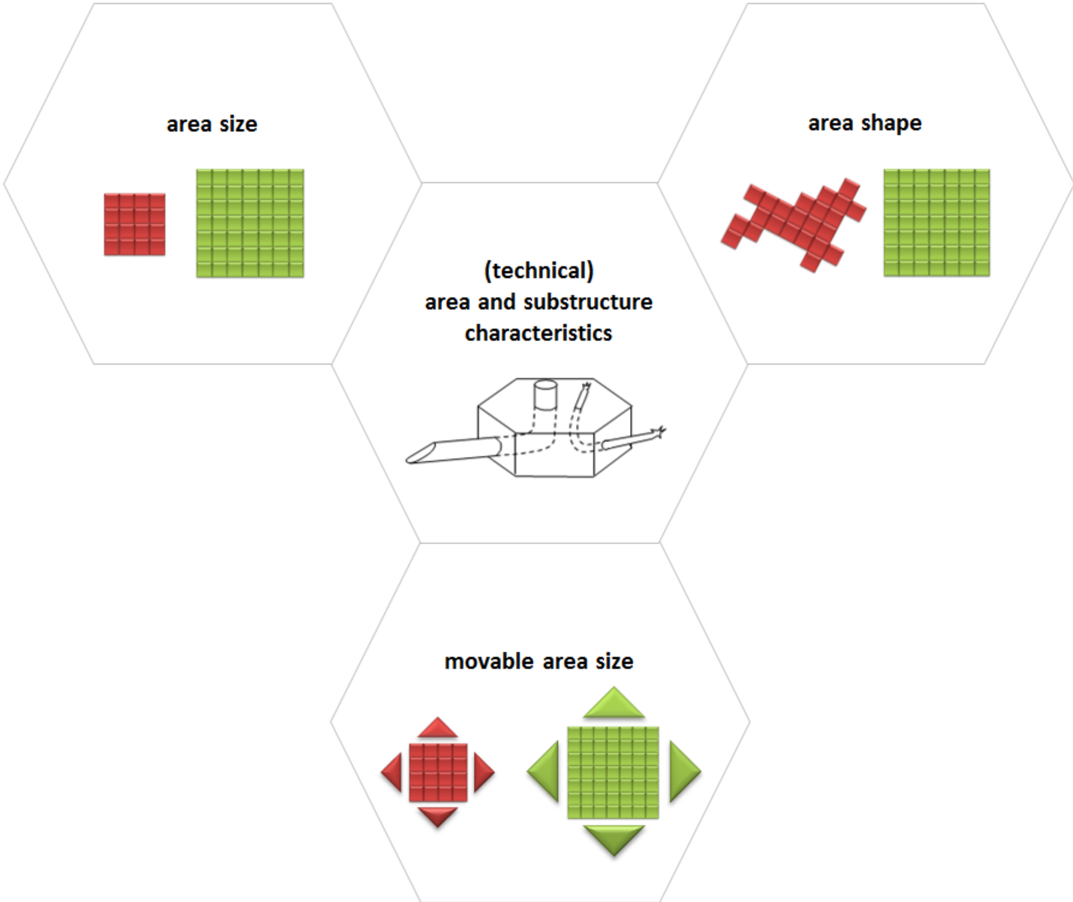


Figure 64: Fundamental enablers of TFCs

The area shape of the factory boundary of terTFCs and today's factories are identical, but inner shapes of terTFCs are transformable. The shape of marTFCs is largely freely configurable. The area size of terTFCs is limited, as in the case of today's factories. Free areas are immanent with marTFCs, which enables huge area sizes. At the beginning of their implementation terTFCs require earthworks for the TAS-substructure(s), while marTFCs require earthworks for their dock(s)/ connection(s) to the shore. Areas and substructures of TFCs are then largely definable and transformable (excluding the ground/soil for TAS-substructure extensions (terTFCs) and wave forces (marTFCs) etc.). The area and substructure quality is for every defined area part known and consistent. MASs of terTFC-Greenfields are initially limited to container sizes, while MASs of implemented FOs/FSs exceed container sizes (prerequisites are a TAS-substructure and that FOs/FSs are combined with a TAS-element(s)). To keep TAS-substructure-areas within buildings and a larger TAS-substructure-area(s) outside buildings free is recommendable for transformations and movements, e.g. extensions and exchanges of sections.

MASs of terTFCs_bw-Greenfields that are connected to appropriately large waterways and involve an appropriately large interface(s) between waters and the TAS-substructure(s) are not limited to container sizes, and require fewer free TAS-substructure-areas. This is because waters, depending on their size(s)/dimensions, can be used as further area(s) for transformations and movements, which can take place by means of ships and/or marTASs/marTAS-elements. TerTFCs_bw thus enable movements of production lines and buildings (maximum MAS of terTFCs_bw) not only within the TAS-substructure. If the framework conditions are appropriate, larger MASs are conceivable, e.g. of combined buildings and areas (see subsection 6.3.3 for further information). Location changes of terTFCs are similarly limited to those in today's factories, but are slightly more advantageous, while these of terTFCs_bw are simpler and less limited. MarTFCs enable MASs of entire factories and production networks (agility) (terTFCs_bw and marTFCs also enable smaller MASs). Cases which lead to a requirement for additional areas are not as problematic for marTFCs, as these are provided by nature. Location changes of marTFCs are almost limitless. Furthermore, movements on waters are not restricted to predefined directions, as in the case of rail-based terTFCs.

Compared to today's factories, the inner and outer mobility and transformability of TFCs are increased in all respects, while the capabilities and limitations of the different TFCs differ from one another. Micro, meso and macro level mobility is possible. Small and large FOs/FSs and inhibitors (including areas and substructures) can thus be removed and/or moved/relocated without the need for dismantlements/disassemblies, which is seldom possible with today's factories. Hence, transformations are simpler as fewer FOs/FSs are impacted.

Through TASs/TFCs, construction-, production- and technical infrastructure-related shapes, forms, functions and (form-related and functional) interfaces are more transformable and decoupled from one another than before. This is because TASs/TFCs enable 'TAS-/TFC-element combinations and exchanges' (of single and/or combined elements) and, on a lower level, 'module combinations and exchanges'. Furthermore, higher factory structure level-transformations are enabled, as transformability (particularly modularity and mobility) experiences new dimensions.

Unlike today's factories in which the general structure is largely fixed, the transformability (and transformation velocity) of TASs and thus of all FOs/FSs is increased. Extended possibilities of superstructures are enabled through extended possibilities of TASs and substructures, while TASs also increase the possibilities of substructures (figure 65).

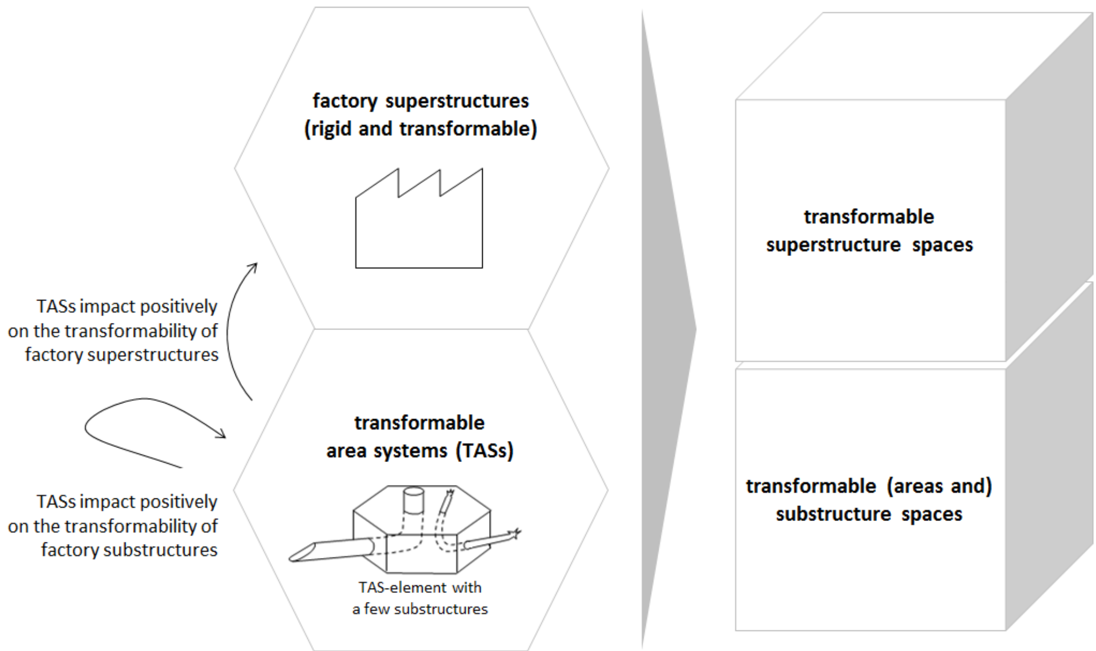


Figure 65: Impact of TASs on sub- and superstructures

Areas, sub- and superstructures are transformable (at least mobile/movable), independently if TFOs/TFSs or RFOs/RFSs are combined with a TAS. TFOs/TFSs are consequently less necessary, even if their combination with TASs is sensible. Different flows are influenced by changing FOs/FSs, walkways, fire protection-related objects and structures, steel structures, technical infrastructures and conveyors, and vice versa (see appendix 6.3.2 for further information about FOs/FSs, efficiency, universality and diverse relations to the general structure). The additional transformable dimensions provided by TASs are therefore a big advantage.

Transformation velocity, which depends on the transformability type, is also increased. Technical transformability enables faster transformation than spatial transformability. Quick fixing and release systems, movable robot cells, manufacturing migration concepts (see, for instance, Meichsner, 2007) and TBSs provide proof of this statement. Through TFCs, spatial (or nature-related) transformability becomes technical transformability, which increases implementation and transformation velocity. It can be claimed that these transformability types are combined.

The transformability of areas, sub- and superstructures are significantly increased through terTASs and marTASs. These systems can operate autonomously and enable active transformations of factories. Highly transformable factory concepts – TFCs – are now possible. Furthermore, agility is enabled, particularly through marTFCs. Further differences between terTFCs (also terTFCs_bw, which are not additionally mentioned if it is obvious that these are also meant) and marTFCs are provided throughout the next subsections and sections.

6.3.3 Application of Accelerators and Fundamental Enablers

It is possible to pre-produce and pre-test TAS-elements and their structures, as well as TAS-substructures and their structures. This can lead to faster and more effortless implementations and transformations of areas and substructures, superstructures, and therefore of factories. After the definition of functions and interfaces, these elements can be configured, assembled (e.g. out of a lean production supermarket), and tested. Elements and structures can be partially available already (i.e. partly and/or completely pre-produced standard elements and structures). TAS-elements and TAS-substructures which consist partly or completely of non-standard structures (e.g. special floor layers) can be entirely assembled after these structures are produced. Their production dominates the point in time when required data must be available, although TAS-elements themselves in particular are transformable/customisable, while adapter plates can also be used. This makes special FOs/FSs more rapidly producible than with today's factories, e.g. a special machine that is combined with one or more TAS-elements. Furthermore, changes are more easily implementable.

Acceleration units correspond largely to the MASs of the respective TFC. MASs of terTFCs also depend on the completion of the TAS-substructure(s). Off-site, MASs of terTFCs are limited to container sizes. Pre-produced and pre-tested FOs/FSs (without or with TAS-elements) which are larger and brought in from outside must be dismantled/disassembled prior to their transportation to the site/TAS-substructure. On-site, MASs are larger and therefore acceleration units are larger if these are pre-produced and pre-tested on-site. Reusability is largely required for Brownfields. Therefore, reusability-related acceleration units directly benefit (at least) on-site from larger MASs. The TAS-substructure must be completed (at least at a part of the site) to enable larger MASs. In the case of terTFCs_bw, acceleration units depend on waterways and on the interface(s) between waters and the TAS-substructure. Thus, pre-produced (and pre-tested) sections can be brought to the TAS-substructure from the start (Greenfield). It can be possible to move larger structures. In the case of marTFCs, even larger structures can be combined and moved as a whole, e.g. production networks. Because there is the possibility that marTASs can be used to relocate FOs/FSs of terTFCs_bw, it is conceivable that terTFCs_bw can reach similar MASs. Nevertheless, this requires further analyses, which cannot be done within the scope of this thesis. Therefore, buildings are kept as the maximum MAS of terTFCs_bw. Hence, plug-and-produce is enabled for dimensions ranging from container sizes over entire sections and up to larger structures. It is relevant in these regards that parallel processes dominate terTFCs_bw and marTFCs, and that these are possible with terTFCs (see also subsection 6.3.4). In this context it is crucial that product, process (e.g. production and logistics) and factory planning can be better synchronised with TFCs.

TASs/TFCs have a significant impact on accelerators/acceleration units. Movements of areas, sub- and superstructures that exceed container dimensions are possible without disassembling and rebuilding efforts. Restrictions such as limited road widths, lifting forces and portal dimensions are either non-existent or can be removed. In the case of terTFCs this can only occur on-site. Transformability (transformation scope) and implementation and transformation velocity are also significantly increased. This leads to competitive advantages and engenders the sustainability of industrial structures that can accommodate flexible lifecycles.

6.3.4 Resulting Factory Planning Processes

Site selection for terTFCs and terTFCs_bw requires rather more time than for today's factories. Approvals are for every factory concept a K.O.-criterion, e.g. if an implementation is not permitted. Initial approval processes of terTFCs are comparable to those of today's factories, but require rather more time due to the excavation depths that are required for the TAS-substructure(s). TerTFCs_bw also require water-related/maritime approvals and works at the land/TAS-substructure-water-interface, which can be done in parallel with the TAS-substructure approvals and works. Site selection for marTFCs can take either less or more time (more time is probable for most cases). This depends for example on the location, dock(s), required area size, marine ground/seabed/riverbed, marine biology and life/ underwater world, environmental issues and on institutions and authorities which are involved. These aspects must be clarified and resolved. In addition to terrestrial approval processes, maritime approvals are also required. Compared to today's factories and terTFCs, this therefore leads to additional efforts. Positive aspects must also be considered. MarTFCs lead to less land sealing and problems with high water. Tsunamis, earthquakes and other environmental disasters are also less problematic (marTFCs can be decoupled from the shore). TerTFCs_bw can also experience advantages in these regards. Litigation land is furthermore less problematic with marTFCs, which can furthermore lead to dewatering advantages.

Technical processes dominate TFCs which require fewer nature-related, physical/chemical and human-related processes. With increased mobility and MASs, FOs/FSs can be moved/relocated without earthworks and construction works, and without or with less area and substructure works. Transformations are simplified. Areas and substructures can be pre-produced and pre-tested instead of constructed, which also leads to advantages for other FOs/FSs. Tests and tryouts can be reduced. Except for unknown grounds of waters and area conditions that are relevant for TAS-substructures and docks, area and substructure characteristics are known. Area content integratability and better area- and substructure-transformability/-customisability (also of TAS-structures) lead to additional advantages. Generally, fewer FOs/FSs are impacted by transformations (consider difficulty factors), which decreases the number of required FPPs (except for the moves/movements that are required to free ways for transformations). It is also possible to transform specific FOs/FSs in a more targeted way, which decreases the number of FOs/FSs that are impacted by transformations and the required FPPs in addition. Thus, systems are not impacted entirely. Production systems and other systems are decoupled from the structure. These aspects lead to advantages in terms of approval processes (further aspects are disclosed below), and to faster implementations and transformations, which lead to fewer data changes and smaller scenario funnels. Moreover, fewer future factory developments and configurations are required to be considered upfront. Simpler, better and faster planning is also possible, as well as automated and autonomous implementation and transformation processes. Subsections 6.3.5 and 6.3.6 provide further details.

Shipyards or comparable industrial structures are required in order to enable some of the potentials provided by terTFCs_bw and marTFCs. Shipyards can also be afloat. TBSs, TAS-elements, building contents and other FOs/FSs can be completed in shipyards (including tests and tryouts) and finally combined before their transportation to the site (Greenfield and diverse Brownfield cases). Thus, it is not necessary for TBSs to be finalised on-site before the installation of production and other process facilities, tools and equipment can occur. Large industrial structures can also support terTFCs.

Both terTFCs and terTFCs_bw require approval processes, earthworks and a TAS-substructure(s). The TAS-substructure of terTFCs must be completed on at least part of the site before TAS-elements can be integrated and to enable the later assembly of TBSs. TBSs can be implemented after the required TAS-substructure(s) has been completed and after required TAS-elements for columns and for required works (e.g. TAS-elements as working platforms) have been implemented. These aspects are decisive for the critical path(s) of terTFCs. Other TAS-elements with or without FOs/FSs (e.g. building contents) can then be implemented, along with the combining of TAS-element-structures and other FOs/FSs which can be larger than containers (this is valid for buildings). These can be pre-produced and pre-tested. Generally, smaller pre-produced and pre-tested TAS-elements and FOs/FSs can be brought to the site, while larger ones must be combined on-site. Possibilities to pre-produce and pre-test small and large TAS-elements and FOs/FSs off-site are decisive for terTFC-Greenfield-durations. Large ones must be dismantled/disassembled before their transportation to the site, which does not apply to terTFCs_bw and marTFCs.

It is not sensible to construct foundations before these are required, as one does not know which characteristics will be required, and where. This can look different for office buildings, s&d plants, other outdoor FOs/FSs, parts of press and paint shops, and for parts of other sections if these are constructed with the same characteristics. Nevertheless, it happens rather by accident if these characteristics fit. To construct a larger TAS-substructure(s) than actually required for the forthcoming factory configuration(s) is sensible if this TAS-substructure(s) involves the ability to accommodate TAS-elements with maximum loads, dimensions and further requirements, e.g. for each section. This should be done within BFPS-2 of terTFCs in particular, as terTFCs are dominated by sequential processes. These processes increase project durations, even though parallelised processes, which accelerate implementations and transformations, are possible.

To construct a larger TAS-substructure(s) for terTFCs_bw is not necessarily required. A longer initial approval process impacts negatively on the critical path of terTFC, but not on the critical paths of terTFCs_bw and marTFCs. This is because TAS-elements, TBSs and other FOs/FSs can be done in parallel to one another (and combined later) and in parallel to the TAS-substructure(s)* or, in the case of marTFCs, the dock(s)* *(and required interfaces). This has a positive impact on timelines and critical paths.

All TFCs handle Greenfield-changes and most Brownfields better than today's factories. Better transformation enablers/units, accelerators/acceleration units and fundamental enablers (particularly MASs) also enable parallelised processes, pre-productions and to some extent pre-tests and pre-tryouts, which compensate for longer initial approval processes and works in BFPS-1 and BFPS-2. To summarise, terTFCs are dominated by sequential and parallelised processes. Small and large MASs are possible on-site in BFPS-2, BFPS-3 and BFPS-4. Off-site, large FOs/FSs must be dismantled/disassembled. TerTFCs_bw and marTFCs are dominated by parallelised processes, while small and large MASs are possible on-site and off-site.

TFCs probably lead to longer initial approval processes. Nevertheless, it is conceivable that no or fewer approval processes will be required later, and these will also be simpler and can be processed faster (all TFCs). Once approved and implemented, TAS-elements enable FOs/FSs to be environmentally and/or structurally neutral through area-mobility and MASs. Thus, FOs/FSs can be moved/relocated within permitted areas, which leads to advantages for different BMEs (e.g. changes of uses), as these lead to movements but not to demolitions etc. Inner transformations and movements are thus possible without new approval processes if larger areas were approved for specific uses. Thus, there are mainly no fixed points, and also not for special processes (except for when an approval is only granted for a specific area). MarTFCs can lead to further advantages (e.g. in the case of extensions), as docking is possible; in this situation the docking is better than in the case of ships. Furthermore, after several works which can be required to be done by people, transformations of all TFCs can be performed without people (see also subsection 6.3.6). Thus, fewer safety issues must be considered in the event of BMEs (consider automated and autonomous TAS-/TFC-element-movements and structural works). No earthworks are required after the initial ones. Fewer area, substructure, construction, installation/setup, building, building content, and related works are required. Moreover, demolitions, reconstructions and new constructions are less required, or not at all required (rather unpluggings, dismantlements/disassemblies, movements, assemblings and/or pluggings). Area and substructure characteristics are known. All this leads to advantages for approval processes and other FPPs.

Schenk and Wirth (2004, p. 154) argue that fixed points should be placed on the periphery. Nevertheless, this makes factories less competitive, e.g. due to longer distances. In the case of TFCs, such recommendations are pointless, as fixed points are mainly non-existent. Schenk and Wirth (2004, p. 154) argue further that the building planning should take place in a way that is appropriate to the location and that enables position/location changes at a Greenfield level. This statement must be extended to areas.

TFC-related fundamental enablers provide not only fundamental advantages for transformability, but also (besides a vast transformability increase) an increase of the implementation and transformation velocity; accelerators and TFC-related acceleration units also play their part in this. In addition, approval processes-related advantages can be expected. Generally, much faster implementations and transformations are possible with TFCs. Compared to today's factories, terTFCs can lead to longer durations for Greenfields and some simpler Brownfields. Project durations are conclusively discussed in section 6.4.

6.3.5 Application and Validation of the Model

The transformability of terTFCs is determined by the TAS-substructure(s). Their transformability is comparable with the transformability of a today's factory's Greenfield, but with known area and substructure characteristics and large MASs after the TAS-substructure is (at least at parts of the site) completed. The transformation potential of terTFCs is determined through the basic definition, allocation and partitioning (i.e. positions, sizes and shapes) of sections and other FOs/FSs, similarly to today's factories. However, terTFCs involve inner mobility and transformability. In addition, the TAS-substructure(s) can be designed based on the maximum requirements of sections, which leads to oversizing but enables increased inner mobility and transformability. This is cross-sectional and should also cover other FOs/FSs together with their TAS-elements. Extensions beyond the given TAS-substructure(s) (i.e. in BFPS-4) require earthworks and the extension of the given

TAS-substructure(s) and/or the implementation of an additional TAS-substructure(s). In the case of factory relocation, the location decides whether only parts of the TASs-substructure(s) remain or whether this also includes larger FOs/FSs. Site selection is not as crucial as it is for today's factories, as more FOs/FSs can be moved/relocated; this is also simpler. Larger FOs/FSs can be delivered and transported away (e.g. to another site) without dismantlements/disassemblies if terTFCs are connected to waters. This also applies in the case of terTFCs_bw. This optional characteristic is crucial for the transformability of terTFCs. If terTFCs do not have such a connection, terTFC first enable large MASs when the TAS-substructure is (at least at parts of the site) completed. Large FOs/FSs can therefore not be brought in from outside. However, the inner mobility and transformability of terTFCs are in any case advantageous for all BFPCs and BFPSs. Smaller and larger displacements, for instance, are solved simply by moves. In any case, moves/ relocations of FOs/FSs are simpler with TFCs than with today's factories, as a further transformable dimension is available. Thus, outer mobility and transformability are increased.

MarTFCs are unbound(ed) and enable free position and location changes. Site selection is no longer a site determination and a substantial decision that is determinative for a large number of framework conditions such as product and labour market proximity, as well as area size, shape and quality, external infrastructures and a political stability, of which several can change over time. Small and large MASs simplify transformations in BFPS-3, while BFPS-4 is never entered if sufficient areas are available, as is possible with marTFCs. Initial and future factory configurations of terTFCs, terTFCs_bw and marTFCs are not as decisive as in the case of today's factories. The transformation potential of marTFCs is also not determined through a TAS-substructure(s). TFCs keep the level of transformability high (figure 66).

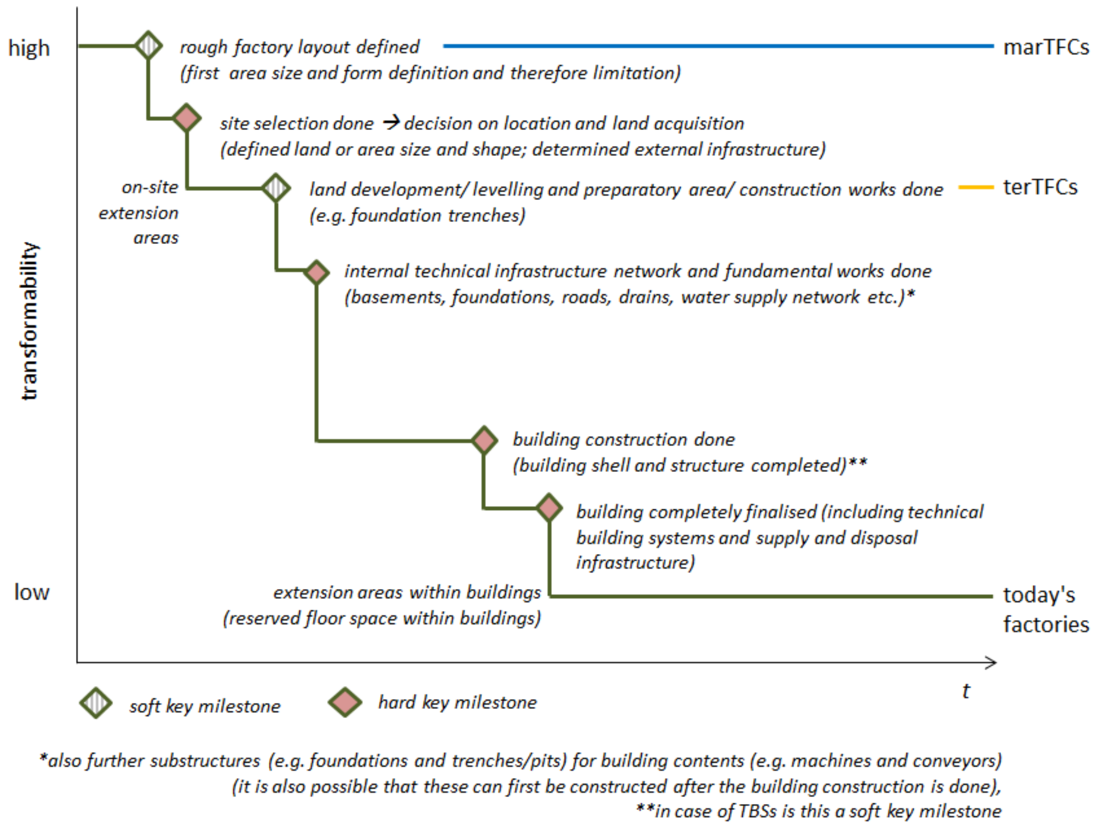


Figure 66: TFCs maintain their level of transformability

TFCs can retain their structuredness through their inner mobility and transformability, as TFCs can retain their inner mobility and transformability throughout the BFPSs. Thus, UHPs can be avoided. Organic transformation and growth are enabled and modern factory and production concepts can be made possible, e.g. ‘Holonic Manufacturing’ and ‘Bionic Manufacturing’. Free areas for transformations are especially recommendable for terTFCs (single smaller ones within buildings and at least one larger at the site), while terTFCs_bw (at least to some extent) and marTFCs involve these by nature and/or these are artificial. Column-free buildings would simplify transformations and are recommendable but not necessarily required.

BFPS-1 of terTFCs and BFPS-1 of terTFCs_bw are more difficult than BFPS-1 of today’s factories. BFPS-2 of terTFCs is comparable to BFPS-2 of today’s factories, as advantages and disadvantages are compensated for. The first part of BFPS-2 is dominated by longer durations and higher difficulty levels until the TAS-substructure is completed. Transformability advantages can then be utilised to solve transformation requirements, which decreases difficulty levels and durations (the TAS-substructure(s) must be appropriate). BFPS-2 of terTFCs_bw is in sum shorter and involves lower difficulty levels. BFPS-3 and BFPS-4 of all terTFCs are characterised by lower difficulty levels, while those of terTFCs_bw are lower than those of terTFCs. BFPS-1 of marTFCs can involve lower or higher difficulty levels, while higher ones are more probable; the same applies to longer durations. BFPS-2, BFPS-3 and BFPS-4 involve the shortest durations and the lowest difficulty levels of all developed factory concepts, and there is a possibility that BFPS-4 is never reached (see section 6.4 for details about project durations).

The fact that marTFCs never reach BFPS-4 is not totally crucial, as negative transformability-effects (i.e. the limited transformability of today's factories decreases throughout the BFPSs) are eliminated by TFCs. Nevertheless, required areas must be considered and kept free in order to enable advanced TFC transformations.

Area-mobility and MASs in particular lead to advantages for TFCs and create lower difficulty levels. Moves/relocations of small and large units (i.e. of single or combined TAS-/TFC-elements) are less problematic. Thus, BMEs are simpler and more easily manageable. Difficulty factors are less problematic, as fewer difficulty factors occur. Difficulty factors can also be better handled and more easily solved, e.g. through known area and substructure characteristics, area content integratability, which leads to fewer intertwinings, and better area- and substructure-transformability/-customisability. Displacements lead mainly to moves/relocations and thus to faster transformations and shorter durations, which in turn leads to no or fewer substitution processes, outsourcing and/or the pre-production of parts. Furthermore, substitution processes can be moved to (quasi-) final locations and are less often required. Moreover, no or fewer requirements to pre-produce parts and perform outsourcing occur, while here TFCs also lead to advantages. Fewer domino effects/chainings occur. Generally, less works are required, as fewer FOs/FSs are impacted through transformations. More targeted transformations increase this effect, as does the fact that different factory configurations can be more easily met. It is also not necessary to demolish FOs/FSs, as these are coupled and/or can be moved/relocated. Fewer simultaneous projects and operation phases occur; if these do occur, they are more easily manageable. This leads to fewer negative impacts of transformations on operations and vice versa, and also to fewer negative impacts between operations and between transformations. Mixed cases can also be better handled and also if these change, while fewer changes also occur. This is because of shorter project durations. Fewer and shorter production stops are required. Vicious cycles can be avoided and 'as is'- and 'to be'-factory statuses can be better defined. TFCs, particularly marTFCs are furthermore advantageous for off-site cases, e.g. factory relocations. The advantages of TFCs increase together with the BFPSs, as TFCs are especially advantageous for large(r) displacements. Constant switches and exchanges of sections are thus enabled (plug-and-produce). Subsection 6.3.6 provides further details and evidence. Further differences between the developed factory concepts are provided in the following pages.

6.3.6 Consequences

The interviews provided a large amount of data which speaks for TASs/TFCs. Keywords used by the interviewees are, besides 'domino effect' etc., 'mosaic', 'puzzle', 'Tetris' and 'Lego'. The previously provided data and the data in appendix 6.3.6 indicate the importance of different transformation enablers, accelerators and fundamental enablers. Levelled areas without inhibitors and further positive area and substructure characteristics which can be reached with TASs were described as desirable. It also emerged from the interviews that transformable areas and substructures are required. In particular, movable, exchangeable and interchangeable areas and buildings (including building contents and substructures) are requirements that were highlighted by the interviewees. An inner growth of factories and aspects of an alternating and breathing factory which require inner mobility and transformability (e.g. extensibility) could be identified, as the interviewees talked, for instance, about required free areas in the core and at the periphery of factories. The importance of huge areas and large MASs is undeniable.

TASs/TFCs lead to further consequences. Fewer planning capacities are required, as generally fewer FOs/FSs are impacted through transformations, as more targeted transformations are possible, and as fewer future factory developments must be considered upfront. Furthermore, planning, coordination and management efforts can be less complicated (consider, for instance, technical professions and the integratability of interfaces). Moreover, bullwhip effects can be decreased. In addition, a total factory optimum can be achieved, and not only an optimum for a single division or of a lower level. The following aspects speak against the idea that complexity is manageable and controllable: In practice, intuitive planning and/or planning by accident takes place (consider what was said by the interviewees about agile project management); subjective and irrational decisions and actions of people, process owner/user changes (consider also the required digitalisation of such changes, which often does not occur), fluctuations, position changes of individuals and other organisational changes (e.g. centralisations) occur; plants grow and require more people, e.g. professionals; training periods are required; planning and other human-related mistakes occur; industrial and work safety must be considered (consider noise, fumes, smells, dirt etc.). Such aspects are less influencing when systems are more technical and when fewer people are required, which is the case with TASs/TFCs. Increased transformability leads to a reduced human resistance to transformations. Thus, people are rather willing to promote and experience changes. As a consequence, transformations may happen more often with TASs/TFCs.

‘As is’- and ‘to be’-statuses of the operability, transformability, dimensions etc. of FOs/FSs, and thus real implementation and transformation requirements can be better identified and defined. There is no need to plan as far into the future as in the case of today’s factories. This is because the ‘to be’-status(es) can be better defined, as it is closer to the present due to faster implementations and transformations (not always with terTFCs). This is also because different factory configurations are not as mutually exclusive as in the case of today’s factories, as transformability is increased and also does not decrease over time (figure 67).

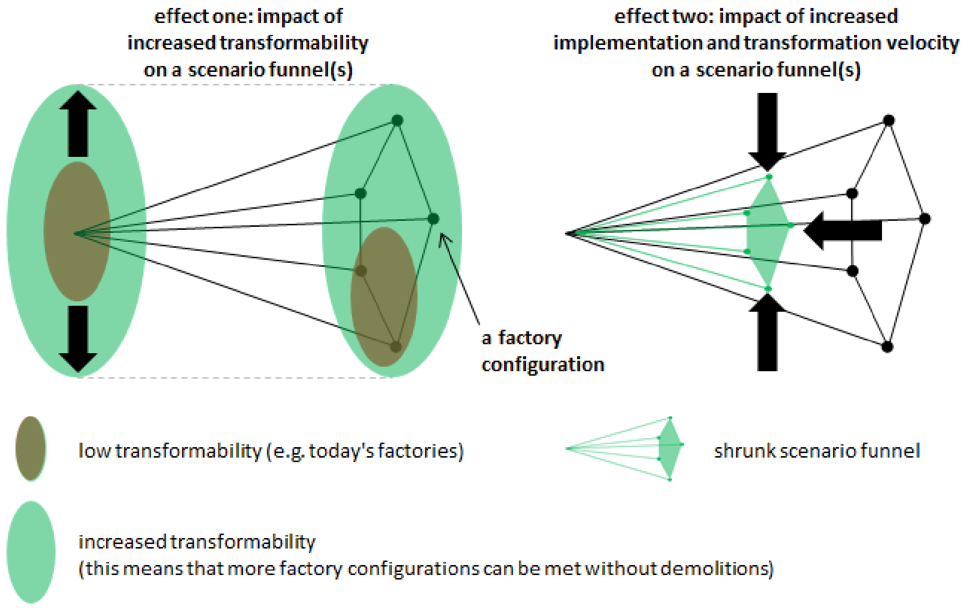


Figure 67: Positive double effect on scenario funnels

TFCs reduce the uncertainty, which increases with the project duration. Reduced uncertainty does not mean that the future can be anticipated, but it is easier to know what will be required. In addition, changing transformation requirements are not as problematic as they are with today's factories.

TASs/TFCs are completely digitalisable technical systems. Statuses and transformability/inhibition levels of FOs/FSs and of their interfaces can be better assessed and retrieved (consider self-analyses and self-diagnoses). Moreover, more FOs/FSs, processes, influences etc. are parameterisable and algorithms are more usable. Required FPPs and their impacts are more assessable, definable and processible. This ensures that factory planning data is correct and up-to-date, and ensures faster information transfer and more effective information. Real-time information acquisition and processing and real-time implementations and transformations are rather possible (consider also Industry 4.0-developments in this regard). Digital answers that are developed before implementations and transformations are more reliable. It is simpler to determine what (e.g. which FOs/FSs) is impacted when, where and how. Thus, direct answers to transformation requirements are possible, while factory projects are more manageable. Improved controlling and monitoring of FOs/FSs, planning, implementations and transformations are possible, e.g. due to more technology-controlled processes.

Responsibilities to FOs/FSs, project organisations, project landscapes, meetings and meeting contents are easier and more definable, but are less necessary. The self-centered nature of groups and individuals is not as decisive as in the case of today's factories. Furthermore, improved leadership is possible and better and more objective decisions which focus on real needs can be made, as these are more assessable and processible under consideration of different influencing factors, e.g. costs, transformation durations and efficient solutions. To reach a total optimum is thus rather possible. Furthermore, synchronisation between product, process and factory planning is also rather possible. Digital factory, virtual reality, and further computer-aided solutions support TFCs, and vice versa. In addition, TASs/TFCs and Industry 4.0 complement one another. Their development can be closely linked, and can achieve new possibilities with regard to transformability, and the planning, implementation and transformation of factories.

Heterogeneous transformations and growth (involving all difficulty factors) and growth of FOs/FSs out of themselves are simplified. Today's factories and their FOs/FSs can hardly be adjusted as desired, e.g. in the same way as the volume control of an audio player. Compared to one larger increase, to increase an object 5 times by 10% for example is generally more expensive and requires more effort. Numerous TFCs' FOs/FSs can grow as required, for example in small steps without reserves (TAS-substructures of terTFCs are excluded), which increases sustainability. Furthermore, TFCs support the change from passive into active and intelligent infrastructures and their management. Moreover, additional capacities are avoided through transformations and/or reuse. Furthermore, more self-sufficient solutions are possible. A close connection between energy, media, supplies/suppliers and consumers/producers (FOs/FSs) is enabled. This increases energy and resource efficiency, which is in line with Duflou *et al.* (2012). Due to reasons of complexity and motivation, technology can "help [to] produce economies of scale" in a way that is hardly possible just with people (McDonald, 1986, p. 83).

The transformability and structuredness of TFCs can be retained. Complexity and factory planning effort are decreased. A better definability of 'to be'- and 'as is'-

statuses enables a better ability to plan. Fewer collisions and difficulty factors occur (not only because of reduced collisions), while these can be more effectively and more efficiently handled. (Quasi-)Inhibitors, for instance, are mobile/movable. There are, in relative terms, fewer project changes and simultaneous projects; these can also be handled better. Factory structure recovery programmes are not required, as an effective general structure can be permanently enabled. Furthermore, the risk of vicious cycles is reduced. Configurations of terTFCs and especially marTFCs are not as decisive for future developments as the configurations of today's factories. Transformations have fewer negative impacts on transformability. Factory transformability and efficiency can be retained, and these continuously enable a green factory. RFOs/RFSs, which are often more efficient than TFOs/TFSs, can also be made transformable (at least mobile/movable) through TASs. Compared to today's factories, transformability is increased and implementations and transformations can be performed faster, while the exception proves the rule (see section 6.4). Both a fast transformation and an optimal solution/flows are simultaneously possible. It is also simpler to make decisions and to follow specific aims (figure 68).

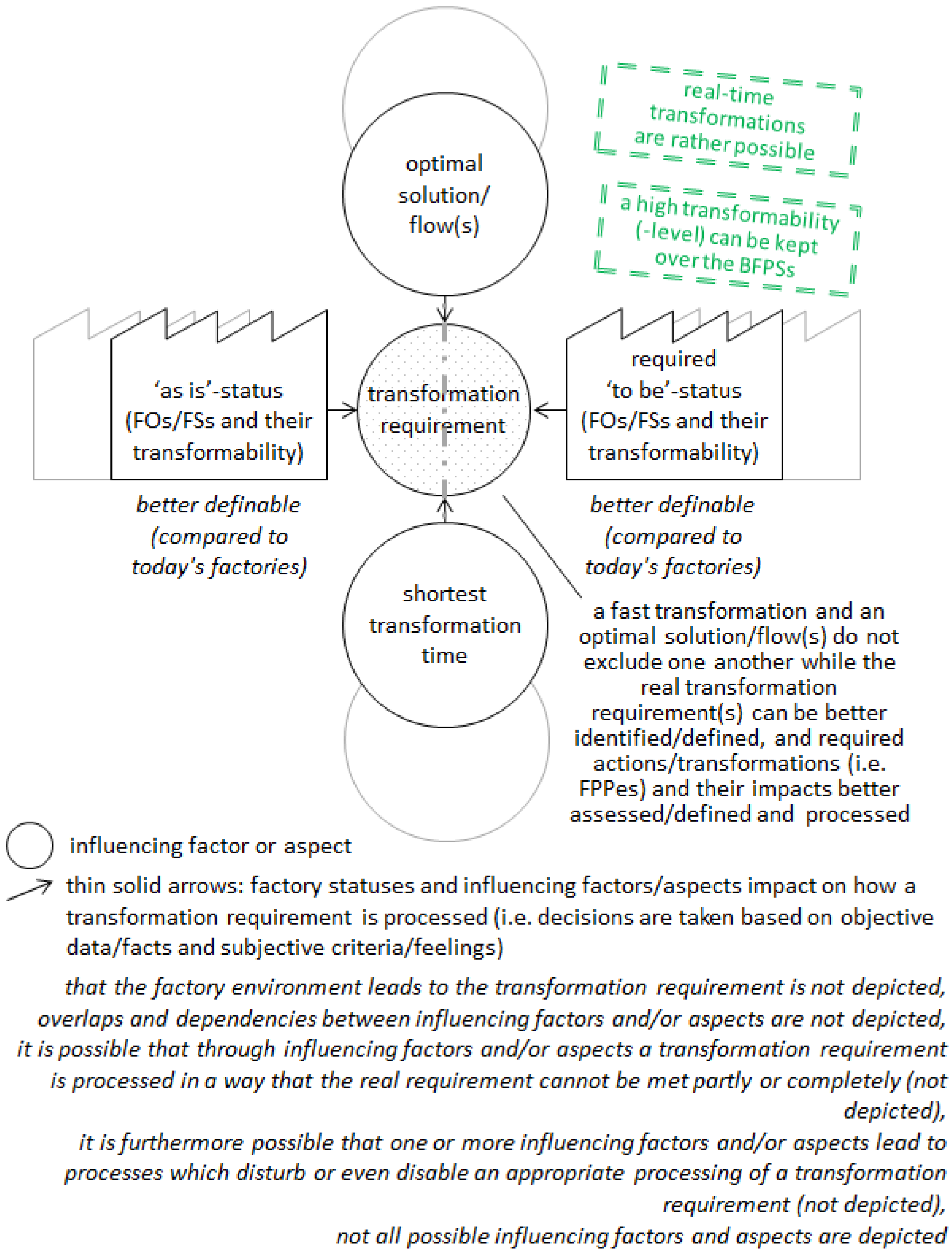


Figure 68: Combination of requirements

Lifecycles of all factory structure levels (i.e. all FOs/FSs) can be made flexible and also increased, as demolitions are avoided. Better lifecycle management at all factory structure levels is also possible. Numerous real-world factories show that industrial structures last over 100 years and that large parts of them are demolished over the decades, both of which speak for the need for sustainable solutions. Transformability and reusability are essential in this regard. It emerged from the interviews that the reusability of FOs/FSs is important, and that its importance is increasing steadily. IP3, for instance, argued that if one observes the global situation, which becomes more and more extreme, it is clear that a global change in thinking must take place. Furthermore, there is no need to decommission TFCs, as there is no end to their lifecycle.

TASs/TFCs enable both of Hildebrand's (2005) factory structure types in one factory. Thus, (quasi-)exceptional cases can be better mastered. Wars, political dangers, natural disasters, economic crises and other risks underscore the significance of the transformability (particularly mobility) of large FOs/FSs, whole factories and larger structures. The same applies to economic upturns, booms and other changes related to factory/production capacities and capabilities. Furthermore, 'factory structure forming' and 'element structure forming' capabilities of the modularity can be increased and new capabilities achieved: the 'location structure forming' and 'production network structure forming' capabilities of the modularity. Entire factories, sections, objects, and structures can be integrated, disintegrated and linked as desired. Thus, new dimensions of structural, functional, and capacitive independence are achieved. Hence, it is always possible to achieve an effective arrangement of FOs/FSs, factories and production networks, which enables 'dynamic corporate partnering concepts', as production network partners are no longer as static and bound to one location as in the case of today's factories. Agility is consequently enabled through TASs/TFCs. Splitting and fragmentation of production networks can come to an end. Factory structures can be combined and separated as required. It can be seen in Küpper *et al*. (2016) that suppliers should be integrated locally into huge production networks together with their OEM(s). This is often hardly or not at all realisable with today's factory structures, especially over time. Maximum production network and supplier integration enable maximum horizontal and vertical integration and thus high value addition, but TFC transformability is required in order to keep such networks efficient and green. As a result, interfaces can be eliminated, distances decreased, synergies better utilised, redundancies eliminated, and consequently less energy and media are required; this leads in sum (and in relative terms) to area reduction and decreased utilisation and operational costs. Furthermore, better and faster perception of problems and disturbances throughout the process chain is possible. Fewer bullwhip effects (e.g.

transformation-related bullwhip effects) occur, and these can also be handled better through local proximity.

In the case of relocation, BFPS-1 is more decisive for terTFCs than for terTFCs_bw, while relocations are least challenging for marTFCs (at least physically). In BFPS-2, transformability remains high for all TFCs, but the TAS-substructure(s) must be appropriate for terTFCs and terTFCs_bw. The TAS-substructure(s) is decisive for terTFCs and terTFCs_bw. Project durations of terTFCs can be increased by the extension of a TAS-substructure(s) and/or the implementation of an additional one. In BFPS-3 and BFPS-4, transformability (and transformation velocity) remains high. Displacements and other difficulty factors are less problematic, as these occur less often and can be more easily resolved. Domino effects/chainings can be reduced and/or avoided. Changes can be absorbed and complex projects and programmes handled in a better way. The imposition of a point of no return is unnecessary, because transformation requirements are not such a great problem as they are in the case of today's factories when factory structures have been already implemented.

TASs/TFCs lead to/enable the following (* means 'compared to today's factories'):

- total lean constructions
- most efficient processes and highest lean performances
- highest utilisation of synergies
- new levels of flexibility and transformability that can be retained (e.g. factory configurations do not exclude one another) and lead to increased provision/precaution and reaction capability
- fewer capacity-unrelated area extension requirements and better breathing of factories*
- a reduction of overcapacities* through transformations, e.g. fewer areas in sum are required, even though terTFCs can require more areas for transformations than today's factories if movements of areas take place,

while terTFCs_bw and marTFCs can have these areas through waters, which leads to additional advantages

- a factory framework that can be retained (e.g. s&d plants and technical infrastructures) and that provides the transformable basis for sections that follow a ‘plug-and-produce’-principle (such frameworks can also be advantageous for other purposes, see subsection 7.3.3)
- a reduction of overcapacities of factories and production networks* (the larger the factory/production network, the fewer areas are (in relative terms) required in sum, e.g. as more synergies can be utilised)
- a new level of agility (particularly marTFCs)
- a better definability of factory requirements and required FPPs*
- fewer bound investments*
- sustainable industrial structures with *fewer demolitions, reconstructions and new constructions

Transformability enables TFCs and production networks to be and to remain efficient and green. Compared to today’s factories, increased transformability and implementation and transformation velocity lead to faster and simpler factory implementations and transformations, and consequently to closer market entries and faster and simpler relocations. Scenario funnels undergo a positive double effect with the increased transformability and implementation and transformation velocity.

6.3.7 Summary and Conclusion

The results of section 6.3 are substantiated through the interviews and the application of the developed model and concepts (which were themselves developed mainly based on the interviews), while the importance of cause-and-effect relationships and abduction/logic increased throughout sections 6.1, 6.2 and 6.3.

The importance and functionality of the model and associated concepts could be validated further through their application and the interview data. The TAS-requirement profile was developed and the impacts of TFCs researched and assessed. Thus, RO1, RO3 and RO4 were achieved.

This section shows that TFCs open the door to a new dimension in factories (other industrial and non-industrial structures) and production networks, and to the Fourth Industrial Revolution which cannot be reached with today's factories due to structural limitations.

One innovation in a single technology can change large parts of a factory. Vast changes can hardly be absorbed by today's factories. TASs can change the whole system of factories and make factories viable in the context of changing factory requirements, which occur differently at different points in time throughout the lifecycle of a factory. This is possible because TASs involve an increased area-transformability, which leads to an increased and retainable transformability of TFCs. This leads to huge advantages for factories etc. Of particular importance is the fact that the basic capability of TFCs 'to move areas together with sub- and superstructures' is not only advantageous in its basic form, but particularly in a wider context, which involves the erasure and/or reduction of diverse domino effects etc. This capability leads to fundamental advantages in reducing and managing the complexity of real-world factory projects and in factory planning.

TASs and TFCs must be integrated into factory planning, and pursued and developed further. This is substantiated further throughout sections 6.4, 6.5 and 6.6, which will clarify how the developed factory concepts differ in comparison to one another (RO3).

What degree of transformability of factories is sufficient? One could argue that this question is valid and that it cannot be generally answered, as it depends on numerous framework conditions such as initial investments. This is an incorrect line of thought.

When does a factory's structural lifecycle (or, in other words, an area's lifecycle) end? This is the question we need to ask and answer. It does not end when a factory becomes useless and is abandoned, e.g. due to new requirements at another location or when a company becomes bankrupt. Even though costs of TASs will decrease when these become serial/series products, the mindsets of the (top) managers and investors, who dominate the whole human-globe system, must change. If we wish to keep our world green and habitable, the worst approach is to focus on potentially low investments and high short-term profits. With a long-term mindset and a focus on sustainability, factories require substantial change; TASs can enable this change.

A further change in thinking must take place. Even though TFCs can fulfil customer desires much better than today's factories, we must at least to some extent return to our roots and ask ourselves which goods we really need and how long these can be used. For instance, it is not necessary to buy a new car every second year, and planned obsolescence must be (globally) strongly discouraged. Therefore, the tendency toward self-centeredness in individuals and groups must be critically examined. Furthermore, from a sustainability perspective controversial events such as the large scrappage allowance in Germany in 2009 and the recent diesel scandal, which both boost the automotive industry, must be critically examined. Nevertheless, in the light of world-wide competition and against the backdrop of the current adjustment of our economic system, capitalism, and further aspects that form our human-globe system, it is hardly possible to overcome such actions if a country(/ies) wants to retain its wealth, power and global influence (consider that the automotive industry is an important pillar of industrialised countries, as many jobs depend on this industrial sector). Thus, it is understandable why a change of the human-globe system for the better of flora, fauna, and mankind requires global consensus and unity.

For the better of flora, fauna, and mankind, we must develop a long-term perspective and also enable more transformable, efficient and green production systems, factories and production networks. This is possible with TASs/TFCs. TASs can enable super-sustainable factories. From a long-term perspective, competitors of an OEM that utilises TFCs have virtually no chance of surviving in the market if the costs for TASs are appropriate or if increased costs for TASs can be survived. Despite this fact, we must change the human-globe system. This system must stop facilitating the environmental destruction that occurs through its current characteristics and settings, e.g. current compensation systems in which not only actions that lead to environmental relief and ensure the life and survival of our and other species are rewarded, but also those actions which act against life and survival. Meant are actions that are based on self-centredness, profit-orientation and short-term thinking. Actions which value our species must be rewarded, and not the other way around. Furthermore, we must change the human-globe system in a way that sustainable long-term solutions can be implemented, regardless of the fact that initial investments are normally higher. All of this must take place at a global level. If attempts are made to make these changes within individual countries etc., we will fail. There are many additional aspects which require a serious encounter at a global level. The characteristics and settings of the human-globe system are the root of many problems in the world. As in the case of today's factories, in which terrestrial areas are the root for many problems: We must stop fighting only against effects and symptoms. We must identify and eliminate the roots of the problems, which are in the human-globe system; otherwise, these man-made problems will destroy mankind.

Many people want more and want to go higher, faster and further, but not necessarily for the better of flora, fauna, and mankind. TASs must not be forgotten in further technical and factory-related developments, and must not be misused. What is most important is to not forget our globe and other people and beings.

6.4 Qualitative Comparison of Project Durations

This section is based on the results of the previous sections, and is concerned with the question of how the developed factory concepts impact on the durations of different factory project cases. Numerous real-world factory projects provided the required data and the testing field for the factory concept comparison in this section. This testing field is based on a Greenfield and on simple and more complex Brownfields.

In this research, TASs and TFCs are considered to be fully developed. This comparison must be repeated when a further development of TASs has taken place (including site selection of marTFCs, area acquisition, environmental impacts of TFCs, required approval processes, earthworks, construction and assembly works for TAS-substructures, and many additional aspects).

Table 22 recapitulates important aspects of the previous sections on a high level in order to assist the reader.

<table>
<tr><th colspan="2">Recapitulation of sections 6.1, 6.2 and 6.3</th></tr>
<tr><td colspan="2">Overall: Factory transformations and growth can lead to displacements and other difficulty factors (consider heterogeneity). Displacements, domino effects, chainings, project overlaps and other difficulty factors can occur in a mix at the same time. The probability of this increases with BFPSs.</td></tr>
<tr><td colspan="2">Today's factories in general: The transformability and transformation velocity of today’s factories are low and decrease further throughout the BFPSs, while complexity increases throughout the BFPSs. FPPs are effortful and time-consuming, and these efforts and FPP durations increase throughout the BFPSs (consider sequential processes). Moreover, the manageability of factory projects decreases throughout the BFPSs and the risk of vicious cycles increases. The likelihood that a factory project is not at all manageable also increases.
This means that rapid and effortless transformations are required.</td></tr>
<tr><td>TFC key aspect 1</td><td>The transformability and transformation velocity of TFCs are high and can be retained.</td></tr>
<tr><td>TFC key aspect 2</td><td>Displacements can be more easily solved with TFCs. In the case of displacements, moves take place instead of effortful and time-consuming FPPs (consider the MAS(s)). The larger the maximum MAS and the more different MASs that can be generated, the better it is.</td></tr>
<tr><td>TFC key aspect 3</td><td>Fewer domino effects and chainings occur. These are also shorter, as they can be cut/reduced and/or avoided.</td></tr>
<tr><td>TFC key aspect 4</td><td>Not only is the transformability of superstructures given but also the transformability of areas and substructures, and transformability can be retained (TFC key aspect 1). Thus, transformability covers a 'new dimension' which positively impacts sub- and superstructures. This has an additional positive effect on difficulty factors, e.g. chainings.</td></tr>
<tr><td>TFC key aspect 5</td><td>FPPs are generally less effortful and can be performed more rapidly with TFCs than with today’s factories (consider parallelised processes; consider exceptional cases, which are explained later). More rapid implementations and transformations lead to fewer changes and fewer impacts between projects, e.g. overlaps. This, in turn, has an additional impact on domino effects and other difficulty factors.</td></tr>
<tr><td>TFC key aspect 6</td><td>Parallelised processes can be better utilised with TFCs than with today’s factories.</td></tr>
<tr><td colspan="2">TFCs in general: The thesis results, and fundamental enablers in particular, suggest that in comparison with today’s factories, TFCs lead to significant advantages. Transformation units, acceleration units and fundamental enablers of TFCs are better than those of today's factories. This leads to the TFC key aspects 1 to 6. Complexity is significantly reduced. The manageability of factory projects is increased. The risk of vicious cycles and unmanageable projects is reduced.</td></tr>
</table>

Table 22: Recapitulation of sections 6.1, 6.2 and 6.3

6.4.1 Premises and Relevant Information

The comparison of project durations takes place based on realistically estimated timeframes under consideration of the capabilities and limitations of each factory concept. To enable fair, valid and reliable comparability, the same timeframes have been used for identical processes, e.g. for building installations which lead to dirt and dust. Longer initial approval processes were considered for TFCs than for today's factories. Longer durations for earthworks, construction and assembly works were considered for TAS-substructures than for the initial area and substructure works of today's factories, i.e. earthworks and construction works of foundations etc. Accessibility, obstructions through construction machinery etc., the dewatering of areas and further aspects were considered.

Site selection and area acquisition are assumed to have already taken place for the Greenfield case (even though the acquisition could also be on-going). Furthermore, the land-use is already appropriate (industrial zone). Even though they can be handled better with TFCs, difficulty factors, planning changes etc. (except for the considered ones) are excluded. The considered displacements involve area and substructure works. Worst and best cases are analysed and reflected for each factory concept and project case. Relevant information is included as required. For terTFCs, larger TAS-substructures are considered for best cases, the same as extension areas for today's factories. Pre-produced TAS-elements with different sizes/dimensions are available. Furthermore, different optional and exchangeable structures for TAS-elements are available. In addition, the planning and production of special TAS-element-structures and FOs/FSs is considered.

Comparable product and process planning, and comparable planning and production of process facilities etc. are considered, even though TASs/TFCs can lead to advantages in these regards. If these processes, which can be better synchronised with a TAS-/TFC-related factory planning than with a today's factory-related one, are excluded or this additional potential considered, TFCs can be even more advantageous.

6.4.2 Results

TerTFC-Greenfields can take longer or shorter than today's factories' Greenfields. Area and TAS-substructure works take longer than area works for today's factories. If today's factories' substructure works (e.g. dewatering of the plant and foundation works) are considered, it can look different. Smaller pre-produced TAS-elements etc. can be brought to the site, while larger ones must be combined on-site. Thus, the disadvantages and advantages of terTFCs compensate for one another. The possibilities to pre-produce and pre-test TAS-elements, building contents and other FOs/FSs before their on-site installation therefore decide which factory concept can be earlier implemented. If best cases for both factory concepts are considered, terTFCs are accomplished faster. Parallelised processes enable Greenfields of terTFCs_bw to be completed more quickly than Greenfields of terTFCs and of today's factories; larger MASs are the main reason for this. MarTFCs enable the most rapid Greenfields due to their having the largest MASs.

A new construction with simple building contents (e.g. an empty warehouse) or a simple extension at free areas (BFPS-3) without displacements, chainings etc. can take longer with terTFC than with today's factories if the TAS-substructure(s) must be extended. In the best case, terTFCs can finalise these cases more rapidly. TerTFCs_bw top these results and are topped by marTFCs.

In the case of TFCs, small displacements mainly require moves. In the case of today's factories, small displacements result in more complex planning, approval processes, substructure works and/or more difficult moves/relocations requiring more time and efforts. Thus, in the case of more complex and extensive Brownfields with displacements etc., today's factories have no chance to reach the project durations that are possible with TFCs.

In the 'TFC worst case', a large displacement (e.g. a building displacement in BFPS-4) can be better and faster accomplished than in 'today's factories best case'. This difference increases if small displacements and other difficulty factors (e.g. chainings) are also required. TerTFCs_bw and marTFCs accomplish a large displacement (e.g. in which a building is displaced to the outside of the factory boundary) even more quickly. The TAS-substructure(s) or/and water-related dimensional restrictions impact rather negatively on terTFCs_bw, which makes marTFCs accomplish this displacement-type most rapidly.

6.4.3 Summary and Conclusion

Based on the results to this point (including the application of the model and concepts), it can be concluded that from short-, medium- and long-term perspectives TFCs are generally better than today's factories. Only terTFCs (not terTFCs_bw) which have no extended TAS-substructure(s) (worst case) might lead to longer Greenfield durations, but even these factory concepts later lead to advantages compared to today's factories. It is thinkable that (Brownfield) new constructions and simple extensions in free areas and without displacements (which occur rarely) can be done faster with today's factories than with terTFCs. TerTFCs are in the case of more complex Brownfield cases, which occur often, much better and faster (not to mention terTFCs_bw and marTFCs).

Displacements are for TFCs less problematic than for today's factories. This leads to advantages for many Brownfield projects. TFCs are particularly advantageous for small and large displacements and therefore in late BFPSs even more than in early ones. A simpler exchange of single FOs/FSs and entire sections is possible (with marTFCs exchanges are normally simpler than with terTFCs_bw, and with terTFCs_bw these are simpler than with terTFCs) (see also section 6.6). Other BMEs also experience advantages. For terTFCs, a free on-site exchange area(s) with an appropriate TAS-substructure(s) is recommendable. The other TFCs can use waters (not necessarily for smaller transformations within buildings as the decoupling etc. could be disproportionately effortful, which means that it is recommendable to keep free exchange areas within buildings). This means that area extensions can be avoided in several cases with terTFCs_bw and marTFCs. The advantages with regard to parallelised processes and their positive impacts with regard to TAS-substructures of terTFCs_bw which lead to advantages in terms of extensions were described previously. Overall, marTFCs enable the fastest implementations and transformations, followed by terTFCs_bw, terTFCs and today's factories. This conclusion is complemented by subsection 6.5.3.

6.5 Reflection of a Factory Lifecycle

In this section, a factory lifecycle is considered, and an explanation is provided for how the developed factory concepts can handle the different factory configurations which occur over time, and what these configurations mean for these concepts. This section is based on the results of the previous sections. Numerous real-world factory projects provided the required data and the testing field for the factory concept comparison in this section. This testing field is based on a Greenfield that is subsequently followed by different Brownfields, i.e. a Greenfield factory configuration is transformed over time. Different factory project cases lead to different BFPSs, factory characteristics and factory capabilities/limitations (which depend on the factory concept in hand). Consequently, lifecycles and transformation cycles are considered. The same factory project cases within the same BFPSs are considered for each factory concept in order to enable a fair, valid and reliable comparison and a verification of the research results. BFPSs serve as a basis while the impacts of different eBFPCs over time suggest how the factory concepts' configurations develop against the backdrop of their basic capabilities and limitations.

6.5.1 Premises and Relevant Information

This application example examines a simplified automotive OEM plant with some sections and without departments, s&d plants, canteens, other FOs/FSs and integrated suppliers. Changes in the horizontal and vertical integration are excluded. Simple cases are considered; there are no mixed cases. Location changes and (quasi-)exceptional cases such as crises, booms and extensive product technology changes (e.g. drive technology changes) are excluded. (Today's factories do not stand a chance in these cases.) This makes the comparison simpler and more understandable. Furthermore, the consideration of such aspects would increase the problems of today's factories. Thus, the application example is supportive of today's factories. The objective is to reach effective factory configurations which enable efficient process flows as quickly as possible.

Earlier factory configurations impact on future ones. The form of an optimal factory configuration depends on possible future configurations, particularly in the case of today's factories. This will be explained in the following sentences. Figure 69 depicts an optimal factory for a capacity of 100% in t=1, and extension areas which are required for a possible optimal factory solution for a today's factory in t=3 (t=3 is the first finalised Brownfield) where a capacity increase to 150% is required after the 100% in t=1.

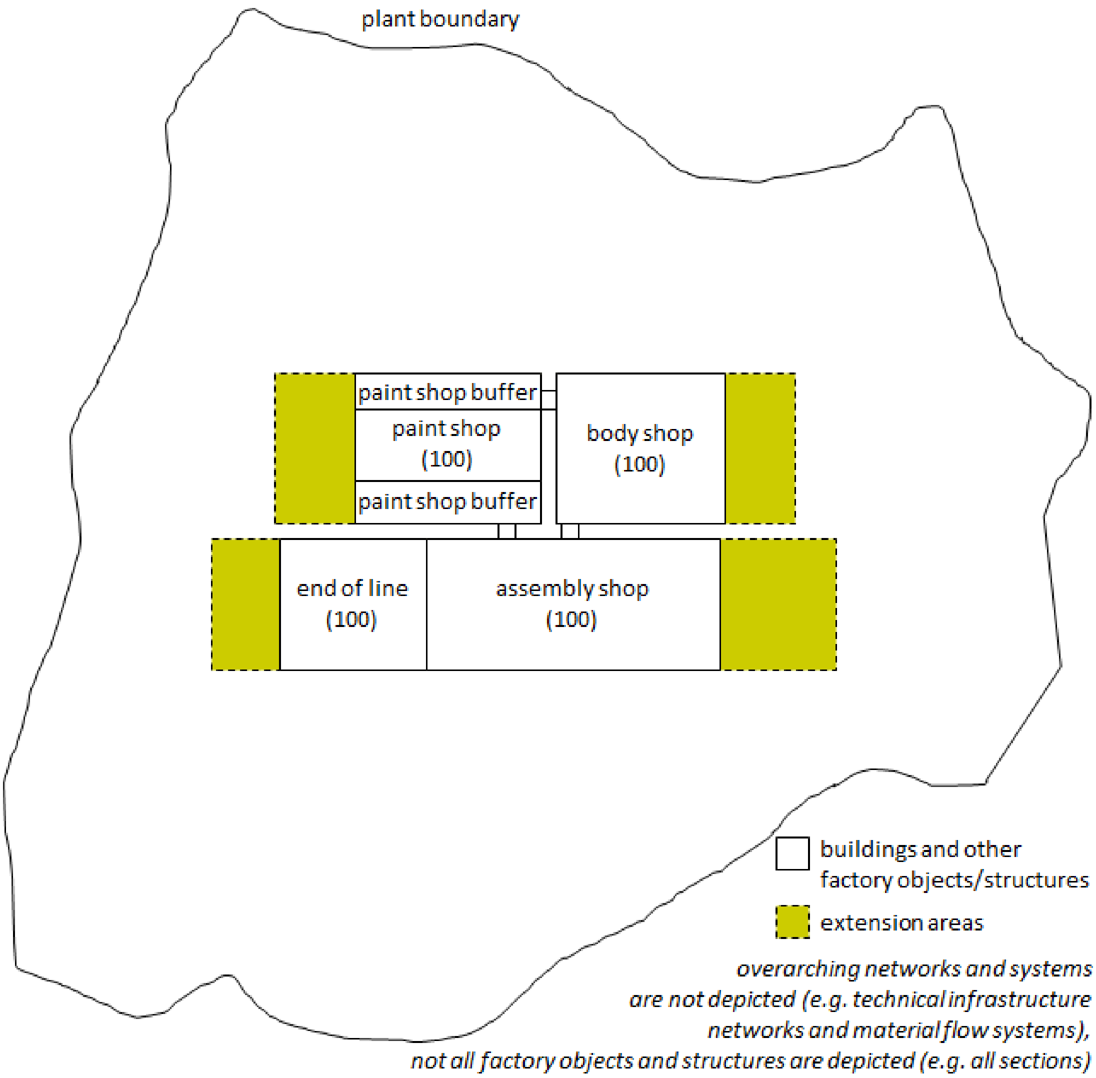


Figure 69: Factory configuration example 1 (100% in t=1 if 150% in t=3)

The solution for 150% can look different if it is clear that later (e.g. in t=5) 200% will be required (not depicted).

If 100% are required in t=1 and an additional 100% are required in t=3, the ideal factory for a today's factory in t=3 under the premise that the 100% were implemented in t=1 could look like the factory in figure 70 (consider also the original positioning of the sections, which is different), while an ideal 200% factory could look like the factory in figure 71 from the start (i.e. in t=1).

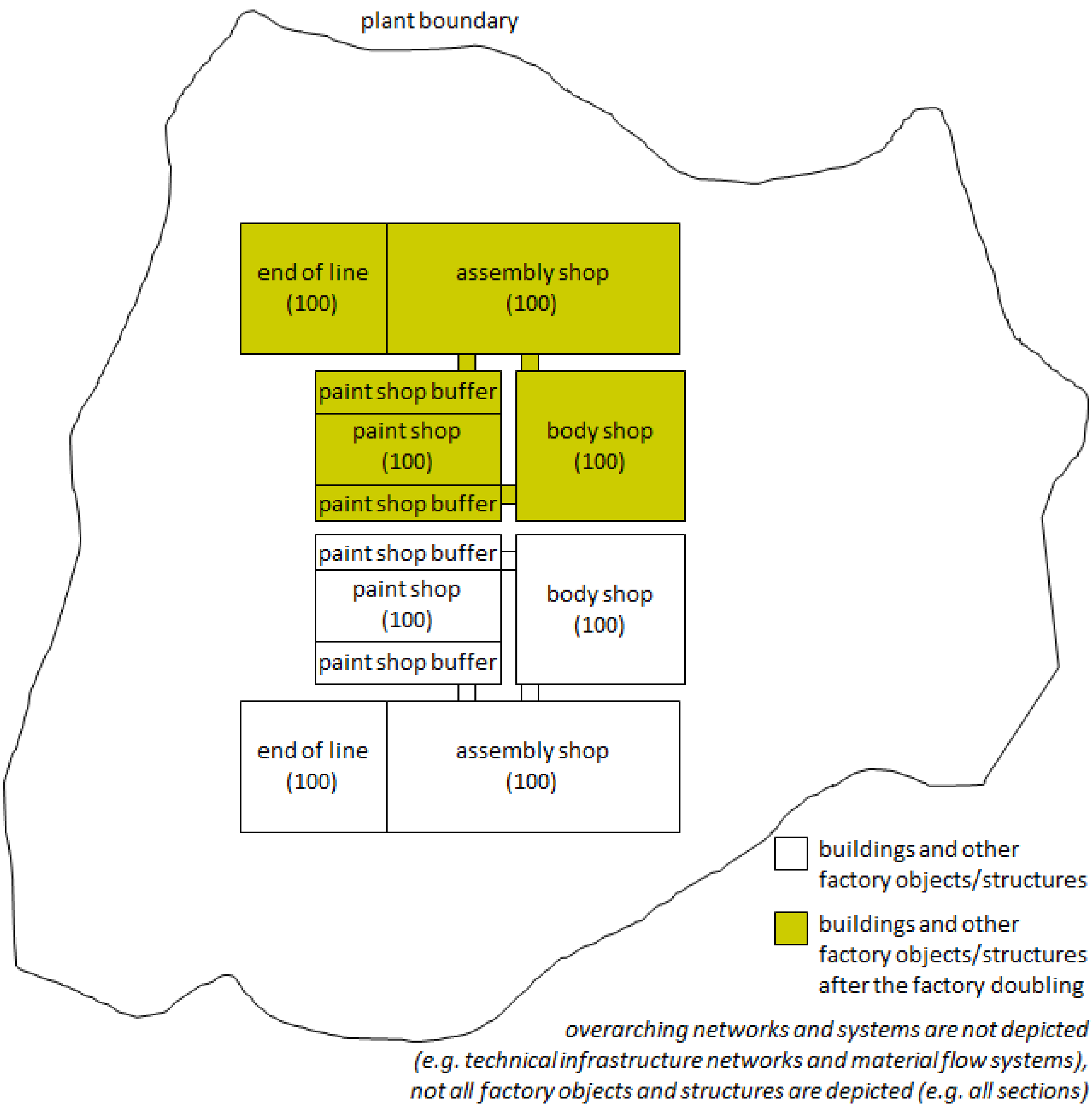


Figure 70: Factory configuration example 2 (100% in t=1 if 200% in t=3)

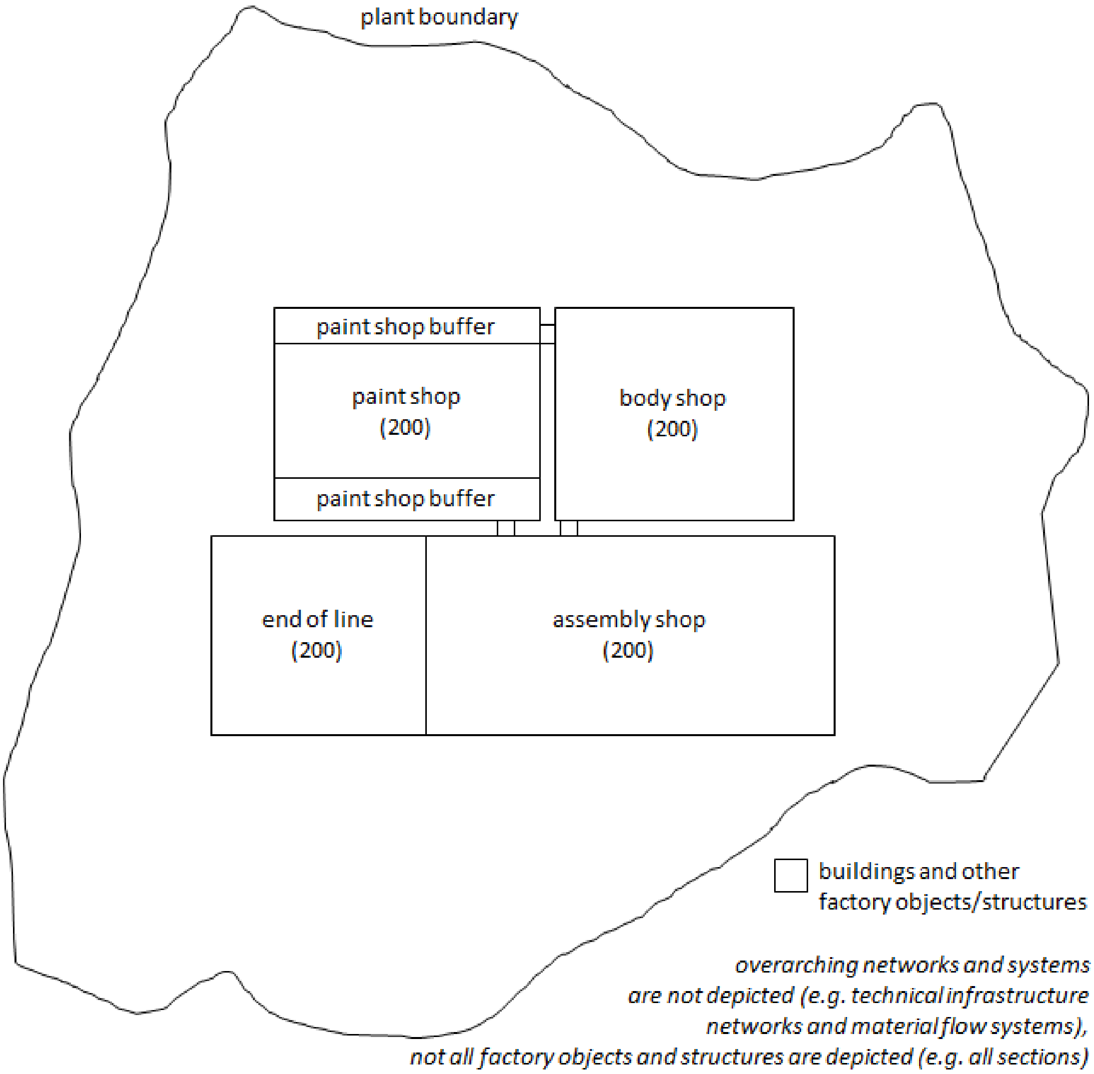


Figure 71: Factory configuration example 3 (200% in t=1)

These figures show that ideal factory configurations exclude one another (e.g. that an ideal factory in t=1 excludes an ideal factory in t=3), and that earlier factory configurations are particularly decisive for today's factories. This is because future factory configurations are to a certain extent predefined by earlier ones, while several others are excluded. This means that a factory configuration 'a' in t=3 leads to other framework conditions and possibilities for t=5 (and so forth) than a configuration 'b'. Configuration 'a' in t=3 enables a factory configuration 'c' but excludes a factory configuration 'd' in t=5 (and so forth). If one anticipates an ideal configuration for t=5 (e.g. before t=3, or even before t=1 in which she/he would also anticipate the configuration for t=3) and wants to reach it, earlier factory configurations will be different and less efficient (compared to a case in which this ideal configuration is not considered).

In the case of today's factories, one must consider implemented FOs/FSs (e.g. a paint shop and its rigidity) for future factory configurations more than is the case with TFCs, while new and more transformable (e.g. scalable) process facility concepts can also be enabled through TASs/TFCs (see also subsection 7.3.3). This can have positive impacts on sections, e.g. that a paint shop facility can be more easily extended than today. Despite this potential, even with the available factory solutions, TFCs are more future robust.

Each configuration and the works required to reach this configuration strongly depend on earlier configurations, and on how well anticipated the new configuration(s) has been, and on how well the required works could be defined and accomplished. Each configuration is to a certain extent either good or bad for future configurations and transformations. Configurations of today's factories are more decisive and to a certain extent worse for future configurations than configurations of TFCs.

Cases other than a capacity increase are not considered in the above figures. The following information takes another case into account in order to bring real-world circumstances closer to the reader: A product model change can make a future capacity increase more difficult and can restrict it, while a capacity increase can make a future product model change more difficult and can restrict or even disable it, as both cases require additional areas of a different size and in different positions.

Different factory configurations over a factory lifecycle are considered next.

6.5.2 Results

If one imagines a factory lifecycle in which a Greenfield with a capacity of 100% (configuration 1 in t=1) is followed by a capacity increase to a capacity of 150% (configuration 2 in t=3) and a product model change (configuration 3 in t=5), it is possible to understand that at the latest in t=5 a today's factory is at least partly intertwined, and that the characteristics and capabilities of this factory become negative over time with almost every upcoming factory project, while it becomes increasingly difficult to generate an appropriate factory configuration. Due to the limitations of today's factories, long project durations and vast demolitions are required to change between these configurations, while different risks must be considered, e.g. the occurrence of vicious cycles. This already shows that today's factories can hardly handle the different factory configurations which occur over time. If configuration 3 (instead of configuration 2) was to be required after configuration 1, the factory development would be a different one. Furthermore, this would impact differently on subsequent configurations. Today's factories would be already unstructured in BFPS-3, which underpins the dilutive effect. BFPS-4 would be reached earlier with today's factories than with TFCs. As described throughout section 6.2, all factory characteristics and capabilities would develop negatively throughout the BFPSs.

TFCs can handle such circumstances better. It should be remembered that real-life factories are much more complex than the depicted ones, and that much more complex cases occur over time, besides all the other relevant aspects provided throughout this thesis.

6.5.3 Summary and Conclusion

Based on the results to this point, it can be concluded that different factory configurations which are required over time cannot be reached by today's factories without vast demolitions, reconstructions and new constructions. Earlier factory configurations predefine future ones to a certain extent, particularly in the case of today's factories. This means that which future factory configuration is sensible to aim for is largely predefined, as earlier configurations restrict future ones.

As the transformability of TFCs is higher and does not generally decrease, factory reconfigurations are less problematic and transformations more sustainable. Despite the fact that TFCs are advantageous for transformations, new constructions of TFC-sections and their exchanges (plug-and-produce) can be simpler and more preferable than transforming (and partly directly reusing) given/old FOs/FSs. Which of these options is more preferable depends on the specific case. To reuse old FOs/FSs after such an exchange is in any case possible, either through direct reuse, or through dismantling/disassembling and then reuse. The conclusions of sections 6.4 and 6.5 are complemented by section 6.6.

6.6 Final Comparison and Rating of Factory Concepts

This section is based on the results of the previous sections and compares the most relevant concepts for each factory concept. The factory concepts are finally rated.

Area-modularity, area-mobility, area-linking ability and area-pluggability of today's factories do not really exist. Area-universality can be given in BFPS-2 and the general structure can be almost freely defined, but these possibilities are lost throughout the BFPSs. Factories are scalable until BFPS-4.

Transformation enablers/units of marTFCs reach the highest levels that can be maintained. Those of terTFCs_bw are somewhat lower, but are higher than those of terTFCs.

Fundamental factory characteristics and capabilities are summarised through three fundamental enablers (table 23). Accelerators/acceleration units were considered in section 6.4, can be reflected in sections 6.2 and 6.3, and are mainly determined by MASs (table 24).

	today's factories	terTFC	marTFC
area shape	not always as favoured (i.e. not rectangular/spuare-shaped) and required	more advantageous than in the case of today's factories, except for the plant boundary	largely freely definable, but restricted by legal, artifical and natural conditions
available/free area size	limited; relatively seen large at the end of BFPS-1, decreases throughout the BFPSs, the same as (area-)transformability	as in the case of today's factories, but (area-)transformability can be retained	can be almost limitless; (area-)transformability can be retained; consider natural etc. conditions
area and substructure characteristics	'spatial/nature-related' terrestrial areas: rather inappropriate and inconsistent area and substructure quality/conditions; additional efforts are required to make these conditions appropriate; largely unknown soil conditions/area and substructure characteristics, while the knowledge can increase over time if it is well documented (consider digital factory solutions); hardly transformable (rigid) areas and substructures after their first definition or, in other words, the implementation of sub- and superstructures; throughout the BFPSs becomes the situation even worse (i.e. with the construction of further sub- and superstructures); area and substructure characteristics and requirements (which are anyhow seldom appropriate) are the more insufficient/inappropriate, the higher the BFPS (consider also: the MAS is disabled)	'technical' TASs: rather appropriate and consistent area and substructure quality/conditions; an additional transformable dimension (quasia transformable basement) is provided by TASs; largely definable and completely known* area and substructure characteristics *terTFCs: except for the soil/earthworks for the TAS-substructure(s) and the interface(s) between the TAS-substructure(s) and waters, which are required for terTFCs_bw; *marTFCs: except for the soil/earthworks for the dock(s); marine grounds etc. must be considered (also in the case of terTFCs_bw) largely transformable/customisable area and substructure characteristics: TASs involve an area flatness, while exchanges of TAS-element structures and substructures are simplified; requirements are definable; contaminations are less problematic; TASs lead to many further advantages, e.g. if area and substructure characteristics are not as required, it is not as worse as in the case of today's factories (consider also MASs)	

Table 23: Fundamental enablers (without MASs)

Factory implementations and transformation become faster as the sizes that can be moved at once become larger. Through the MASs, difficulty factors are no longer real difficulty factors. Demolitions and numerous dismantlements/disassemblies can be avoided.

		today's factories	terTFC	marTFC
movable area size (MAS)	production network	disabled	disabled	enabled
	factory	disabled	simplified* **	enabled
	building (section/department)	disabled	enabled**	enabled
	production line/group	disabled*** ****	enabled**	enabled
	process facility/workstation	(quasi-)enabled (only TFOs/TFSs) ****	enabled	enabled

*Compared to today's factories, simpler and faster location changes are possible (with terTFCs_bw even more).
**The MAS of terTFCs is limited until the TAS-substructure is completed (areas should be available/kept free for transformations, e.g. for exchanges (recommendation). TerTFCs_bw can enable such (i.e. **) MASs (off-site) from the start.
In the case of TFCs, entire buildings can be moved at once, while TBSs must be disassembled in the case of today's factories and require adequate foundations at target locations, the same as other factory objects, which can lead to demolitions. The inner and outer mobility and transformability of today's factories are limited, as these depend on several area-related transformation units (e.g. the area-mobility and area-pluggability), and as the MAS is zero/disabled.
***When a production line/group consists of TFOs/TFSs, relocations are possible in parts (container sizes must be considered).
****Areas and substructures with their area and substructure characteristics are not movable/mobile.

Details about accelerators/acceleration units and relations between accelerators/acceleration units and fundamental enablers are provided throughout chapter 6 and must be considered.

Table 24: MASs

Today's factories are largely fixed, and the same applies to off-site areas. Implemented FOs/FSs are largely fixed and become inhibitors when their characteristics are not appropriate. This, for instance, often applies to ((quasi-)predefined) sections. Negative developments of factory characteristics and capabilities and their impacts were previously discussed. In cases where no areas are available or where there are other reasons which can make a location inappropriate, numerous FOs/FSs are lost. The mobility of factories (and production networks) is not possible, while buildings, building contents and other FOs/FSs can only partly be relocated and only with restrictions.

Parts of the TAS-substructure(s) would be lost in the case of a terTFC-relocation. Compared to terTFCs, TerTFCs_bw enable simpler and faster relocations, and marTFCs enable the fastest relocations of complete factories (and production networks) or at least of larger parts of them.

Areas and area and substructure characteristics are changed over time. In the case of today's factories, available areas become mainly built-up/overbuilt/covered and therefore decrease. Thus, area and substructure characteristics become determined, while area-mobility is impossible and therefore the MAS is zero. This leads to wasteful FPPs. Area and substructure characteristics are mobile/movable with TFCs and MASs, which leads to less wasteful FPPs. This indicates the importance of MASs for transformation enablers/units, which are limited in the case of today's factories.

Table 25 summarises further relevant capabilities and aspects.

	today's factories	TFCs
transformability	is limited and decreases further	is high and can be largely retained
exclusion of different factory configurations	relevant	irrelevant (except for terTFCs if a change of the TAS-substructure(s) is required)
definability of the 'to be'-status(es)	hardly possible to impossible	rather possible (due to faster implementations and transformations*)
definability of the 'as is'-status(es)	difficult and can even be disabled in late BFPSs	simpler definable* (*technical system)
risk of vicious cycles	high in late BFPSs (consider the dilutive effect)	reduced

Table 25: Overview of important capabilities and aspects

Figure 72 provides an overview of the transformability and transformation velocity of the developed factory concepts. The transformation velocity is comparable with the implementation velocity. TFCs enable the most rapid implementations and transformations (and therefore no or at least shorter shutdowns).

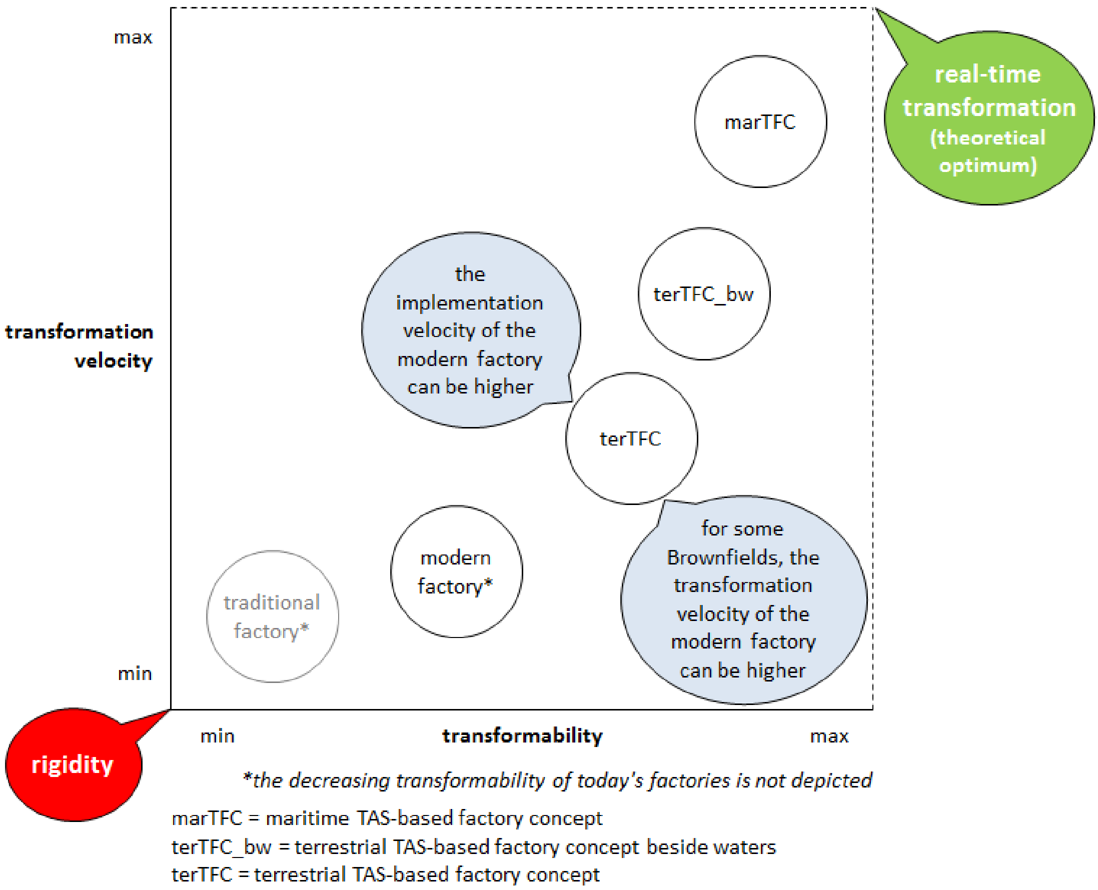


Figure 72: Transformability and transformation velocity of factory concepts

Even though some authors superficially describe the advantages of area system-based structures and factories (Scanlan, 1974; Lui, 2004; Sredic, 2011), such a picture of today's factories has not been provided in the literature nor are factory planners aware of how badly today's factories perform compared to TFCs.

To conclude: Decisions determine the transformability and future factory configurations of today's factories more than in the case of TFCs. Despite the option to implement overcapacities, today's factories become unstructured over time – particularly if several product models are produced, which can lead not only to synergy effects, but also to faster development into UHPs. To produce several product models in one factory is rather recommendable for TFCs.

Generally, today's factories are either 'more heterogeneous and efficient and less transformable' or 'more transformable and less efficient and heterogeneous' (consider universality). Both options lead to UHPs, as the achievable maximum transformability of today's factories is too low to avoid this status (consider also the contents of subsection 6.1.10). TFCs are more efficient, as they can be both heterogeneous and transformable at the same time, which is a great advantage. TFCs provide the capability to transform (e.g. reduce, extend and move/relocate) buildings and building complexes, technical infrastructure networks and further sub- and superstructures more rapidly and with a reduced effort and less negative impacts than is possible with today's factories. Companies can transform their general structure as required more quickly and easily. Factory structure recovery programmes are not required for TFCs. TFCs lead to clear advantages for Greenfield and Brownfield projects. Requirements can be fulfilled more effectively, efficiently and rapidly than before. Physical and non-material processes experience major advantages. Closer market entries for Greenfields and Brownfields are possible, while the real-life factory can always be equivalent to the ideal factory, which is not possible with today's factories. This enables closer and longer cashflows, while the risk for investments is decreased, as investments are not as bound as in the case of today's factories. Advantages for (quasi-)exceptional cases and location changes are given. TFCs require fewer or no demolitions, reconstructions and new constructions, and lead to better reusability and sustainability. Sustainable industrial structures over entire and increased lifecycles are possible.

TerTFCs are more advantageous than today's factories, while terTFCs cannot attain the advantages provided by terTFCs_bw. MarTFCs entail all benefits of terTFCs and the benefits specific to maritime solutions. TerTFCs_bw come close to marTFCs but cannot reach their potential. To compare today's factories with terTFCs_bw and marTFCs is senseless, as these are far superior than terTFCs. TerTFCs, which from a long-term perspective are more recommendable than today's factories, lead most probably to too many difficulties and are, compared to other TFCs, less advantageous. TerTFCs_bw are rather recommendable, as their difficulties/ advantages ratio is better. From all viewpoints the marTFC is the best of these factory concepts, even though environmental aspects must be seriously considered and resolved, which applies similarly to terTFCs_bw (see also subsections 7.2.3 and 7.3.3).

Today’s factories are to some extent transformable and lead to a partly transformable production system. Superstructures are partially transformable, but areas and substructures are not. Transformable production networks are disabled. TFCs enable completely transformable production systems, factories and production networks which can be structurally decoupled from one another. Hence, not only can factories continue to be efficient and sustainable, but also production networks, as these are agile.

When numerous real-world factories are viewed, it can be seen that not every transformation requirement can be pre-considered and appropriately processed. It is also recognisable that these develop into UHPs (there is not necessarily a need to consider transformations within buildings, as this circumstance is already recognisable from the outside).

One does not know how a factory needs to change, and even if this were known, it would not lead to considerable advantages in the case of today’s factories, as the limited transformability of these factories decreases over time and as different factory configurations exclude one another to a certain extent. In the case of TFCs, different factory configurations and the ‘to be’- and ‘as is’-definability are not that crucial. This is because increased transformability can be retained, and ‘to be’- and ‘as is’-statuses and the delta between them are better definable due to reduced project durations and complexity as well as increased technology use. Anticipations are more reliable, as these are closer to the reality due to shorter timeframes. Thus, the collection and processing of data is simpler.

In the case of today’s factories, the following development is normal: First, on a macro level (i.e. the factory with its sections, departments, s&d plants etc.), there are free areas that enable a well-ordered and therefore efficient factory. Second, extension and exchange areas are more and more occupied and one is enticed and partly forced to make more and more compromises. Finally, there is only the possibility to displace buildings, which means to demolish them and to construct new ones/extend remaining ones. The same happens at the meso and micro levels. Inner spaces in buildings are normally first well-ordered, then become more and more intertwined with FOs/FSs such as s&d elements, and finally require demolitions etc.

Thus, factories are in fact comparable with living organisms. It is a fallacy to believe that dynamic systems such as factories which change dynamically can survive perfectly on top of rigid structures (including areas). This applies to all dynamic systems, especially if they change rapidly, e.g. fast-growing cities with their industrial and commercial areas. Through a sensible interplay of modern physical sub- and superstructures (including Industry 4.0-developments), TASs, appropriate organisational forms, and humans, the Fourth Industrial Revolution is possible. TFCs are unrivalled, particular over the course of years. Today's factories are no longer an option, as the competitive advantages of TFCs lead to a more advantageous competitive position. It is more important that TFCs and TASs are required in order to meet current global challenges, e.g. to achieve environmental relief.

6.7 Chapter Summary and Conclusion

In this chapter the model and concepts have been developed and applied, the limitations of today's factories researched, assessed and defined, the first TAS-requirement profile developed, and the impacts of TFCs researched, assessed and defined. The differences between the developed factory concepts are now known.

The limitations of today's factories can now be better considered than before. It has been demonstrated that today's factories are not up-to-date. Industry 4.0 goes in the right direction, but forgets the core problem – the limited transformability of terrestrial areas, which has numerous negative impacts on today's factories.

Factory planning literature and practice require an update based on the new knowledge provided by this thesis.

There is no doubt that we must focus on TFCs and TASs, as without transformable areas the limited transformability of terrestrial areas can hardly be overcome.

7 Discussion and Conclusions

This chapter summarises and concludes the research project.

Section 7.1 discusses the research methodology and section 7.2 covers the research findings in relation to the ROs. Section 7.3 explains the contribution of the research. Section 7.4 answers the research questions.

7.1 Reflexions on the Research Methodology

This research required a qualitative research approach for the following reasons:

- A new topic was examined (Punch, 2005, p. 16; Edmondson and McManus, 2007, pp. 1171–1173).
- Various complex fields of study and knowledge were examined. Before this research, these were largely independent from one another (Creswell, 2009, p. 18).
- Numerous variables of interest are barely or not at all quantifiable and comparable.

Marshall and Rossman (2010, p. 68) claim that "Many qualitative studies . . . build rich descriptions of complex circumstances that are unexplored in the literature." A qualitative research approach can provide wider and better results in this research project than other approaches. This thesis involves a lot of ground work which means that references are partly not available.

Interviews played a key role in the research methodology for reasons discussed in chapter 4. The interviewer is familiar with this method, knows the relevant literature and was very well prepared. He has followed diverse rules and has applied known techniques.

The number of interviewees can be seen as a limitation of the research, despite the fact that the interviews were conducted deeply. To perform more interviews was not possible due to time restrictions. Nevertheless, important patterns are recognisable and would most probably not change to a large extent if more interviews were to be conducted, as the interviewees were very experienced and were serious. Furthermore, all relevant interview questions were answered by all interviewees (Bailey, 1994), and all topics were sufficiently followed-up. Sufficient data was gathered, as fewer relevant aspects came up with each interview. The last two interviews did not lead to any new core aspects. This validates the statement that a small number of interviews can be sufficient if these are conducted with experts (Aghamanoukjan, Buber and Meyer, 2007, p. 428).

7.2 Discussion of Research Findings

7.2.1 Research Objective 1

research objective 1: To develop and apply a new model (and associated concepts) to enable the assessment of today's real-world automobile factory requirements and of the capabilities and limitations of newly developed factory concepts.

The model and concepts were developed and applied, and their functionality validated. Recurrent real-world factory project cases and experiences from the semi-structured interviews provided the empirical data that built the basis to develop the model and concepts based on the grounded theory-based research approach (which was supported by the research and analyses of literature and technologies), while the single BFPSs in particular were validated through the interview data. Basic elements of eBFPCs have been identified. Concepts such as BMEs, difficulty factors and fundamental enablers closed a gap in factory planning theory, as factory development stages (i.e. BFPSs) and impacts of eBFPCs (which change throughout the BFPSs) are now considered, and as dynamic factory requirements can now be better assessed than before. Furthermore, dynamic factory developments and their consequences can be explained by means of the model and concepts. Dynamics in factory planning were considered, and together with the model and concepts this enabled a more comprehensive operationalisation of the development of factory characteristics and capabilities/limitations than had previously been possible. The designation 'breathing factory' was given new meaning, and the importance of the active transformability of areas could be revealed. Nevertheless, these results may serve only as the starting point for the further development of dynamic factory planning.

Dynamic structural factory developments over a factory lifecycle are hardly considered in the literature. This gap has been addressed in this thesis. Nevertheless, this research has allowed only a basic definition of the model and associated concepts, and must be understood as a basic work. The dilutive effect between BFPS-3 and BFPS-4, and relations between the BFPSs were briefly discussed, but can be analysed further. This dilutive effect in particular suggests that there can be a further improvement of BFPSs, which requires further analyses. Furthermore, the model and associated concepts (e.g. eBFPCs) can be specified for diverse factory concepts and types, and sectors. The identification of which difficulty factors occur, the timing of their occurrence, and the causes of this should be analysed further. Thus, possible future transformations can be considered and conclusions can be drawn about the required transformability of each FO/FS in order to improve their transformability. In addition, transformation enablers/units, accelerators/acceleration units and fundamental enablers, and their relations can be further analysed and differentiated, or new concepts developed.

The new model is functional and the BFPSs are valid. BFPS-1 and BFPS-2 can be retained. BFPS-3 and BFPS-4 can be subdivided into further stages in which the factory structure and complexity are focused on more than was possible in this research. Thus, the dilutive effect could be better considered. Furthermore, more complex (e.g. unstructured) parts of a factory could be mapped differently than less complex ones. This could support the abovementioned analyses of difficulty factors.

Despite the difficulties in developing parameters and the limitations of algorithms, based on the new knowledge, software solutions could be developed by which factories, changing requirements and their impacts can be better identified, assessed and defined. This can increase the potential of digital factory solutions, in which aspects such as collision checks are considered.

This research can lay the foundation for a further development of factory planning. The model and the associated concepts are generally valid for SMEs and OEMs, and can be used in addition to available factory planning theories.

The developed model and associated concepts provide an overview of factory development steps and changing factory characteristics, requirements and capabilities/limitations. The model, concepts, and results should be further developed and deepened. Difficulty factors, model exceptions and the dilutive effect between BFPS-3 and BFPS-4 should be analysed further.

7.2.2 Research Objective 2

research objective 2: To research and assess the capabilities and limitations of today's factories with regard to the technical and spatial transformability, transformation velocity, and factory planning processes (FPPs).

The capabilities and limitations of today's factories with regard to technical and spatial transformability, transformation velocity, and FPPs throughout different factory development stages (i.e. BFPSs), which are normally passed through by every real-world OEM plant, were identified and described and are evidenced in the interviews. Through the application of the model and associated concepts, it is possible to explain how efficiency and sustainability, which both depend on the development of the transformability of today's factories, develop throughout the BFPSs. This development and all other RO2-results are evidenced in the interviews.

It emerged from the interviews that the transformability of today's factories is limited and decreases further over time, and that the limited transformability of terrestrial areas is the root of the problem, as this limits the transformability of numerous FOs/FSs and thus of entire factories. This could be described and depicted with the model. To meet today's transformation requirements is hardly possible, particularly in late BFPSs. Furthermore, project durations increase over a factory's lifecycle, during which the factory passes through the BFPSs while different factory configurations exclude one another. How characteristics and capabilities of today's factories change over time and why they become UHPs could be explained by means of the model and concepts. Furthermore, the occurrences of vicious cycles and complete planning inabilities could be identified and explained, particularly through the analyses of cause-and-effect relationships and the sound combination of outcomes of these analyses. Long project durations, which also increase through changing requirements, are crucial in this regard. These are evidenced in the interviews.

The limited and furthermore decreasing transformability of today's factories leads to physical necessities that cannot be overcome. These necessities evoke such long project durations that different difficulties occur, such as new transformation requirements that occur during Greenfield and Brownfield projects which cannot be absorbed by meanwhile constructed and/or installed FOs/FSs. Numerous further and more numerous difficulties occur the higher and later the BFPS. Additional possible problems that can occur are vicious cycles and the possibility that necessary actions (i.e. required FPPs, especially in sum) cannot be defined for a specific factory development stage(s). This is exacerbated by the fact that factory requirements often cannot be anticipated. Even if future factory requirements were known, this would not lead to considerable benefits for today's factories, as their transformability (and transformation velocity) is insufficient to generate changing factory configurations as required. This is understandable when different factory configurations, which are required over time and exclude one another, are considered. This makes the problems in factory planning even worse and leads to numerous demolitions, reconstructions and new constructions over the years, which makes today's factories unsustainable and inefficient (at least less efficient than possible with TFCs). Even though today's factories produce products, after at least several years of existence they are not green/sustainable, efficient and transformable.

With today's factories, current time- and content-related challenges cannot be sufficiently met, and sometimes partly not met at all. Today's factories are not sustainable (particularly if their lifecycle is considered), whether or not one tries to maintain their efficiency. This thesis demonstrates that terrestrial areas are the root of numerous negative developments of the characteristics and capabilities of today's factories. This results in negative consequences for factory planners (e.g. increasing planning complexity throughout the BFPSs), transformational inability and UHPs.

It is possible that new factories can retain their structuredness throughout the first decade of their lifecycle. Nevertheless, this changes nothing with regard to their inappropriateness if entire factory lifecycles are considered, which can be seen 'on the living object' (as IP8 said) if older real-world factories are considered. OEM plants develop in any case into UHPs if their lifecycles are long enough.

The fact that that terrestrial areas and related transformation possibilities are taken for granted could be the main reason why the root of the problem that leads to the limited transformability of today's factories has not been identified prior to this research, and why stopgap solutions in factory planning are periodically developed.

The latest technologies and Industry 4.0-developments provide only little benefit (without TASs) when real-world factory structures (including areas and substructures) are considered against the backdrop of real-world factory transformation requirements. This research shows OEM plants in a new light, as it considers the dynamics of the factory environment and the impact of these dynamics on largely static factories.

The heterogeneity of factories (which is required for their functionality and efficiency) and real-world transformation requirements already ask for TFCs' fundamental enablers – particularly different MASs. It has been demonstrated that these are not and cannot be provided by today's factories due to the rigidity of terrestrial areas and other conditions. This circumstance and its overall consequences are now identified and described, which has closed a considerable gap in factory planning theory.

It could be demonstrated that terrestrial areas are the root of the problem that leads to the limited and furthermore decreasing transformability of today's factories. This system error of today's factories can be solved with TASs.

The way in which today's factories and diverse cooperations between factories function calls for a paradigm shift. To get rid of demolitions and to increase transformability, efficiency and sustainability must be the overall aims for all industrial and other structures.

The collected evidence suggests that the general RO2-results are correct, e.g. the limitations of today's factories, including Industry 4.0. Nevertheless, the frequency of occurrence and the extent of transformations could only be analysed against the backdrop of the collected interview data and real-world factory layouts. Furthermore, there is a difference between what is actually done in today's factories and what would be done if there were other possibilities. Moreover, it is difficult to capture the actual transformation requirements which occur over time. Not all transformation requirements are actually implemented within today's factories, as this is hardly possible and not reasonable in the light of their limitations. Factories other than automotive OEM plants require further analyses.

7.2.3 Research Objectives 3 and 4

research objective 3: To develop the first requirement profile for transformable area systems (TASs), develop TAS-based factory concepts (TFCs) and identify how they differ in comparison to one another, and to today's factories.

research objective 4: To research and assess the impacts of TFCs on the technical and spatial transformability, transformation velocity, and on FPPs.

Through this thesis, TASs can be seriously considered in factory planning theory. This thesis provides a basis for their further development, which is required in order to make TFCs real. The first requirement profile for TASs has been developed based on the interviews. It can be concluded that:

- TASs make areas transformable and can significantly increase the transformability of factories. Furthermore, a high level of transformability can be maintained.
- TASs are an equivalent counterpart to available transformable solutions, and also complement them, enable their full potential, and make RFOs/RFSs mobile/movable.

- TASs are universally usable.

Consequently, TFCs were developed conceptually, and it was identified how the developed factory concepts differ from one another. Interviews provided real-world factory project cases which were used as basic data for analyses of TFCs (particularly factory layout analyses, which were also based on other real-world factory layouts and their developments). Capabilities provided by large industrial structures (e.g. shipyards) were considered, as these enable the parallelised processes that are crucial for some TFC-related capabilities and advantages. Elements of grounded theory or, in other words, the grounded theory-based research approach in combination with abduction/logic and analyses of cause-and-effect relationships were required for these analyses.

The RO4-results in section 6.3 show that the root cause of the limited and furthermore decreasing transformability of today's factories can be resolved through TASs, and that the main problems in factory planning can thus be resolved. Besides the abovementioned approach, the capabilities and limitations of TFCs with regard to technical and spatial transformability, transformation velocity, and FPPs throughout the BFPSs could be identified through the application of the model and associated concepts. A fully transformable factory is no longer just a vision. Furthermore, it is better understandable why basic considerations of modern concepts such as 'Holonic Manufacturing' make sense. In addition, these concepts can be made real by means of TASs/TFCs.

TFCs significantly increase the transformability of factories and impact positively on FPPs, which enable faster factory implementations and transformations (or market (re-)entries). TFCs have positive impacts on the planning, implementation, and numerous transformations of factories, which can all be achieved more simply and better than before, i.e. with today's factories. Sensible factory planning is rather possible when the ability to maintain increased transformability ensures the efficiency and sustainability of factories over increased and flexibilised factory lifecycles, and thus future robustness is ensured. The chain of decisions and processes which result in inhibitors can be broken by means of TASs/TFCs. Factory planning-, implementation-, transformation-, operation- and efficiency-related advantages (also with regard to synergies) and environmental advantages which cannot be achieved with today's factories can be achieved with TFCs. Nevertheless, TASs and TFCs require further analyses and development.

Further development of TASs and engineered solutions and designs, in which relations between forces, dimensions and masses etc. are considered, could slightly change the TAS- and TFC-related results. Furthermore, it might be particularly difficult to implement terTFCs, as the required efforts could exceed the benefits. Moreover, environmental aspects (e.g. environmental risks and disadvantages) could only be superficially considered. These could also impact on TASs and TFCs. Nevertheless, new technologies, systems, and solutions could, on the other hand, lead to positive aspects (see subsection 7.3.3).

Despite these points and even though the research results are basic, they are valid and reliable.

This thesis shows that factories are comparable with living organisms. Thus, modern concepts (subsection 2.1.3) are much more relevant than is acknowledged in the current literature. If areas and substructures continue to be not transformable, this knowledge is largely useless for factory planning, as these modern concepts cannot be implemented in practice and therefore remain visionary, despite numerous Industry 4.0-developments.

To enable organic transformations and growth would be beneficial, and is possible through TASs. TFCs can lead to the Fourth Industrial Revolution in which the ideas of 'holonic manufacturing' and 'bionic manufacturing' etc. can be re-examined.

Thus, FOs/FSs (including areas and substructures) can be more heterogeneous as required and factories can be more efficient and sustainable. The described parallelised processes are feasible. This is crucial for rapid factory implementations and transformations, which can be extensive and wide-ranging. Furthermore, TASs/TFCs can be perfectly combined with Industry 4.0 and digital solutions, e.g. digital factory and control systems.

Economic viability and profitability were not analysed. Despite the limitations of the research, enough evidence was gathered to demonstrate that the transformability of areas (sub- and superstructures) should be increased. The RO3- and RO4-results might be perceived as superficial, but these results are valid and reliable.

7.3 Contribution to Knowledge

7.3.1 Contribution to Theory

The developed model and associated concepts could be relevant to factory planning, as they enable a more comprehensive assessment of the capabilities and limitations of the developed factory concepts throughout their lifecycle than is possible with today's factory planning theories and concepts. Together with the other concepts, BFPSs provide a new perspective that enables this assessment. EBFPCs and difficulty factors help to understand how impacts of factory project cases change throughout the BFPSs (this could also contribute to the further development of chaos theory). Furthermore, movements were recognised as the basic elements of factory implementations and transformations which led to BMEs, and in addition important transformation and transformability requirements were identified. Fundamental enablers in particular enable the assessment and definition of the abovementioned capabilities, limitations and requirements. Thus, a comparison between the developed factory concepts is possible against the backdrop of real-world factory requirements, which can now be better assessed than before.

Furthermore, limitations of some factory planning theories (which are to some extent evoked by or partly based on the limitations of today's factories) were revealed, which can also have an impact on factory planning practice.

In the past, symptoms rather than causes have been treated, as the root of the problem was not identified. This means that it was not recognised that terrestrial areas lead to the circumstance that the transformability of today's factories is limited and decreases further over time, i.e. throughout the BFPSs. This is harmful, as different factory configurations exclude one another, which leads to vast demolitions, reconstructions and new constructions, and makes today's factories unsustainable and less efficient than is possible with TFCs. These and further aspects can be used to further develop factory planning theory and particularly practice. The RO1-results in particular can be combined with factory planning approaches, FPP models etc., but should be developed further. The difficulty factors in particular provide a basis for a further development of factory planning theory and practice.

The limitations of today's factories should be erased, which is possible with TASs/TFCs and based on the RO2- and RO3-results. The RO4-results provide a picture of the potential provided by TASs and TFCs. All main RO-results are an original contribution to factory planning theory.

7.3.2 Contribution to Practice

The model and associated concepts make the impacts of factory project cases throughout the BFPSs and the backgrounds to these impacts more concrete. The BFPSs provide a framework by which the complexity of different factory projects can be overlooked in a structured and relatively simple manner. This model helps to more specifically explain the real and intensified problems within factory development stages. This is possible because BFPSs provide a new viewpoint, which enables a realistic assessment and evaluation so that the far-reaching limitations of today's factories with regard to their transformability and their planning, implementation and transformation can be explained and portrayed. Project durations can be roughly estimated through the model and associated concepts, as the required tasks/works can be roughly assessed, which can support factory planners in their daily work life. Furthermore, an impression about the real conditions in factory planning and the challenges that are faced by factories and factory planners today can be given through the RO1- and RO2-results.

Even if the model and concepts can already be used (e.g. to explain key issues in complex projects and to define FPPs), the difficulty factors in particular should be further analysed and developed for use in practice, as they can help to define the impacts of factory projects better than before. Subsection 6.1.10 and the related appendices are relevant for this development.

Moreover, the findings of this thesis can help to improve the transformability and other capabilities of FOs/FSs in a more targeted way (consider subsection 7.2.1). Nevertheless, increasing the transformability of factories through TASs is possibly the only way to appropriately manage current challenges, as it has been demonstrated that terrestrial areas are not sufficient as a basis for OEM plants. The model and associated concepts also provide an additional possibility to the already existing approaches to assessing transformability and other requirements.

This research shows the need for exchange areas. From an 'area-related viewpoint', extension and exchange areas at different layout positions must be reserved, while future position changes of numerous FOs/FSs should be considered, which is almost impossible or impossible. Whether these areas will be required at all is unclear, but is highly likely. Furthermore, it is unclear when and which areas will be required, and how/for what. To have sufficient extension and exchange areas is advisable for OEM plants (i.e. today's factories)*, even though all future requirements cannot be known upfront. These areas can be split into sections to enable their extension and/or other transformations, *but distances to other FOs/FSs will be increased.

From a 'structural point of view', current OEM plants should be implemented with a defined capacity and defined production technologies. The production of several product models in one plant should be avoided, or these should be structurally separated as far as possible, despite the fact that several synergy effects will not be available. Successor products should be largely comparable (consider the constant switch in subsection 6.1.7 and appendix 6.1.7_02). All this is hardly possible, as the market decides what is required. If an additional new Greenfield factory is built when there are transformation requirements in order to maintain the structuredness of a factory (instead of transforming a given factory which would lead to an unstructured factory), competitors might be more competitive first if these transform their factories (e.g. if the transformation can be effected much faster than the Greenfield), even if developing into a UHP. A factory structure recovery programme is a further option which might help to retain the factory structure, but if competitors transform their factories without such a programme, they would again be more competitive. Thus, if recommendations which aim solely toward a better factory structure are followed, the factory might not survive. If not, it will most probably survive but will develop into a UHP. *(From a long-term perspective, competitors of an OEM that uses TFCs have hardly a chance to survive at the market if the costs for TASs are appropriate or if increased costs can be survived (quite apart from the fact that TASs/TFCs are sustainable). TAS-/TFC-based production networks can be more competitive than those which are based on terrestrial areas, even if costs for TASs are higher than for terrestrial areas. Due to the fact that today's factories are all based on terrestrial areas, there is no significant difference between their transformabilities. This is the reason why most factories survive.)* To develop further TFOs/TFSs and TFOs/TFSs further is recommendable, but problems with regard to areas and substructures must be considered and will remain unsolved. FOs/FSs will face limited possibilities as long as these penetrate rigid areas and structures (particularly below ground level). To position departments etc. at the periphery in order to free the centre for sections can be sensible. Nevertheless, effective arrangements of sections and other FOs/FSs (e.g. factory fire brigades) change over time. Therefore, such positionings are only temporary solutions that impact on a factory's efficiency, sustainability and safety.

From a 'factory planning perspective', it is difficult to make generally valid recommendations, as too long planning but also too superficial planning can lead to problems. What can be said is that the limitations of today's factories and the other outcomes of this thesis should be considered. One never knows which project case will come up, but one can know the impacts of different cases, at least roughly. The contents of this thesis at least can help to define project durations, required capacities, investments and risks better than before. BMEs and difficulty factors can provide support to make correct decisions against the backdrop of the reached BFPS and factory configuration/status, e.g. its structuredness. Thus, the thesis results can be used to improve the practical application of factory planning theory – especially after their further development (consider the potential of digital solutions). Furthermore, difficulty factors can be considered within investment analyses and calculations.

Most eBFPCs lead to demolitions in BFPS-3 and BFPS-4, not to mention the unstructuredness of today's factories which occurs over time. Factory structure recovery programmes are destructive, hardly manageable, increase the risk for vicious cycles, and can lead to more serious problems, in the same way as other eBFPCs. Today's factories are not sustainable or appropriate to meet the Zeitgeist. Thus, the only sensible recommendation is to get away from today's factories and to focus on TFCs, and in particular marTFCs, as terTFCs still involve some of the disadvantages of terrestrial areas.

Current developments in drive technologies show that existing OEM plants can hardly handle current transformation requirements, which demonstrates why it can be advantageous to implement TFCs. OEMs that were late with such technological changes can thus experience advantages. Nevertheless, TASs and TFCs require further development.

"*Every great and deep difficulty bears in itself its own solution.*
It forces us to change our thinking in order to find it."

Niels Bohr

Today's factories are not sensible for the automotive sector and other comparable sectors, as their transformability is not capable of fulfilling transformation requirements in an appropriate way. Vast demolitions, reconstructions and new constructions are required. Numerous FOs/FSs of today's factories are hardly reusable or are not at all reusable. We must abandon the illusion that today's factories are appropriate for today's challenges; it is necessary to break away from these limitations and think about alternatives. The transformability of factories should be significantly increased, and this is possible through TASs.

Different factory concepts can also be combined as required, which can lead to advantages. It can be advisable to implement press shops and/or paint shops without TASs, or with a separated TAS-substructure. The former option destroys at least partly the basic idea of TFCs. From a long-term perspective, we should get rid of outdated solutions.

TASs/TFCs provide lifecycle and transformation cycle advantages. Even though horizontal and vertical integration changes are currently possible, TAS-/TFC-based production networks are more advisable. Besides the described advantages in subsection 6.3.6, flexibility and capacity strategies can also experience advantages. MarTFCs in particular lead to advantages for factories and production networks, and should be developed further and implemented. Nevertheless, environmental risks must be prevented.

TASs as universally usable serial/series products can lead to synergies between different TAS-based solutions. Maritime developments and other developments (not only of technical solutions) and needs accelerate the need for marTASs (consider global warming, sea-level rise and world population growth, which create pressure on available terrestrial areas).

TASs not only require a change in thinking, but can also help to carry out this change. To question current systems and mindsets is not sufficient. The change to a future-oriented world is only possible together, either freely or under constraint (the environment will force us to change our thinking).

7.3.3 A Basis for Future Research

The research results should be used to improve risk management and methods of investment analyses and calculations. Moreover, scenario techniques should be developed further, as should factory planning theory. Digital factory and control systems can support this further development, and can themselves be improved through the results of this research. In this context, the new model and associated concepts should be elaborated and should also be specified for diverse factory concepts and types, and industrial sectors.

Factory planning theory should be developed further for TFCs (and theories for other TAS-based purposes/structures). Additional development and specification of TASs is required in order to further develop TFCs and to develop (physical and non-material) FPPs. The TAS-requirement profile requires additional development and specification (also for purposes other than as a basis for factories). It must be ensured that TASs meet their requirements. The most important aspect is to prevent environmental risks.

New flexible production plant and machine concepts can lead to advantages for TFCs. Instead of large capital-intensive deep-drawing presses and punching/ stamping machines, a further development of smaller, modular and movable/ mobile machinery (e.g. based on other functional principles) is recommended. Through these new concepts, it is even more sensible to integrate suppliers into TAS-/TFC-based production networks. It is also conceivable to develop new machine solutions for raw material producers, which could be integrated into such production networks. TASs can enable the development of new, more transformable and otherwise advantageous process facility concepts.

The properties of water, TAS-substructures and/or TAS-elements could have positive impacts on diverse processes and on the quality of produced parts. Furthermore, machines could be decoupled from solid TAS-element combinations. Decentralised s&d plants and other FOs/FSs are also conceivable. This requires deeper analyses.

By means of TASs, paths to new factory concepts that are capable of permanently meeting high factory requirements and that can enable concepts such as ‘Holonic Manufacturing’ and ‘Bionic Manufacturing’ are accessible. These concepts require an update, and must be reconsidered based on the knowledge provided by this research.

TASs provide advantages for both centralised and decentralised (as well as diverse combinations of centralised and decentralised) control of systems and processes (not only of factories); this requires analyses.

For a reliable business case and for comparison between today's factories and TFCs, not only the costs for TASs should be considered. A comprehensive business case and reliable comparison are currently hardly possible due to an insufficient quantifiability of relevant factors. This suggests starting with an argumentative balance sheet until sufficient data is available. A business case and quantitative comparison between today's factories and TFCs will then be possible.

Today, the analysis and assessment of value streams occurs mainly within factory boundaries. Interfaces to other factories are partly considered, but not the entire production network and related processes (particularly as segmented factories are not locally joined and often produce products for different customer factories). Methods for the analysis and assessment of value streams should be improved in order to enable a more comprehensive operationalisation which crosses factory borders and preferably also involves bullwhip effects, opportunity costs (including those of savings), logistics costs etc. This can support the further comparison of different factory concepts and the previously mentioned business case (consider locally joined factories in a combined network).

Laws, regulations and approval processes for implementations and transformations of TASs and TFCs should be developed, developed further and/or specified. Furthermore, marTFCs should be analysed deeply (e.g. from a maritime law perspective) against the backdrop of different positions, sizes and configurations with respect to nautical-mile-zones. MarTFCs can be connected to the shore and fixed (e.g. to the marine ground) or unfixed. MarTFCs can also be disconnected from the shore, fixed or unfixed, i.e. afloat. Against the backdrop of these possibilities, the following aspects must be clarified:

- laws, regulations and approval processes for implementations and transformations
- positive and negative dimensional restrictions
- production-related possibilities, advantages and disadvantages
- safety and efficiency of vessel traffic

- governmental, public and private affairs/aspects
- marine environment and water protection, e.g. pollution, contamination, fire protection etc.

Some of these points are also relevant for other TAS-based structures and purposes.

TASs can be used not only for factories, but also for energy conversion (e.g. wind, sun, water/wave energy and solids) and storage, container yards, harbours, shipyards, other industrial structures, agriculture, aquaculture, living and working spaces, and many other purposes, including the removal of garbage in waters. Knowledge about possible emergency situations – for instance an emergency situation caused by a tsunami or another natural disaster(s) with an extensively demolished technical infrastructure, destroyed hospitals and missing food and drinking water – and about the capabilities of marTASs can lead to the idea to develop and implement a floating platform(s) with health facilities for first aid and further support. Combinations of these purposes are also conceivable, e.g. a factory using direct energy conversion. This can lead to synergies and further advantages such as lower expenditure of money, time, effort and resources, while huge structures can be directly brought to their (quasi-)final location and relocated as required.

Furthermore, frameworks for different purposes can be provided by means of TASs which means for instance that s&d plants and technical infrastructures can be provided as basic elements for changing purposes.

It is necessary to bring together representatives from different disciplines in order to ascertain whether new disciplines for TASs and TFCs are required, and if so, to identify which disciplines and how these can be established. Additional aspects for future research and needs are the further development of TASs, legal issues, other possible uses and their combination, environmental risks and their prevention, and other factors.

7.4 Summary Responses to Research Questions

research question 1: What concepts are required to assess today's real-world automobile factory requirements and the capabilities and limitations of newly developed factory concepts?

Transformation enablers, accelerators, fundamental enablers, eBFPCs, difficulty factors and BFPSs are the main concepts that are required in order to access today's real-world automobile factory requirements and the capabilities and limitations of newly developed factory concepts.

research question 2: What are the limitations of today's factories with regard to the technical and spatial transformability, transformation velocity, and FPPs?

The transformability and transformation velocity of today's factories decrease throughout the BFPSs. This has negative impacts on FPPs, such as extended durations. Furthermore, different factory configurations exclude one another.

research question 3: How can the transformability of areas be increased?

The transformability of areas can be increased through area systems – in particular through TASs.

research question 4: What would be the impacts on the technical and spatial transformability, transformation velocity, and on FPPs if areas were transformable?

The transformability and transformation velocity could be maintained if areas were transformable. This would have positive impacts on the FPPs and project durations of most project cases; these can be significantly decreased compared to those of today's factories.

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Appendices

Appendices to Chapter 2

Appendix 2.1.1: Backgrounds to the Definition of Terms

In practice, the term 'plant' is often used synonymously for a huge factory. The VDI 5200 (2011, p. 7) describes a plant as "a closed production unit spatially bounded by virtue of its location and ... may have several buildings. In addition, there may be a network of internal traffic routes, outdoor facilities and also [a] connection to the infrastructure outside the plant." Furthermore, the terms "production site" and "manufacturing plant" are used synonymously for the term 'factory' (Chryssolouris *et al*., 2014, p. 500). "Manufacturing plant", in turn, is used synonymously for the term "production plant" by Westkämper *et al.* (2004, p. 6). Both manufacturing plant and production plant are identically described as a "...technical system or subsystem executing an individual production task, often automatically or semi-automatically." (Westkämper *et al.*, 2004, p. 6). The term "manufacturing plant" also relates to facilities that are suitable for the "...production of individual parts by means of machining and processing equipment..." (Schenk, Wirth and Müller, 2010, p. 8). This definition is comparable with the definition of Westkämper *et al.* (2004, p. 6), but Schenk, Wirth and Müller (2010, pp. 1–11) use the term "manufacturing plant" in different ways and therefore inconsistently and partly contradictory, especially in conjunction with the terms "factory" and "production facility". These designations are not clearly delimited, which can lead to confusion. A "manufacturing plant", for instance, can be interpreted as the highest hierarchical factory structure level (Schenk, Wirth and Müller, 2010, p. 10) and also be equivalent to a part of a production line (Schenk, Wirth and Müller, 2010, p. 8). "Production facility" is a further synonym for the terms "manufacturing plant" and "production plant" in accordance with Westkämper *et al.* (2004, p. 6), while the first-mentioned can be interpreted as a further synonym for the term 'factory' (Schenk, Wirth and Müller, 2010, pp. 1–11), which increases the confusion because relevant literature with regard to factories is obviously not coordinated. According to Köhler and Legat (1955, p. 64), a "production plant" is furthermore equated to large-scale and high-duty plants. Numerous other definitions can be found in the literature.

Appendix 2.2.1: Details to BFPCs

Helbing (2010, pp. 88–90) mentions the integration of factories into the s&d infrastructure of locations. 'BFPC-1' and 'BFPC-2' of Helbing are basically comparable with Grundig's (2015) BFPC-A, even if Helbing's BFPC-2 is considering an area limitation through narrowing (Helbing, 2010, p. 89). This narrowing is not specified, and existing FOs/FSs could be meant. Narrowing appears also as 'BFPC-6' without further specification, while it is probable that Grundig's (2015) BFPC-D is meant. 'BFPC-3' of Helbing is broadly equal to BFPC-C, while 'BFPC-4' and 'BFPC-5' can be associated with BFPC-B. BFPC-4 refers to renewals and BFPC-5 to rearrangements of FOs/FSs.

Appendix 2.2.5: Scenario-related Details

On the one hand, Grundig (2015, pp. 18–20) claims that production programmes can be relatively exactly determined. On the other hand, Grundig (p. 23) talks about a dilemma in factory planning, as work results become more precise when they are processed (which means over time). He recognises that information for site selection and the definition which buildings will be required must be accessible before the abovementioned work results are available. Therefore, factory planners must work on the basis of key figures, comparisons, and estimations, which must meet the real requirements almost exactly. Grundig emphasises the importance of the experience of planners which must determine and specify required information that can only be validated in a later step. Thus, continuous factory planning is required, while factory planners involve often scenarios within their planning.

Scenarios are developed in strategy planning (Gausemeier, Stollt and Wenzelmann, 2006), while Hartkopf (2013, p. 44) shows that strategy and factory planning have a strong connection, as both must be synchronised. Hartkopf (pp. 64–65) claims that a retrospective quantification allows a prognosis of future demands on resources. He talks about continuous developments and claims further that discontinuous developments such as technology innovations can be systematically pre-planned. An approach for this pre-planning (of which's functionality is doubtable) is shown in his thesis. Further scenario-based planning procedures are described in Wemhöner (2005) and Friese (2008). All they have in common is that a chosen factory or production network configuration influences future configurations (p. 39). 'X' determines 'Y'. This means that if X machines (e.g. two) have been bought within a Greenfield project and Y further ones (e.g. five) are assumed to be required by the end of a first Brownfield project, a different number will be bought depending on the decision within the Greenfield project. Numerous X-Y-relations must be considered. Market, technology and product changes – besides numerous further ones – are influencing these relations (Wiendahl *et al.*, 2013; Wiendahl, Reichardt and Nyhuis, 2015, pp. 341–342).

Non-steerable key factors are, for instance, "market dynamics, laws and developments", globalisation, "economic development[s]", "innovation speed[s]", "technology development[s]", customer characteristics and the "demand trend[s]", "import[s] and export[s]", "price requirements", "market strategy[/strategies] of competitors", "[structures of] supplier[s] ... [and their] power", "industry-specific standards and norms" and "financial ... [and] ecological [policies]". Steerable key factors, on the other hand, are, for instance, numbers, models, "types" and "variants" of products, "product prices", locations and related development strategies, levels of investments, "vertical integration", lifecycles and diverse strategies (Wiendahl, Reichardt and Nyhuis, 2015, p. 380).

Based on a number of scenarios that consider key factors and their possible outcomes, a factory layout can finally be chosen (out of a number of developed ones) that is often a compromise that fulfils the main requirements of one or several of the considered scenarios. The possibility to transform the chosen layout/factory configuration in order to reach other factory configurations (e.g. of the other scenarios) is often considered, e.g. through extension areas outside and inside buildings. Factory planning is either based on scenarios or not based on scenarios, while a scenario-based planning can optionally involve probabilities

(Hernández, 2002). Scenarios involve mainly estimations, forecasts, and assumptions or, in other words, anticipations (Friese, 2008). A planning without scenarios would lead to a hand-to-mouth planning that has no database at all.

A planning with scenarios is designated as scenario management or scenario technique (Hernández, 2002). Numerous scenario techniques are available. They are differentiated into explorative and anticipative techniques. The available techniques are not differentiated in this research project, as they are mainly based on anticipations (Fink, 2002b). Hernández (2002, p. 96) argues that it is not about prognosticating the future when scenarios are used, but to pre-think and pre-plan it (which is basically the same as one needs prognoses/to prognosticate alternative futures to be able to pre-think or pre-plan the future) (see also Fink (2002b, p. 297)). Based on these considerations, plausible pictures of the future or scenarios emerge. Thus, entrepreneurial decisions and strategies can be planned and evaluated based on these scenarios. This is doubted by the author of the thesis in hand (see subsection 6.1.2 for further details). Hernández (2002) uses scenarios to assess and plan factory developments and the transformability of factories. Future factory developments depend on factory configurations (Friese, 2008) and on the transformability of factories (Hernández, 2002). The scenario-based planning procedure of Hernández (2002) that has been developed to anticipate, assess and plan required transformations considers time horizons of maximally 10 years. It has been recommended by Hernández (p. 106) that this time horizon for the scenario-based planning of factories should not be exceeded. Furthermore, the number of key factors which influence possible scenarios has been limited to maximally 40 (p. 98). Vester (1999, cited in Hernández, 2002, p. 98) claims that twenty to forty key factors suffice to describe a complex system fully (see also the statements of Vester (2012) in subsection 6.1.2). These influencing factors are mutually influenced, as argued by Hernández (2002, p. 111). An application example which has been used in Hernández’ thesis to demonstrate the usefulness of this procedure considers 20 key factors and a time horizon of 7 years in the light of a factory with an area size of 1.2 hectare that can be extended to maximally 1.6 hectare (Hernández, 2002, pp. 130–133), which is a further simplification of the reality’s complexity. The way in which the mutually dependent and influenced key factors are considered remains furthermore unclear.

Heger (2006), who has defined a further method for the assessment and planning of transformability and of transformations, claims that factory planning experts or participants need to have a special feel for future factory developments in order to make his method work (p. 106). Assumptions must be defined not only for the 'to be'- but also for the 'as is'-transformability to make this method fully work (p. 69). Velkova (2013, p. 117) goes a step further and argues that (it is appropriate to compare the 'as is'-transformability with future transformation requirements and that therefore) a coupling of an early warning system and the method for the assessment of the transformability of production systems, that has been developed by her, is appropriate. How such an early warning system can provide required information remains undisclosed. A scenario planning with a number of generated scenarios is designated as future-robust planning (Hernández, 2002, pp. 95–107).

Appendices to Chapter 4 and Chapter 5

Appendix 4.2.3 Search Terms and Boolean Searching

The following search terms and related verbs, adjectives, nouns, plural forms, gerunds etc., synonyms and/or equivalent German words, if any, were used and combined to find sources:

	search terms (excerpt)
a	ability, advanced, advanced building system, advanced machine system, advanced manufacturing, advanced production, agility, approval, approval process, approved, area, assembly, assembly line, assembly shop, automobile, automobile manufacturer, automotive, automotive manufacturer, automotive industry
b	basic, basic factory planning case, Brownfield, Bluefield, body, body shop, building, building land
c	capability, car, case, cell, change, change ability, changeability, characteristic, column, compatibility, compatible, configurability, construction, construction site, converted ship, cycle
d	department, develop, development, development stage, disposal, division, dock, docking, docked
e	element, engineering, environment, external infrastructure
f	facility, factory, factory concept, factory development, factory development stage, factory planning, factory planning process, factory planning project, factory project, factory sector, factory section, flexibility, floating, floating production storage and offloading, floating structure, foundation, FPSO
g	geology, Greenfield, global, globe, grid
h	hard infrastructure, hydro, hydraulic, hydraulics
i	implementation, industrial, industrial engineering, industry, infrastructure, internal, internal infrastructure
l	land, land development, law, layout, lean, lean manufacturing, lean production, lifecycle, limitation, line, locate, location, location change
m	manufacturing, manufacturing system, maritime, maritime development, maritime law, mobicell, mobile, mobility, modern, modular, modularity, module
n	new, new technology
o	OEM, operation, original equipment manufacturer
p	paint, paint shop, permission, permit, permitted, pillar, plan, planning, planning project, plant, platform, pontoon, practice, press, press shop, produce, producer, production, production line, production network, production sector, production system, project, projecting
r	rail, real, real world, real-world, reality, reconfigurability, reconfiguration, reconfigure, region, regional, relocate, relocation, research, requirement, requirement profile, robot, robot cell
s	scalability, sector, section, semi-submersible, site, soil, solution, spatial, stage, sub, submersible, substructure, subsystem, superstructure, supplier, supply, supply chain, sustainable, sustainability, synergies, synergy, system
t	technical, technical infrastructure, technological enabler, technology, terrestrial, terrestrial area, terrestrial law, theory, transform, transformability, transformable, transformation, transformation ability, transformation cycle, transformation enabler, transformation object, transformation rate, transformation unit, transformation velocity, truck
u	unit, universality
v	vehicle, ventilation, vessel
w	water, workstation
Information: Names of numerous suppliers and automobile manufacturers (OEMs) such as Bentley, BMW, Ford, Jaguar Land Rover and Toyota, and names of authors and scientists were searched too. Furthermore, area systems and diverse maritime structures were searched. Required terms for these searches are recognisable in subsections 2.3.4 and 2.3.5.	

'Boolean operators' are "AND", "OR" and "NOT". They are used when two or more search terms are combined. The combination of operators and search terms leads to the creation of search strings. The AND operator retrieves literature that includes both key terms. This operator is "used to narrow a search." The OR operator retrieves literature that includes either of them (key terms). It is "used to broaden a search." In addition, the NOT operator is "used to narrow a search by excluding documents [that] contain specified keywords". The positioning of brackets around key terms and operators defines the succession of the search process. The use of brackets is normally analogous to mathematical rules and determines the searching sequence. Search engines can work differently. It is therefore safer to use brackets (University of Gloucestershire, 2009). Search engines were also used on web pages of patent offices.

Appendix 4.3.1 Basic Consideration

Factory planning is functional – otherwise, factories would be non-existent. Consequently, factories can be in fact planned and implemented or re-planned and transformed. The question is which factory with which factory characteristics and capabilities is finally the outcome of these efforts and if this factory meets its actual requirements and to what extent, as there are clear limits in factory planning. If a factory meets its actual requirements at the end of a factory project is often hardly (directly) recognisable by the majority of factory planners, as not all relevant information and framework conditions are provided to them or recognisable by them. Market researchers, strategy planners and top managers are rather aware of these requirements, even if scenario techniques are inoperative. These people know earlier premises and can compare them with current (or real-time) requirements. Therefore, the following statement is self-explanatory: When a factory project does not lead to the required factory (characteristics), it is normally not recognisable by the public.

The best case in factory planning is always when the real factory is equivalent to the (theoretically) ideal factory in terms of its functional characteristics, e.g. efficiency and sustainability. Before and at the beginning of each Greenfield project – during the strategy phase and the first planning phases – many premises are open to change, as the transformability of developing factories is high at this stage. Consequently, FOs/FSs can be re-planned in order to reach the best possible factory solution against the backdrop of given framework conditions, e.g. restrictions. Thus, an almost ideal factory with an efficient operation can be reached and preserved, at least in this theoretical phase.

Theory is only as good as practice allows. Over time, factory planning turns into reality. Time has a great impact on both the transformability of factories and the quality of required planning data. Factory planners must work with this data. The shorter the planning and implementation or re-planning and transformation phases, the better the data quality and in consequence the clarity of 'what' is required to be done to implement or transform a factory or in other words, the less required are forecasts. Future market and other future factory environment requirements (i.e. required factory planning input data) can the better be prognosticated the closer the data is to the present. Consequently, factory premises can be defined and planned actions performed the better, the shorter the respective periods of time. The longer these periods of time the worse becomes the quality of originally acquired data due to continuous data changes. Today, substantial changes of the factory environment are normal. The problem is that one single change of the factory environment can change large parts of the required factory planning data (as the factory environment data determines the factory planning data) and have significant impacts on the planned and – in the meantime – partly or completely implemented or, in the case of Brownfield projects, transformed factory in consequence of a huge, complex and mutually influenced amount of data. Consequently, earlier performed actions can become void while new transformation requirements might come up. These requirements can also lead to (re-)transformations of initially planned and performed implementations and/or transformations. A further and more relevant problem is that the transformability of today's factories is limited and decreases further over time. The problem with regard to the data is discussed more detailed in the following paragraph before transformability aspects are discussed in the then following paragraph.

To anticipate and project (in the sense of depict) all relevant future factory environment statuses and, in turn, all relevant factory requirements to the present is not possible at all due to an enormous data complexity and continuously changing factory environment developments, i.e. changes of product technologies, markets, customer requirements/wishes, production technologies and labour markets etc. As the factory environment data leads to the factory planning premises/data (i.e. production output figures etc. and thus required factory capacities in terms of areas, buildings, energy conversion, energy consumption, water consumption, wastewater generation etc.), continuous changes of the first-mentioned impact on the latter. Data are classified as non-steerable and steerable data. The non-steerable data – which is mainly the data from the factory environment – leads finally to the steerable data, while the steerable data is only steerable within a limited frame. This has not been highlighted so far. Due to the fact that the steerable data is determined by the factory environment, the size, position and shape of this frame can change. A change of the size of this frame means that if, for instance, the market requires a production volume of 120,000 units (e.g. of vehicles) per year and one year later 240,000 units, one can change shift models and working times to increase the production capacity of a factory that can produce 120,000 units, but the required capacity cannot be reached. The requirement to produce vans instead of cars would be rather equivalent to a change of the form of this frame, while the requirement to relocate a factory could be perceived as a position change of this frame. Many further examples of changes that can appear and require transformations are conceivable. The data complexity is that high and the relationships between data that manifold that no factory planning approach can be defined that considers all relevant backgrounds and framework conditions in the required manner. Too many single data fragments that are relevant and influence one another exist. Furthermore, each data fragment has its own development and thus an individual prediction interval. In addition, numerous spatial and technical detail requirements that can first be defined during the work progress evoke further (micro and meso) prediction intervals. These mutually influenced data fragments with their prediction intervals lead in sum to an unpredictable macro prediction interval. The single statuses of these data fragments – which are continuously changing over time – form together the necessary factory planning data that cannot be considered upfront, e.g. at the beginning of a Greenfield or Brownfield project. Consequently, the factory planning data is continuously changing during the project duration. Scenario techniques may lead to some advantages but strategy and factory planners are no truth tellers. Estimations, forecasts and assumptions (anticipations) that are made based on vast simplifications do therefore hardly serve their purpose in factory planning against the backdrop of our manifold and ever-changing world. Prediction intervals are not considered in factory planning to the required extent. The considered number of key factors is limited, while the probability of occurrence of these key factors is hardly or not considered. Mutual dependencies/influences of the key factors are furthermore hardly or not considered, while it is highly questionable if these data can be handled with probability theory, and how. Time horizons of more than 10 years are anyway neither considered nor considerable in factory planning. Further aspects such as the limited transformability of today's factories which decreases further over time are not considered at all.

Even if it were possible to anticipate all relevant developments of the factory environment and, in turn, all required factory characteristics (which is not actually possible at all from the perspective of a realist), it would not provide considerable benefits to today's factories. The reason for that is the transformability of today's factories which is limited and decreases further over time, as decisions are taken, processes initiated, performed and/or completed, and leads consequently to mutual exclusions of ideal factory statuses and configurations. (This means that a (ideal) factory in t=1 (e.g. a factory in which a car model 'a' with a capacity of 'x' is produced) disables at least partly the transformation to a (ideal) factory in t=3 (e.g. a factory in which a car model 'b' with a capacity of 'y' is produced). The factory in t=3 is quasi/can be seen as another factory at the same location (t=2 is the starting point of the transformation phase which starts with the recognition of a transformation requirement that leads to the initiating idea for a transformation and consequently to the start of a Brownfield project).) Such processes are the acquisition of building land and area-related preparatory and construction works. The acquisition of building land, for instance, determines the location, area size, shape/form and quality (e.g. soil condition and maximal floor load capacity), and finally possible factory layouts and factory layout developments (or transformations), while construction works lead to rigid (not transformable) FOs/FSs such as solid foundations, technical infrastructure networks, s&d plants and other objects and structures that are mainly fixed and not non-destructively transformable after their construction. These rigid FOs/FSs are of high relevance, as they inhibit the implementation and/or transformation of factories if their characteristics (e.g. foundation types, dimensions and positions) do not meet the latest requirements. In such a case, FOs/FSs can be designated as 'inhibitors'. Laws and regulations can also be inhibitors. Inhibitors are the reasons for time-consuming FPPs. If, for instance, an FO must be removed to free the required area and room for a new (and then required) FO, it can be required to demolish areas and substructures of the first-mentioned. This can be time-consuming and result in production capacity shifts and moves of other FOs to free the room for transformations/demolitions. Furthermore, processes which are required for the new FO must be fulfilled, e.g. product development, production, assembly and installation processes. Further processes such as purchasing, awarding and construction processes can be required, e.g. for the construction of new machine foundations. Numerous kinds of inhibitors exist. They are ranging from rock layers within areas over water pipes and up to buildings that disable direct/immediate implementations and/or transformations and require FPPs that must be performed to reach a required intention or status. These processes (which could also be designated as time-eaters) emerge consequently during the planning and implementation or re-planning and transformation of factories. Entire factories and even larger structures can be inhibitors.

Preparatory operations (e.g. the land levelling and excavation of pits/trenches) can first lead to an increase of transformability and afterwards to a decrease (when the characteristics of created structures do not meet the latest factory requirements). The same applies to FOs that are a result of construction processes. A user-specific building foundation with an (reserved) extension area, for instance, can first enable a factory transformation (e.g. in the case of a building extension) and disable further ones afterwards, e.g. in the case of a road construction at the same layout position. Capacities and accuracies of machines and the like can also require/lead to inhibiting objects and structures. Hence, FOs/FSs can first increase and later decrease the transformability of factories.

Thus, not only planning mistakes but also and especially decisions that were once reasonable can have extremely negative effects on the 'newest presence' if the already started or accomplished actions become – in consequence of changes of the factory environment – void (right becomes wrong over time). Latest requirements can thus not be absorbed by the factory without demolitions and/or intertwinings, as the transformability of the latter can meanwhile be insufficient to appropriately meet new transformation requirements.

In sum, actual factory requirements that are relevant for factory operation phases cannot be anticipated due to a complex and ever-changing amount of data, while the transformability of today's factories is limited and decreases further over time. This applies to both Greenfield and Brownfield projects and is consequently relevant for today's factories in their first years of existence, but especially for factory lifecycles of 10 and more years.

At the beginning of a factory lifecycle, a relatively ideal factory can be planned and implemented against the backdrop of defined premises and factory requirements (e.g. required factory capacities) if the factory environment does not change significantly. The same applies to the first (e.g. two to three) Brownfield projects if appropriate areas are available and if the already existing and new FOs/FSs can be reasonably involved and combined in order to enable an effective 'general structure'.

Different factory capacities require different factory object and structure dimensions over specific distances, i.e. building volumes, road widths and lengths, pipe diameters and lengths etc. This means that these objects and structures are located at specific positions and involve specific sizes. Capacity changes can lead to changes of these factory object and structure sizes and/or positions (in X, Y and Z), and furthermore impact on the shapes/forms of and distances/connections between these FOs/FSs. This leads to different ‘effective transformation and/or movement directions’ of different FOs/FSs.

Transformations can lead to changing characteristics of all flows and therefore of numerous FOs/FSs, e.g. building contents, buildings, s&d plants, overarching networks and systems. Changing/displaced spaces – especially of areas and substructures (i.e. FOs/FSs and changes of their dimensions and positions in X, Y and Z, which, for instance, determine the soil/floor depths and can lead to further impacts such as the displacement of other FOs/FSs) – are consequently assumed to be crucial for transformations.

The ‘area size’, ‘area shape’ and ‘area-transformability’ (e.g. the area-mobility including sub- and superstructures) are therefore assumed to be significantly important for transformations. Difficulties of factory projects play in this context also an important role, besides other aspects. The ‘modularity’, ‘mobility’, ‘pluggability’, ‘scalability’ and ‘linking ability’ of terrestrial areas are disabled, while the ‘universality’ of terrestrial areas is limited after their first re-definition/ transformation. This limits the transformability of all objects and structures of today’s factories (also of transformable ones) and leads to a limited transformability of the general structure of today’s factories. Overall, the capabilities of today’s factories are limited. Thus, changes disable the ideal factory more and more.

These backgrounds are not only difficult to manage, but also lead to intertwined FOs/FSs and/or demolitions in consequence of collisions. *(A single collision leads either to intertwined structures or to demolitions, depending on the decision that is taken. In addition, further collisions etc. can be evoked through a performed action.)* Transformations can thus not only be required in extension areas, but concern also inhibiting objects and structures. Collisions can occur already during Greenfield and first Brownfield projects, but are especially relevant for factory lifecycles of more than 10 years, which lead finally to UHPs. This can lead to a chaos in factory planning. Also the upfront acquisition of extension areas (e.g. factory doubling areas) cannot prevent this circumstance and factory development into a UHP due to the described backgrounds. The more Brownfield projects are carried out, the more collisions, intertwined structures and/or demolitions emerge, while demolitions can increase the transformability of factories because inhibitors can be neutralised by them.

The difference of a today’s factory to its theoretically ideal factory increases throughout a factory lifecycle if demolitions are not performed. Transformation efforts and needs to perform demolitions to reach again an ideal factory status of today’s factories increase together with the factory lifecycle. Project durations also increase, while possibilities to define required actions decrease, i.e. what must be done to perform a transformation.

Transformability is the most important characteristic of factories. Its importance has been recognised, as a large amount of literature about the transformability of factories is available. The problem is that the importance of the transformability of areas is still underrated, as numerous essential aspects are underestimated or not considered in factory planning which leads to a considerable gap in the latter. The transformability of factories can have either positive or negative impacts on the planning, implementation and transformation of factories, depending on its availability and characteristics or in other words, peculiarities. If transformability is insufficient, future factory requirements cannot be met. The transformability of single FOs/FSs is disabled in this case. Transformability can also be limited, which leads to the situation that factory requirements can only be met to some extent, delayed (because diverse FPPs are required which require more time than a rapid transformation of transformable objects and structures), or both the latter two. It may also happen that factory requirements cannot be met at all. Hence, the transformability of factories can have a tremendous influence on the capability of a factory to be efficient and green. The transformability of the general structure – which is mainly determined by the transformability of areas – plays a key role, especially in the light of long factory lifecycles. A preferably ideal arrangement and linking of all FOs/FSs is required to enable an efficient and green factory.

Complexities and numerous unpredictable developments of the factory environment with regard to the market and so forth lead to different factory requirements and, in turn, to different transformation requirements at different points in time. These requirements are underestimated within factory planning theory, especially in the light of factory lifecycles of more than 10 years and the limited transformability of terrestrial areas. Thus, factory planning theory is not up-to-date against the backdrop of the indicated circumstances. Current theoretical and practical solutions in factory planning try to handle these tough requirements and to enable an ideal factory in terms of its functional characteristics at relevant points in time. This is not possible with terrestrial areas – especially in the light of long-lasting factories – due to an unmanageability of the described circumstances, and as the active transformability of areas is inaccessible. Consequently, not only are the strategic factory planning and the factory planning with scenarios a great misapprehension or fallacy in the light of factory lifecycles of 10 and more years, but also other factory planning theories that are overestimated.

Factory and factory planning scientists/authors and practitioners were able to develop different transformable solutions such as transformable buildings and movable production cells, but they failed to improve the transformability of areas. The transformability of current factories is consequently hardly able to meet today's factory requirements, especially over time. Thus, it is not factory planning theories that need to be primarily developed, but the transformability of factories must be significantly increased in order to meet current factory requirements.

To improve the transformability of factories is possible with TASs. The limitations of today's factories must be researched and assessed in order to develop the first TAS-requirement profile, while TASs serve as a basis for TFCs. Available area systems and their capabilities must be considered during this process. Afterwards, TFCs must be analysed in order to define their capabilities and limitations. Furthermore, TFCs must be assessed in comparison to each other and to today's factories. To research and assess the capabilities and limitations of today's factories and TFCs requires new concepts, which are currently not available in the factory planning literature.

Appendix 4.3.2 Real-World Factory Layout Analyses

Many real-world factories and their developments were analysed, and the development of the Mercedes-Benz Sindelfingen Plant indicates the general patterns which are followed by all of these factories (none of which was closed). This appendix therefore focuses on the Sindelfingen Plant. The analysis of this plant initially took place based on data from 1915 to 2015. Data from 2016 was analysed in research phase 3, which did not change the overall picture of real-world factory developments that could be gained by the author. The sources from 2016 and 2017 and the related contents were added during research phases 2 and 3.

Riedel, Hahner and Eichhorn (2013) provide a real-world factory development example. It shows that the John Deere Bruchsal Plant passed through different development steps over the years of its existence (e.g. extensions, reconstructions and a production depth increase). These development steps seem to have been easily passed through without any major difficulties, which is understandable if one considers the relatively small size and low complexity of the factory compared to most automotive OEM factories. If one reads other factory planning literature or absorbs different forms of media, one might gain the impression that today's real-world automotive OEM factories are trouble-free, and that their developments are also mainly unproblematic. Information about numerous real-world factories and their characteristics is available, and information about their developments is partly disclosed (Daimler AG, 2016, 'Die Top 5 der Mega-Fabriken', 2012; Jordahl GmbH, 2012; Pander, 2015; Reagan, 2015; 'Megafactories', 2016; Toyota Motor Manufacturing Kentucky, Inc., 2016). The problem with the available sources is that mainly factory statuses are presented. A dynamic perspective over years/decades often remains concealed.

A factory development example which is openly accessible (Pander, 2015) has been provided by Daimler AG. According to Pander (2015), the area of the Sindelfingen Plant has increased from 38 hectares in 1915 to around 300 hectares in 2015 after quite a number of extensions. Figure 73 depicts several development steps, which provide an impression of how the factory grew over the decades.

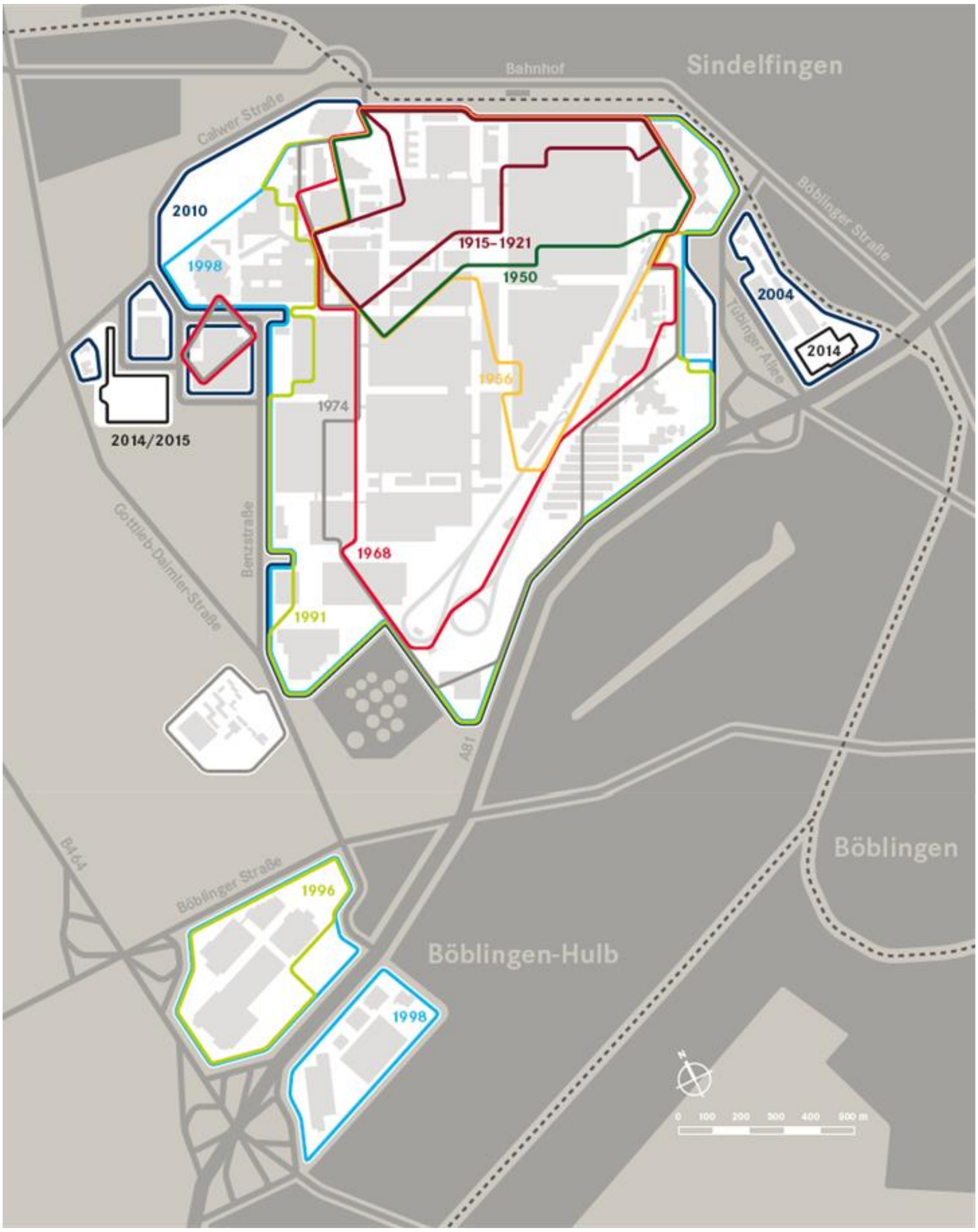

Figure 73: Development of the Mercedes-Benz Sindelfingen Plant (used by permission of Daimler AG)

This figure, which can be seen in Pander (2015), indicates that the factory grew out of itself (while numerous FOs/FSs also grew out of themselves). This means that different sections and other FOs/FSs displaced one another over the years and decades. If it could always be recognised that a 'factory structure recovery programme' (see subsection 6.1.7) is performed is another question, but this can be doubted (this does not mean that the depicted factory development steps (not BFPSs) indicate the final factory shapes after such programmes). It is conceivable that several projects were undertaken at the same time, and that these projects could have been bundled and processed in the same way as a factory structure recovery (or other) programme, but it is probable that this did not always occur (consider also the text in subsection 6.1.7).

Unfortunately, the figure is not able to show the number/extent of the extensions and other transformations that occurred during and between the depicted development steps. There is diverse documentation covering the main building and technical infrastructure construction/development steps of this factory from 1915 to 2016. However, these cannot be published but have been reviewed by the author (sources: Daimler AG, city archive Sindelfingen and city archive Böblingen). By analysing this information and using some of it to create flip books, the real extent of the development steps and measures emerged. Hundreds of measures such as demolitions, reconstructions and new constructions took place over the decades. What is also not depicted in figure 73 is the growth to the Z-direction and numerous transformations of sub- and superstructures (e.g. pipes, canals, tunnels, basements, machines and buildings) which shaped the factory into what it is today. Today, the Sindelfingen Plant is characterised by several multi-storey buildings and a sophisticated substructure system. During the analyses, it was notable that transformations occurred non-stop during the century of documented developments, and that the larger the factory became the more transformations happened, which impacted not only the single extension areas but also the inner buildings. It can be claimed that world wars had no significant impacts within these decades if unexploded ordnance, factory configurations during and partly before the years of war and the impact of these configurations on future ones are ignored. In addition to numerous physical processes, the number of purchased adjacent off-site extension areas hints that numerous approval, acquisition, awarding and related processes were required to enable these transformations. Such processes were also required for inner transformations which, as a general rule, require approval processes, e.g. in the case of a change in use when logistics turn into production areas or the like. The picture that has been gained by the author shows, in fact, an ‘alternating and breathing factory’. This factory passed through BFPS-3 (i.e. areas are available) many times and later reached BFPS-4, i.e. areas are occupied. After additional adjacent off-site areas were purchased, the factory again reached BFPS-3 and so forth. The problem with this development is that in sum the inner of the factory is inappropriate for the subsequent requirements (mentally superimpose/imagine just the different factory configurations and main production flows which were required over the years, and overlap them). The factory grew out of itself and continues to do so. This is one reason for the demolitions, reconstructions and new constructions. According to Pander (2015), Daimler will invest 1.5 billion Euro by 2020 to transform the factory in order to meet new market requirements. This will again lead to numerous demolitions etc.

By reviewing the following plants that have experienced similar developments and have also grown during their existence, it can be seen that the Sindelfingen Plant is not an exceptional factory: Today, the Volkswagen Plant in Wolfsburg has a size of 650 hectares while the Ulsan Plant of the Hyundai Motor Company involves 505 hectares (Reagan, 2015). Toyota’s Kentucky Plant has a size of 526 hectares (Toyota Motor Manufacturing Kentucky, Inc., 2016). The Tuscaloosa Plant covers 380 hectares while numerous Daimler plants exceed 100 hectares. Relatively new plants also involve such sizes. The BBAC Peking Plant with 230 hectares and the Mercedes-Benz Kecskemét Plant with 140 hectares have been established after 2005 (Daimler, 2016). The same applies to numerous plants of many other automotive OEMs (several plants were analysed in more detail). It must be considered that a transformation of such a plant can lead to transformations of horizontally integrated OEM plants and/or supplier factories, and vice versa. Information about what must be transformed in these factories is often delayed. This recurrent phenomenon can be assigned to the dynamics that occur in industrial companies (Forrester, 1958), and can be compared to the “bullwhip effect”, in which a “systematic distortion ... is passed along the supply chain in the form of orders. … [Distorted and delayed] information flows have [not only] a direct impact on the production scheduling, inventory control and delivery plans of individual members in the supply chain" (Lee, Padmanabhan and Whang, 1997, p. 546), but also on their transformation requirements. Non-automotive factories which involve also huge sizes and complexities such as those of Boeing (Reagan, 2015) and many others ('Die Top 5 der Mega-Fabriken', 2012; 'Megafactories', 2016) as well as their suppliers face similar problems. The bullwhip phenomenon consequently impacts the transformation requirements of horizontally and vertically integrated factories and FOs/FSs within these factories. *(The question arises of when the information about transformation requirements reaches all relevant stakeholders (e.g. other OEM factories, suppliers, (own) factory sections and departments, s&d plants etc.). Delays are pre-programmed and are the consequence of the duration of the information generation and transmission. As a result, an OEM plant or another factory can already perform a transformation while other impacted factories must wait for the relevant information. This results in a transformation-related bullwhip effect. What is crucial in this regard is where a transformation requirement is first identified and defined.)*

What is actually happening throughout the different BFPSs in today's factories might be assumed by considering the above paragraphs, but can be recognised even more clearly by reading chapter 6. The information that can be absorbed there is not a problem of single factories/companies, but applies rather to the whole system which involves diverse automotive OEM factories and other similar industrial structures. Anyone who assumes that new factories such as those for the production of electric drives and/or automobiles are not affected by the patterns revealed in this thesis is wrong. Battery technologies are being continuously improved, which will most likely lead to an increase in battery capacities. In addition, materials and processes might change. Furthermore, production figures of such automobiles will probably increase over the next years. Musk (2017) stated that 100 Gigafactories are required for the future electrification of automobiles, and that up to four new Gigafactory locations will be announced by the end of 2017. It can be seen at Tesla, Inc. (2014) that the substructures of such factories are as rigid as those of other (today's) factories; the excavated pits of the first Gigafactory, which is larger than the Sindelfingen Plant, can be seen here: Tesla, Inc., 2017. *Differences between a factory for the production of batteries for electric automobiles and automobile plants for example must be considered.* It might be sensible to consider the contents of this appendix and of chapter 6, and to consider that, besides other changes, the drive technologies desired by customers might change (e.g. to hydrogen propulsion), before we begin to flood the world with new factories and factory structures which are – particularly from a long-term- and sustainability-related perspective – outdated.

"*An expert is someone who knows some of the worst mistakes that can be made in his subject, and how to avoid them*."
Werner Karl Heisenberg

Appendix 4.3.3 Technology-related Information

TAS-elements can be defined based on maximum FO-/FS-dimensions and requirements. Furthermore, TASs enable different MASs. The combination of TASs with (other) FOs/FSs did therefore not significantly decrease the achievable capabilities of TASs, and had consequently no considerable negative consequences for the capabilities of TFCs. Nevertheless, further developments and analyses are required in order to specify the capabilities and limitations of TASs and TFCs. This cannot be done within the scope of this thesis. Environmental aspects and new developments (e.g. of modular machine systems) must be appropriately and seriously considered. These issues are considered throughout section 6.3 (e.g. subsection 6.3.1), in section 6.4, and in chapter 7 against the backdrop of what is possible and reasonable for this thesis. The feasibility of area systems is evidenced in the literature (e.g. in basic and more sophisticated sources about maritime structures, buoyancy/floatability, physical principles, physical-mechanical properties and relationships etc.) and through feasible technologies and implemented solutions (see the sources about area systems and related technologies, which are required to make area systems work/functional/operational, and see subsection

2.3.5). Already Archimedes' principle in combination with design and engineering fundamentals make one understand that maritime TASs (marTASs) are feasible. That terrestrial TASs (terTASs) are feasible is anyhow obvious, which does not mean that their implementation is sensible and effortless (see subsection 6.3.1). It is probable that a new discipline(s) is required for TASs and TFCs, as fundamentals of environmental, mechanical, marine (not for terTASs and terTFCs) and further disciplines must be combined.

Appendix 4.4 Details to Section 6.1

The results in subsections 6.1.1 to 6.1.5 are based on the interview data. The transition (subsection 6.1.6) combines particularly the contents of subsections 6.1.3, 6.1.4 and 6.1.5, as the contents of these subsections are relevant but not analysable in their prior form. The problems that these subsections convey are the heterogeneity in factory planning (i.e. that factories consist of heterogeneous FOs/FSs which mainly grow and/or are transformed heterogeneously) (subsection 6.1.5), different types of factory growth and transformations (subsection 6.1.4) and a factory growth compulsion (subsection 6.1.3). These contents were aggregated and combined in subsection 6.1.6 in order to provide a general understanding and a basis for the then following subsections and the analyses of the developed factory concepts through the new model and associated concepts (in sections 6.2 and 6.3). The contents of subsections 6.1.7 to 6.1.10 were identified and developed (mainly based on the interviews) in order to indicate generally valid patterns of real-world factory project cases and the impacts of these patterns – primarily in the form of eBFPCs and difficulty factors – on the developed factory concepts (and vice versa), and to enable the analyses of the developed factory concepts. EBFPCs (subsection 6.1.7) as well as the mixed and off-site cases (subsection 6.1.8) provide a high-level picture of these impacts and other relevant backgrounds. To enable reliable analyses and an adequate explanation of these impacts on today's factories and TFCs and about how these impacts can be handled with these factory concepts, and to enable an adequate explanation of the resulting consequences of these issues for these factory concepts, the identification and definition of difficulty factors (subsection 6.1.10) was required. Subsection 6.1.9 provides a transition to the difficulty factors. This transition summarises and combines the relevant aspects of all previous subsections. Further relevant information is provided in chapter 6.

Appendix 4.7.2_01 Interview Questionnaire

The subquestions were only asked if it made sense, or they were modified appropriately; this depended on the answers of the interviewees and on other circumstances. Other questions were also asked depending on what the earlier answer(s) of the interviewee was and how the interview proceeded.

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Questionnaire

You will receive the transcript after its finalisation to ensure its correctness and to sign it afterwards.

interview-partner: ______________	interview-no.: ________	date: ___.___.____	start time: __________
	interviewer: Vejn Sredic	place: _________	end time: __________

Further Information:

Motivation for participation:

Relationship between interviewee and interviewer:

How the first contact was established:

Atmosphere during the interview (after section 5):

Difficulties/difficult passages/problematic situations during the interview (after section 5):

Important information before the start:

- Information about the audio recording and privacy/ data protection (anonymity)
- The focus lies on real-world cases and experiences (also if you had only points of contact) (please explain your answers and provide details)
- Encouragement to be open-minded: "There are no bad or wrong answers."

Interview-Structure

1. Basic questions with regard to factory planning (including introductory questions)
2. The transformability of factory objects and structures (including backgrounds)
3. Factory projects and factory development
4. The impacts of factory developments
5. The future of factories (with concluding questions)

page **1** of **8** (questionnaire)

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1 Basic questions with regard to factory planning (including introductory questions)

1.1 What are the objectives in factory planning?

1.2 How would you characterise an ideal factory?

1.3 How long does the planning and implementation of a factory take and what are the most time-consuming tasks?

What are the most time-consuming tasks in Brownfield projects?

1.4 How would you assess the foreseeability of factory influencing factors/of factors that are decisive for factories (e.g. markets, competitors, products, production figures, new product technologies, new production technologies etc.)?

What happens if such an influencing factor changes?

1.5 What is a routine operation in factory planning (mechanisms of normal/ regular operations)?

What could be an interruption of such a routine operation?

1.6 What are ongoing processes in a factory (direct and indirect ones)?

1.7 Are factories constantly growing?

1.8 Are approval processes required every time that building land/terrestrial areas are impacted?

1.9 What is there to say about the importance of the site selection (particularly against the backdrop of a factory lifecycle of 15 and more years)?

page 2 of 8 (questionnaire)

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2 The transformability of factory objects and structures

2.1 Transformability – how important is this (cap)ability for factories?

For which objects and structures is transformability particularly important, and why?

2.2 Where do you see opportunities and limitations of transformability (i.e. existing degrees of freedom and limitations)?

2.3 Are transformable buildings and building contents (e.g. modular and mobile production cells) capable of meeting all of the transformation requirements of a factory?

2.4 Which possibilities and limitations do you see in relation to the transformability of terrestrial areas?

How important is the area size and why?

How important is the shape of the area, and why?

How easy is it to find large enough area(l)s in the right region?

How relevant is the soil condition/quality of areas?

What impact does it have on the transformability of an object/structure if this object/ structure is positioned in the area/ground?

2.5 Are there cases where it would be sensible if factory objects/structures that are larger than containers would be movable?

2.6 Is it possible to unify factory sections such as a press shop and an assembly shop (e.g. their substructures/foundations, building dimensions, column grids, technical facilities, machines, and equipment)?

2.7 What are the fixed objects and structures of a factory (fixed points) which can hardly be transformed or only with great expense?

page 3 of 8 (questionnaire)

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2.8 How would you assess the importance of exchange areas?

What can you say about substitution processes?

2.9 What could lead (a) to an increase and (b) to a decrease of the transformability of factories?

page 4 of 8 (questionnaire)

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3 Factory projects and factory development

3.1 Can planning assumptions/premises (Planungsprämissen) change during a Greenfield project and have an impact on the resulting factory?

3.2 How often do transformations take place?

3.3 Are large factory projects required during a factory lifecycle?

3.4 Can unplanned changes occur during Brownfield projects?

3.5 How sensible is it to purchase doubling areas or larger areas (i.e. area reserves of additional 100% and more)?

3.6 Is it possible, common and sensible to hold out/reserve technical infrastructure networks and supply and disposal facilities/plants for all possible factory developments (e.g. against the backdrop of an initial and final factory configuration)?

How does a capacity increase of a factory have an impact on factory objects and structures?

Can it happen that overarching structures (e.g. an energy centre or drainage) need to be transformed?

Do factory sections differ in the case of a transformation?

Can a physical chain reaction occur in the case of a transformation?

3.7 What are the characteristics of a factory if all extension areas are occupied?

Which transformations are possible and how if all extension areas are occupied?

Have you ever had a project which other projects overlapped with?

page 5 of 8 (questionnaire)

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3.8 Do project overlaps occur when only certain areas of a factory are occupied (e.g. areas in the centre of a factory whereas extension areas are still available at the periphery/outer borders)?

This question was only asked if overlaps were discussed in 3.7 (which was always the case).

Are unstructured factories a result when extension areas are available?

page 6 of 8 (questionnaire)

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4 The impacts of factory developments

4.1 How does the structure of a factory develop over time?

How does the factory planning effort develop with the age of a factory?

How does the number of simultaneous projects (and operation phases) develop over time?

4.2 Is it possible to enable and maintain lean production (preferably with waste-free processes) in an aging factory?

4.3 United huts plant(s) ('Vereinte Hüttenwerke'/'Vereinigte Hüttenwerke') – why does this expression exist?

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5 The future of factories (with concluding questions)

5.1 What are the impacts of current developments in product and production technologies on factories (e.g. electric mobility, 3D printing, metal printing, electrochemical metal machining processes and so forth)?

5.2 Are changes of factory objects and structures necessary to make a factory future-robust/future-proof?

Is the transformability of terrestrial areas sufficient against the backdrop of long-term factory developments?

What would be desirable?

Would comprehensively implemented basements lead to advantages?

Would it be advantageous if factory objects and structures could be integrated into areas/substructures in a flexible/transformable manner?

5.3 How important is the reusability of factory objects and structures (mainly with regard to sustainability)?

Is the reuse of factory objects and structures only sensible if these objects and structures are transformable?

What is your opinion about long-term investments?

5.4 Is there anything important that you would like to add that has not been discussed during this interview?

page 8 of 8 (questionnaire)

The purpose of the interviews was stated as follows:

> This doctoral thesis focuses mainly on the transformability of terrestrial areas. The purpose of the interview is to investigate the capabilities and limitations of terrestrial areas. The interview data are required for the ongoing research.
>
> You can play an essential role in this research project by reason of your remarkable professional expertise and experience in factory planning. By being part of this research project, you will help to develop factory planning theory and practice. The results of the thesis are still open, but it is already clear that a new knowledge base for professionals, scholars and researchers will be developed.

Before the actual interview started, the following premises and rules were repeated by the interviewer and discussed if required:

> - The focus lies on single factories/plants. Horizontal integration is not considered.
> - Long-term factory developments need to be considered (5 years and more).
> - Technical and spatial aspects are primarily relevant. Therefore, organisational and human-related aspects can be excluded.

Furthermore, the interviewees were asked to adopt a realistic stance, stay on the topic, focus on important issues, and reflect their answers (Dobbert, 1982). This was stressed to ensure non-superficial, realistic and reliable research results.

Factory planners are familiar with FPPs, but often know nothing about how the transformability of factories is defined and how it can be assessed. To reduce the risk of talking at cross purposes, subject-related information about relevant key terms were provided to the interviewees (Aghamanoukjan, Buber and Meyer, 2007). This is in line with Ashkanasy, Broadfood and Falkus (2000), who argue that examples of research contents ensure valid research results. The interviewees were asked to acquire this information before the interviews.

> A factory involves diverse objects and structures. **Factory objects** are mainly buildings and building contents such as production facilities, machines, U-cells and robot cells while **factory structures** refer rather to the technical infrastructure (i.e. the transportation infrastructure and the supply and disposal infrastructure) and to diverse building structures such as columns and beams. A clear delimitation and differentiation between factory objects and structures is not always possible.

Further key terms such as ‘Greenfield’, ‘Brownfield’, ‘flexibility’, ‘transformability’, ‘transformable building systems (TBSs)’ and ‘transformable factory objects/structures (TFOs/TFSs)’ (e.g. modular and mobile production cells) were also described. It was aimed to share and use a common vocabulary with the same meaning (Denzin, 1989). Thus, the chance was increased to receive high-quality answers which are valid, reliable and processible.

More complex advance information would have led to an unacceptable preparation time for the interviewees. Nevertheless, the interviewee preparation was desired since the interviewees should get the time and opportunity to think about the research project, interview questions and answers to be finally able to provide solid data. Therefore, the questionnaire was sent to the interviewees before the interviews, but it was not expected to receive answers upfront. The interviewees were informed that semi-structured interviews are both guided and flexible, and that other questions than the questions in the questionnaire might be asked during the interview. Crucial in this regard is that open or unclear issues could have been clarified before the interviews. This was ensured before, during and after the interviews.

Appendix 4.7.2_02 Informed Consent

The informed consent form was signed by all interviewees. All lines were ticked with yes.

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Informed Consent

Interviewee (first name, last name): ______________________

Email address and telephone number: ______________________

Job role/ professional position: ______________________

Years of work experience in industrial companies and in factory planning: __________

____

Fields of work experience/ core competencies: ______________________

____

Please tick the corresponding answer to each line:	YES	NO
I understand to participate voluntarily in a research project in the function of an interviewee (interviewed person).		
I understand that I can withdraw from the interview at any stage of the latter and that I can end the interview ahead of schedule without justification.		
I understand that I can refuse to answer questions.		
I understand that the researcher will make notes and audio records during the interview.		
I understand that I can reject the audio recording (also part-wise/ in places).		
I agree to the audio recording.		
I understand that I can contact the researcher before and after the interview to ask questions and clarify uncertainties regarding the research project.		
I understand that I can ask questions within a planned timeframe before the interview starts, and also during the interview if required.		
I understand that the research will result in a doctoral thesis (Ph.D.) and that the findings could be published in journals and presented at conferences.		
I understand that I will get the interview transcription to ensure its correctness.		
I confirm that I will not share confidential information about this research project with third persons (especially contents of the questionnaire/ transcription).		
I understand that the anonymisation of my data is guaranteed.		
I agree to participate in this research project.		

____

Place, date and signature

Appendix 4.7.5 Quality, Validity and Reliability of Interview Results

Interviews can provide valid and reliable research results, but can be criticised. The possibility to criticise findings/results that are provided by interviews must be reduced. The aim was to generate high-quality interview results that are undeniable and convincing. Besides the already mentioned information which the interviewees have received before the interviews, the pilot interview, the consideration of new topics/issues in subsequent interviews, rules for developing and asking questions, and rules about the behavior in interview situations, the following aspects have increased the quality, validity and reliability of the interview results:

Interviews were conducted in the native language of the interviewees due to better expressiveness and linguistic spontaneity (Aghamanoukjan, Buber and Meyer, 2007). To avoid an overexertion and ensure that newly acquired knowledge is considered in the next interview(s), not more than one interview per day was conducted. This has improved the quality of research results (Kurz *et al.*, 2009), as the unexpected leads to a higher quality (Kruse, 2007).

All interviewees agreed to the audio recording, which ensured the complete and correct transcription of the said words and supported the interviewer during the interview analyses. Furthermore, the interviewer could pay better attention to the interview (Patton, 2002) and validate his interpretations communicatively (Mey and Mruck, 2011). Thus, it was simplified to permanently interpret data during the interviews and to check if these interpretations are correct (Hopf, 1978, 2016; Mey and Mruck, 2011). This corresponds to a permanent processing of data in order to falsify or validate/verify the correctness of these data or in other words, to check if the interviewer correctly understood the meaning of the said words. The interviewees were aware of their opportunity to make 'off the record'-statements. Furthermore, the interviewees were always informed when the audio recorder was switched on or off (Mey and Mruck, 2011). The relevance of the interview data was also interpreted during the transcription and analyses of the interviews (Aghamanoukjan, Buber and Meyer, 2007).

The interviews were opened with an introductory/opening question to sensitise the interviewee and encourage her/him to be open-minded. Introductory questions were no central questions (Mey and Mruck, 2011), but ensured an easy start and supported the flow of speech (Kurz *et al.*, 2009). This supported the convenient atmosphere.

The more interviews are conducted the more methodical and verifiable are research results, as the responses can be analysed against the backdrop of a larger amount of empirical data which enables a more reliable comparison and analysis of interviews (Nohl, 2009). This is in line with Gräf (2010), as identical answers can be interpreted as ‘statuses of reality’. Equivalent answers led to validity and reliability. The more responses (of one and several interviewees), the better can inconsistencies be clarified (Denzin, 1989). It was ensured that all relevant interview questions were answered by all interviewees, who responded on their own (Bailey, 1994), and that all topics/issues were sufficiently followed-up. Sufficient data was gathered as fewer relevant aspects came up with each interview. The last two interviews did not lead to any new core aspects. This validates the statement that a small number of interviews can be sufficient if they are conducted with experts (Aghamanoukjan, Buber and Meyer, 2007, p. 428).

Concluding questions were asked in interview section five. IQ 5.4 (‘Is there anything important that you would like to add that has not been discussed during this interview?’) honors the experience and knowledge/know-how of the interviewee and gives her/him the opportunity to reflect own thoughts and come up with new major aspects (Mey and Mruck, 2011). All interviewees either said that no topic was left out or that the interview was all-encompassing. Only IP6 added some less relevant logistics-related information. The challenge was to ensure both a generally well-balanced ratio of the single topics/issues (or codes/categories, concepts and relationships among them) and a sufficient research depth for each of them (i.e. a deeper analysis/deep dive where required to achieve the ROs), which was mastered. Furthermore, each interviewee was asked about her/his opinion about the interview and about the atmosphere during the interview (Easterby-Smith, Thorpe and Lowe, 2002; Fichtel and Staltmaier, 2008). All interviewees stated that there were no difficulties/difficult passages. The atmosphere during the interview was indicated as good* or very good* *and/or comfortable. This shows that the interviewees were not overexerted or frustrated with too many and/or too difficult questions. Nevertheless, the questions were also not too simple.

Appendix 5.4.3 Details to the Model and Concept Development

Details about BFPSs, eBFPCs, difficulty factors, BMEs, transformation enablers and units, accelerators and acceleration units, fundamental enablers, and the relation of methods and concepts for the assessment of factory concepts are provided in this appendix.

The BFPSs were brought to the interviewees through interview questions without revealing the model or that the single BFPSs belong to the model or are relevant to it. The BFPSs were camouflaged/concealed. The responses of all interviewees validated the importance of the BFPSs. It was already described in subsection 4.3.2 how the BFPSs were developed.

eBFPCs and difficulty factors	
general information	The author has assumed that BFPCs can be enhanced through the identification and integration of similar patterns. EBFPCs (subsection 6.1.7) and difficulty factors (subsection 6.1.10) were primarily developed based on the real-world factory project cases which were provided by all interviewees. The literature provided also little data which is recognisable throughout this document. Helbing (2010) has described displacements, but only superficially. Difficulty factors were developed based on the difficulties in the real-world factory project cases, but it was unexpected that these difficulties would be conceptualised to difficulty factors and combined with eBFPCs which enhance these cases further (the first enhancement of BFPCs happened through the BFPSs and the second through the difficulty factors). Examples: Large displacements happen rather in BFPS-4 than in BFPS-3 (all interviewees). The complexity of factories and factory project cases increases together with the BFPSs (all interviewees). Relations of difficulties(/difficulty factors) were partly known by single interviewees and were combined in this thesis. This, for instance, led to the development of chainings.
details of the development process and the analyses	Difficulties/difficulty factors emerged mainly directly from the interviews (i.e. when these could be directly taken from the interview statements). The majority of real-world factory project cases and their impacts could be directly described/reproduced by the interviewees. Some cases and impacts were partly retrospectively reenacted by the interviewees. This, for instance, happened through the help of follow-up/probing/specifying questions. Real-world factory project cases involved displacements and other difficulty factors which could be reflected against the backdrop of the BFPSs as each real-world factory project case happens in a specific BFPS. Diverse follow-up/probing/specifying questions led to further details about these difficulties/difficulty factors as causes were backtracked and impacts/effects tracked if these could not be directly identified in the initial interviewees' statements. The impacts of real-world factory project cases/eBFPCs (of which each happened in a specific BFPS) could thus be explored and analysed in detail. These cases were repeated with TFCs. Thus, the analyses of these cases happened based the interview data and furthermore based on real-world factory layouts. Both cases and layouts indicated real-world factory developments.

BMEs	
general information	BMEs were unexpected and emerged as new concepts from the interview data. It was assumed that movements play a role for transformations, factories, and factory developments, but it was not clear that movements would play a substantial role for this research and factory planning which emerged from the interviews.
details of the development process and the analyses	BMEs describe circumstances which lead to movements/the requirement to move/relocate FOs/FSs. It was recognised little by little (during the analyses of the interviews) that movements are always relevant events which can require and/or lead to further FPPs and make implementations and transformations either simple or complex/sophisticated, depending on the circumstances (e.g. the reached BFPS and factory project case/eBFPC) and the capabilities and limitations of the factory concept in hand. The author has put transformations into question and backtracked their root cause which led to the development of BMEs while direct interview statements led also to their development. BMEs are initiating physical occurrences which lead to further FPPs and can lead to difficulty factors (BMEs can be seen as initiating FPPs when approval processes are factored out). Different types of causes for movements/relocations or, in other words, BMEs emerged from the interviews. BMEs were developed out of the interview data as the author has recognised that movements are the basic elements of factory implementations and transformations.

transformation enablers and units	
general information	Transformation enablers were taken from the literature and were applied to the developed factory concepts in order to define their capabilities and limitations. Transformation units for today's factories could be partly used from the literature. Nevertheless, the capabilities and limitations of terrestrial areas and TASs, and their impacts on (other) FOs/FSs have required analyses to define the transformation units of the developed factory concepts and to enable overarching statements to be made about transformation units and enablers (as these impacts were hardly or not considered before this research). Fundamental enablers are decisive for transformation enablers and units.
details of the development process and the analyses	*see the table 'relation of methods and concepts for the assessment of factory concepts' and the following text for further information*

accelerators and acceleration units	
general information	Accelerators were developed based on the literature. Scanlan (1974), Hildebrand (2005) and Sredic (2011) provided basic data for their development, but their importance emerged from the interviews. Acceleration units of today's factories were provided by the interviewees, while acceleration units of TFCs were developed based on the basic capabilities of TASs and TFCs. 'Pre-producibility' and 'pre-testability' were known from the literature, but not as 'accelerators'. The same applies to 'reusability'. Fundamental enablers are decisive for accelerators and acceleration units.
details of the development process and the analyses	*see the table 'relation of methods and concepts for the assessment of factory concepts' and the following text for further information*

fundamental enablers	
general information	Fundamental enablers were not known as fundamental enablers while the 'movable area size' (MAS) was completely unknown. The 'area size', 'area shape' and 'area and substructure characteristics' were mainly known as largely empty concepts/concept shells before the interviews while the designation 'area and substructure characteristics' was developed during the research process. It was not known that 'area and substructure characteristics' would become a fundamental enabler.
details of the development process and the analyses	The data for the development of the fundamental enablers of today's factories were provided by the interviewees, while the fundamental enablers of TFCs were furthermore developed based on the basic capabilities of TASs and TFCs. That the area size, area shape and further area-related characteristics are (to some extent) important could be initially recognised in the literature. That it is sensible to have large and preferably rectangular/ square-shaped areas emerged from the interviews, the same as the required/desired area and substructure characteristics. Thus, the importance of the 'area size', 'area shape' and 'area and substructure characteristics' for factories and their implementations and transformations emerged mainly from the interviews. That the interview data can be formed to fundamental enablers emanated from the interviews and the grounded theory-based approach. FPPs are required when area and substructure characteristics require a change. That these characteristics require a change happens often when FOs/FSs must be transformed. This emerged from the interviews (*see the table 'information to the subsections 6.1.1, 6.1.3, 6.1.4 and 6.1.5').* Required FPPs are generally more difficult, labourious/effortful, time-consuming and expensive when the area-mobility and 'MAS(s)' are not available. That the area-mobility is important knew the author from his practical experience (see, for instance, Sredic, 2011) (and the interviews), but the 'MAS' and its importance were unknown. The data to develop the 'MAS' emerged also from the interviews. *see the table 'relation of methods and concepts for the assessment of factory concepts' and the following text for further information*

<table>
<tr><td></td><td colspan="2">relation of '(research) methods' and 'concepts for the assessment of factory concepts'</td></tr>
<tr><td></td><td>today's factories</td><td>(TASs and) TFCs</td></tr>
<tr><td>transformation enablers and transformation units</td><td>• literature (basics)*
• interviews (mainly)
• abduction/logic and cause-and-effect
*A basic knowledge of transformation enablers and units of today's factories could be acquired from the literature, but not the overarching view of these enablers and units. This overarching view is described in subsection 6.2.2. Furthermore, prior to this research transformation enablers and units were not analysed in combination with or under consideration of fundamental enablers, which is crucial.</td><td rowspan="3">• literature and technology
• interviews (directly and indirectly)****
• abduction/logic and cause-and-effect
• analyses of area systems, TASs and TFCs
****Some interview statements could be directly used or involved at least data which could be directly used to achieve research objectives 3 and 4 (e.g. when an interviewee said 'If buildings would be movable, we could . . .'). Furthermore, it was (in other cases) neccessary to convert interview data to achieve research objectives 3 and 4. This means that interview statements, which provided real-world data about today's factories or were made in the context of today's factories, were used as a basis and were quasi translated into analysable data units (i.e. categories and concepts) in oder to generate results for the research objectives 3 and 4 (e.g. when an interviewee said that 'It is not possible to move an object which is deep in the ground as the area is fixed.', the interviewer/author could use this data in the context of TFCs to analyse how these factory concepts can handle such circumstances).</td></tr>
<tr><td>accelerators and acceleration units</td><td>• literature (basics)**
• interviews (mainly)
• abduction/logic and cause-and-effect
**accelerators and some acceleration units are recognisable in the literature, but were not combined with the concept of accelerators/ acceleration units. Furthermore, accelerators/ acceleration units were not analysed in combination with or under consideration of fundamental enablers, which is crucial.</td></tr>
<tr><td>fundamental enablers</td><td>• literature (basics)***
• interviews (mainly)
• abduction/logic and cause-and-effect
***The mobility of objects and object sizes (e.g. container sizes) are discussed in the literature. The 'area size', 'area shape' and 'area and substructure characteristics' are also described in the literature, but not in the form of categories or concepts. Furthermore, these area-related characteristics and capabilities (or, in other words, fundamental enablers) are not discussed in the context of the area-mobility or 'movable area size' (MAS). The area-mobility and MAS(s) are unknown in current factory planning literature. These elements were not combined with the concept of fundamental enabler(s).</td></tr>
<tr><td>information</td><td colspan="2">That the basics provided by the literature were relevant for TFCs is obvious if one considers the information which is related to today's factories, but these basics provided only a basic framework. Abduction/logic and the analyses of cause-and-effect relationships are always concerned with the grounded theory-based research approach.</td></tr>
</table>

Table 26: Relation of methods and concepts for the assessment of factory concepts

information to the subsections 6.1.1, 6.1.3, 6.1.4 and 6.1.5	
basic information	The number of changes and transformation requirements, the data that shows that factories grow continuously, the heterogeneity in factory planning (or, in other words, of factories) and the types of factory growth and transformations emerged from the interviews. The combination of these elements and the combination of these elements with other elements/concepts of this research project (e.g. eBFPCs and difficulty factors) were done through abduction/logic and analyses of cause-and-effect relationships which are always concerned with the applied grounded theory-based approach. That induction plays a role when interview data is gathered and combined is obvious. Furthermore, it is obvious that deduction plays a role when the developed model and concepts are applied. Based on these combined data and the other data that were provided by the interviewees, area and substructure transformation requirements and required area and substructure characteristics and capabilities could be defined. *It is recognisable throughout subsections 6.1.1 and 6.1.2 that the limitations of (the use of) scenarios in factory planning could have been validated through the research and analyses of literature and are furthermore substantiated in the interview data. That abduction and logic combinations of data units also played an important role for the contents of subsection 6.1.2 is also recognisable.*
concept-related information	This knowledge base supported the author in identifying and developing relationships between BFPSs and eBFPCs, between eBFPCs and difficulty factors, and finally between 'eBFPCs, difficulty factors and BFPSs' (*see particularly subsections 6.1.6, 6.1.7 and 6.1.10*).

Appendices to Chapter 6

Assistance for the Reader

Why is this thesis complex in parts and why is this not a problem?

In current factory planning, there are limitations to how complexity can be handled. This issue is essential to this research, as the unmanageable complexity in factory planning must to be processed further in this thesis. It is necessary to show that factory planning is complex, and in particular, why it is complex. It is logical that the consideration of this unmanageable complexity leads in parts of the thesis to a certain complexity. Nevertheless, the author has reduced this complexity through the use of transitions and difficulty levels, so that the relevant aspects are understandable on a higher level, and so that these aspects can be processed further.

Subsections 6.1.7, 6.1.8 and 6.1.10 were developed with the following aims:

(1) All relevant elements are considered on a level at which the complexity in factory planning can be explained as deeply as necessary.

(2) The explanation must still be understandable.

(3) To come up with valid and reliable (concepts and) patterns that can be processed further.

The theory generated in these subsections explains – based on patterns – the complexity of relevant real-world factory projects and the complexity of the management of these projects. These projects were analysed in great detail whilst taking into consideration factory structures and their capabilities and limitations, and then combined into patterns that are relevant for all developed factory concepts. These subsections explain essential elements and their relations to one another, which lead to the complexity of real-world factory projects and in factory planning and, in turn, to limitations in structurally managing this complexity, as well as limitations in managing this complexity by means of brain power, technology and algorithms.

This thesis not only claims that factory planning is complex, but also provides a structural explanation of complexity in factory planning. This research explains parts of what cannot be explained completely. Therefore, relevant patterns were created down to a level that is still explainable. These patterns were taken up and aggregated into higher level patterns – particularly in the transitions and into difficulty levels. **It is not important to keep each detail of subsections 6.1.7, 6.1.8 and 6.1.10 in mind,** even though these contents are relevant for this research and the research results, as these contents are later aggregated to enable their further use.

What was done to reduce the complexity in order to consider it in the further research?

Complexity reduction through transitions and difficulty levels: **The transitions identified in section 6.1 help the reader to again move to a higher level, as they focus on the most important issues of the previous subsections of section 6.1 and explain what these issues in combination mean.** Furthermore, the difficulty levels help to reduce complexity and to again come to a higher level, which is relevant for sections 6.2 and 6.3. Other sections in this chapter also involve transitions and/or leading over passages.

What are the relevant overarching aspects?

Most theses in factory planning follow the same general direction. This research attempts to create something quite different and relevant, which requires consideration of the following aspects:

- Within different BFPSs, the same eBFPC leads to different impacts. Nevertheless, eBFPCs lead to similar patterns.
- The factory concepts can handle these 'first level impacts' differently (for instance, in the case of displacements, TFCs lead to movements, i.e. moves instead of effortful FPPs).
- As a consequence, the factory concepts lead to different impacts*, e.g. the resulting moves can lead to different impacts (TFCs lead, for instance, to fewer domino effects, which are furthermore shorter).

In order to show the real differences between today's factories and TFCs, the consideration of more complex *wider or in other words, 'second level impacts' is required. These impacts are later considered on a higher level in the model-related research results (subsections 6.2.5 and 6.3.5 'application and validation of the model') and in the 'consequences' (subsections 6.2.6 and 6.3.6), for example through difficulty levels. This second level is required to understand the wider limitations of today's factories, and to show that in this context TFCs lead to crucial advantages and are not only considered as a visionary idea. Thus, the second level is crucial in order to determine and describe differences, which are important but not identifiable without this deep-dive. This is where the complexity arises, and this complexity is required because non-obvious impacts are more important than the simpler ones, e.g. that displacements are often the first level, or in other words, primary impacts of eBFPCs. Therefore, subsections 6.1.7, 6.1.8 and 6.1.10 are required and crucial (the previous subsections of section 6.1 are also required, as they convey data and evidence that is necessary in order to understand the later subsections).

The consideration of these aspects which require an explanation makes the thesis in parts complex. This is required, as the real and wider problems in factory planning (including factory projects) and of today's factories can therefore be demonstrated, and because to define the best solution, e.g. an optimal flow or the fastest transformation, or a trade shown how factory planning can be improved.

What does this mean in detail for section 6.1, and how are the contents of section 6.1 considered in sections 6.2 and 6.3?

Section 6.1: Numerous transformation requirements occur (while scenario techniques are inoperative). Due to various circumstances, factories are forced to grow. Furthermore, diverse transformation requirements (of which not all lead to an increase of the overall factory capacity) lead to a factory growth, and in addition, the positions of FOs/FSs change over time. In the light of heterogeneous areas and substructures, these circumstances lead to problems if areas are not transformable. Details regarding these aspects are provided in subsections 6.1.1 to 6.1.5.

The first transition (subsection 6.1.6) combines the contents of subsections 6.1.1 to 6.1.5 that are relevant but not analysable in their prior form. These contents were aggregated and combined in order to provide a general understanding and as a basis for the subsequent subsections and the analyses of the developed factory concepts using the new model and associated concepts (which take place in sections 6.2 and 6.3).

The eBFPCs and difficulty factors were identified and developed (mainly based on the interviews) in order to indicate generally valid patterns of real-world factory project cases and the impacts of these patterns on the developed factory concepts (and vice versa), and to enable the analyses of the developed factory concepts. In subsections 6.1.7 and 6.1.8, EBFPCs as well as the mixed and off-site cases provide a high-level picture of these impacts and other relevant backgrounds. In order to:

(1) enable required and reliable in-depth analyses,

(2) enable an explanation of these impacts on today's factories and TFCs (e.g. the meaning of these impacts for factory structures and the transformability of factory structures),

(3) explain how and why these impacts can be handled with these factory concepts,

(4) enable an adequate explanation of the resulting consequences of these issues for these factory concepts (e.g. the complexity development throughout the BFPSs, and the content of subsections 6.2.6 and 6.3.6),

the identification and definition of difficulty factors (subsection 6.1.10) was required. Subsection 6.1.9 provides a transition to the difficulty factors. This transition summarises and combines the relevant aspects of all previous subsections.

Section 6.1.7 shows the possible primary or in other words, 'first level impacts' of eBFPCs. Each eBFPC is concluded, and an explanation is provided of the optional* impacts that each eBFPC can lead to, both dependent on and independently of BFPSs. *(Different factory configurations and factory section requirements can lead to different possible decisions which can make these impacts differ. This allows an explanation for why displacements and other difficulty factors occur and why areas and substructures are often impacted.) By means of eBFPCs and BFPSs, details are given about which circumstances lead to which area transformation requirements; these lead finally to displacements and other difficulty factors. Until this point, relatively simple first level issues are described. The displacements which take place then make clear that these frequently occur, and this provides insight into why they take place and which ones (their sizes/extents differ). EBFPCs occur together and with other cases. Therefore, subsection 6.1.8 brings real-world complexity closer to the reader. The transition in subsection 6.1.9 summarises relevant aspects and focuses on first level impacts, considers conditions and aspects that introduce second level impacts and provides a perspective for subsection 6.1.10, which is concerned with elements that lead to second level impacts – the difficulty factors. Single difficulty factors and their relations to one another (e.g. different domino effects/'chainings') and other difficulty-increasing events and aspects are described. The designation 'chaining(s)' refers to more complex domino effects (i.e. chain reactions), which are explained in subsection 6.1.10. It cannot be argued that chainings are specific types of domino effects, as these differ and often cannot be entirely specified. It is impossible for human beings to always comprehensively understand the complexity in factory planning, also if technology and algorithms are used; the reasons for this are explained throughout chapter 6. The focus is therefore on displacements, as displacements provide a hint that will aid the understanding of second level impacts, and as displacements were very often described by all interviewees. Displacements are important for factory planning, but are not sufficiently emphasised in the factory planning literature.

Thus, 'second level impacts' of eBFPCs are explained in subsection 6.1.10, while subsections 6.1.7 and 6.1.8 provide an understanding of 'first level impacts', which are relevant to the understanding of why 'second level impacts' occur. Furthermore, subsections 6.1.8 and 6.1.9 (transition) in particular pave the way for the explanations in subsection 6.1.10.

Sections 6.2 and 6.3 are again at a higher level, but these sections consider second level issues in an aggregated form in the application and validation of the model and in the consequences. Apart from their first subsections, sections 6.2 and 6.3 involve an identical structure. The abovementioned impacts differ for every factory concept, and can also be handled differently by them. Relevant aspects of these issues are mainly described in subsections 6.2.5 and 6.3.5 (application and validation of the model), to which the previous subsections of sections 6.2 and 6.3

provide a further basis (in addition to the basis provided in section 6.1). The resulting consequences for these factory concepts are described in subsections 6.2.6 and 6.3.6, for which the contents of subsection 6.1.2 and of the previous subsections of section 6.2 and 6.3 are crucial. This is because the transformability and FPP-capabilities of the developed factory concepts are crucial, as is the development of their transformability throughout the BFPSs and the development of the complexity throughout the BFPSs. This is explained by means of difficulty levels, as this reduces the complexity of the thesis or, in other words, it makes possible the consideration of the unmanageable complexity in factory planning.

In addition to sections 6.2 and 6.3, section 6.1 (particularly subsection 6.1.10) is crucial to the understanding that the impacts of eBFPCs differ for every factory concept and why, and furthermore to understand the resulting consequences. Nevertheless, it is not important to keep every detail of subsections 6.1.7, 6.1.8 and 6.1.10 in mind.

Summary and brief description of the most important points and aspects:

An eBFPC has different impacts in BFPS-3 than in BFPS-4, for instance. Furthermore, the developed factory concepts can handle these impacts differently, which has an impact on second level impacts, e.g. domino effects. Along with other aspects, these second level impacts in particular lead to the complexity in factory planning.

What else leads to this complexity, and why is this complexity not always manageable?

The first level and some of the second level impacts occur in single projects. In the case of complex projects, the handling of these second level impacts is already almost impossible or impossible. If there are several projects running at the same time, and if changes and/or new projects occur over time, the complexity increases considerably. Changes, project overlaps and the like also belong to the second level impacts.

Why is it a problem if the transformability of areas is not given?

If areas are rigid (not transformable), difficulty factors cannot be handled in the way that is possible if areas are transformable. If areas are rigid, as in the case of terrestrial areas, the required FPPs lead to long durations. Furthermore, process chains which involve domino effects, chainings and similar issues also occur. Sequential processes dominate today's factories. As scenario techniques are inoperative, the 'to be'-factory status cannot be defined. This is crucial, as the 'to be'-factory status and the 'as is'-factory status are required to enable the definition of required FPPs. Due to difficulty factors (i.e. second level impacts) that involve domino effects, changes, project overlaps and the like, it is also possible that not even the 'as is'-factory status can be defined. Thus, it can happen that factory planners do not know at all what must be done (i.e. the required FPPs) in order to reach the aimed 'to be'-factory status.

Why do TFCs lead to significant advantages in the context of these second level impacts?

If areas are transformable, as in the case of TASs and TFCs, the required FPPs are shorter. Furthermore, process chains can be cut. For example, in the case of displacements, TFCs lead to moves instead of effortful FPPs, and also lead to fewer domino effects and the like, which are also shortened. In addition, FPPs can be better parallelised. 'To be'-factory statuses can be better defined, as project durations are shorter. 'As is'-factory statuses can be better defined. Thus, the FPPs that are required to achieve 'to be'-factory statuses can be better defined.

What does this mean for the research results?

Difficulty factors are not the root cause of the problems in factory planning. Except for primary displacements (which can be handled differently by the developed factory concepts), difficulty factors are to a large extent effects of the disabled transformability of terrestrial areas. These second level impacts can be handled differently if areas are transformable, which is crucial. Thus, terrestrial areas are the root cause for the problems in factory planning, and TASs are the means which can eliminate or substitute this root cause.

What does this mean for the thesis?

The handling of complexity is not always possible in factory planning. In this thesis, this circumstance has been made recognisable through the use of appropriate elements and their combinations. This means that the backgrounds which lead to this unmanageable complexity have been explained. To process this unmanageable complexity and the aspects that lead to it was required and has been accomplished in this thesis. The author has left contents out which were not required, because leaving contents out can be progress. In this thesis, a large amount of content is required and the intention has been to process it further in an understandable manner. A significant improvement of factory planning requires turning conventional factory planning upside down while analysing and combining the most relevant aspects. It is inevitable that this approach leads to a certain complexity.

It has been necessary for the author to insert some complexity into the thesis, as complexity is a crucial part of the work (or in other words, the crux of the thesis is that it must handle complexity). Nevertheless, the reader is also considered, as complexity has again been reduced. The transitions and difficulty levels as well as the summaries and conclusions of the thesis help the reader to understand the most relevant parts of this research, which are summarised in this appendix with the aim of assisting the reader. Other crucial aspects, details and evidence are provided throughout chapter 6.

This appendix cannot provide a complete picture of all relevant aspects as this would require more detailed contents, which are provided throughout the thesis.

Appendix 6.1.1_01 Most Time-Consuming Tasks

IP1 stated that continuous changes occur not only during planning but also during physical implementation and transformation phases. This was validated by all interviewees. Unforeseeable problems, a high complexity, and overlaps between product planning and factory planning occur (IP1). This is in line with IP3, who argued that management decisions are changing and that even design freezes were and are knocked over. IP5 stated that it is clear that continuous changes must be considered. The planning is most time-consuming, as we have continuous planning changes. Many times, continuous changes were mentioned and described during the interviews. This happened based on real-world cases. IP7 argued that decisions are taken and afterwards discarded. Furthermore, decisions are postponed. This is the normal case. IP8 stated that changes of planning premises are normal, as are changes in decisions and decision-making processes. IP6 stated that the bottleneck is the weakest element or link in the overall constellation and crucial for the development of the entire factory and for project durations. IP6 further stated that bottlenecks lead to prolonged durations. Depending on where the bottleneck is, other requirements and durations occur, while new changes and new bottlenecks can increase these durations again and again. Difficulty factors and their possible combinations must be considered in this regard. IP4, for instance, stated that when a pit must be transformed, it can lead to a domino effect which impacts on the whole factory (see subsection 6.1.10 for further information in this regard).

Appendix 6.1.1_02 Anticipations

IP6 claimed that it is possible to make forecasts in medium-term, two to three years. This interviewee also stated that it is rather possible to make forecasts for an SME in a regional market than for an OEM in a global market. This seems logical already by virtue of a smaller number of competitors. IP5 stated that the sales department changes output figures up to one and a half years after the first figures were declared (required production figures are meant). This means that they change numbers after the point in time from which they should avoid changes so that demolitions, reconstructions and new constructions can be avoided. IP7 talked about unforeseeable changes which come from the management and lead in most cases to complications (because of then required FPPs). This interviewee argued that it is not sensible at all to plan longer than a cycle of an automobile model and that even this is hardly possible. If everything were static in the case of a Brownfield and one would exactly know which model comes into which building and how, then everything would be quite foreseeable, but there are additional influences. IP8 claimed that long-term forecasts make no sense nowadays – maximally medium-term ones can be sensible. After the question how changes impact on factories, IP8 talked about dramatically decreased production figures of [redacted] (fuel-type) aggregates (e.g. engines). This has an influence on the OEM and on all factories of the respective supply chain, i.e. other horizontally integrated OEM and vertically integrated supplier factories. Consider also bullwhip effects in this regard (e.g. the newly identified transformation-related bullwhip effect). IP8 also stated that market changes and so forth make it impossible for automotive OEMs to plan in development steps. IP1 talked in this context about a substantial change of production figures. IP3 argued that forecasts are not possible and that a design freeze is therefore so important. To predict the future is not possible. This was also stated by IP7, the same as that forecasts are not possible. IP8 used the words 'hardly predictable' in this regard. Changes, which occur during the implementation of a factory, underpin the agility and dynamics of markets. IP2 said that it happened in most cases differently than planned. This interviewee stated in this context that the future cannot be predicted and that decisions are taken delayed, as it is possible that one knows something better next week. IP4 argued that changes happen more and more often. Forecasts and premises are not reliable. This interviewee used the words 'increasingly volatile' in the context of markets and factory environments. The expression volatile was also used by IP6. This interviewee said that the market is very volatile, very largely uncertain, and changeable. To assess the development of factory influencing factors is thus impossible.

Appendix 6.1.1_03 Permanent Transformations

It has been repeatedly stressed by all interviewees that it is hardly possible today to make a reliable detail(ed) planning. The interviewees were asked how often transformations take place. IP1 repeated the word 'always' three times in a row. IP2 said that transformations always happen within car plants. There is always something being demolished, or elsewhere something is being newly constructed. In the case of OEM truck plants, it depends on how deeply you go into the detail. Transformations always happen within production sections. IP7 used the words 'annually' and 'steadily'. IP3 argued that transformations always happen, even after the finalisation of a Greenfield. The word 'often' was used by IP4. Parking lots, employee functions, and functions within the assembly shop are attached or optimised. Then you realise that because of any quality-related reasons you must add something. You must change media routes during the ongoing production. Furthermore, legal requirements change and impact significantly on the factory. This happens throughout the year. IP6 argued that extensions happen often. Large demolitions and new construction happen in the case of SMEs every five to ten years. These happen in the case of large companies more often. A product model changes permanently. This validates that continuous transformations happen in OEM plants and explains why the interviewees used words such as 'always', 'permanently', 'continously' etc. to explain how often transformations take place. IP5 validated what IP8 said.

Appendix 6.1.1_04 Greenfield Cases

IP2 revealed a Greenfield case that took place in [redacted] (a country*) and in which a capacity reduction of more than 60% of what was initially planned occurred, while the planned total production capacity and ratio between models changed continuously over a period of more than three years. *(The continent also cannot be disclosed in order to protect the interviewee; this also applies to other statements and is not mentioned again.) This led to an unplanned integration of other production facilities, additional production sections, and furthermore of entire factories. This cannot be specified in order to protect the interviewee. IP3 recounted several real-world cases. An extension of a [redacted] shop (production section) was required after the point in time when the corresponding building was ready for the equipment installation and after the installation of equipment, which means far after the point of no return. After the unplanned extension, a further unplanned extension was required. In another case in another factory, an additional [redacted] room was required which required a constant temperature of [redacted]0 degree Celsius. This led to numerous difficulties and problems. In another case, it was required to demolish a floor to integrate media routes, which was not planned before. Numerous further cases were revealed by the interviewees. Further real-world cases are described throughout this document, while all real-world cases cannot be described in order to protect the interviewees.

Appendix 6.1.1_05 Brownfield Cases

IP4 recounted a case in which a logistics concept changed and had significant impacts on a factory. This interviewee said that overlaps and collisions occur in Greenfields and the more the Brownfield, the stronger they become. (The author has kept the translations of this and the previous sentence very close to the original statements.) IP3 revealed a case in which the construction of a factory in [redacted] (a country in Central Europe) was stopped. The associated plans were completely changed, which led to considerable impacts. IP1 described an extensive change of production figures of internal combustion engines. This changed large parts of a factory. IP5 provided details of an automobile model shift from one plant to another. More than thousand production facilities were moved from one continent to another. IP2 described a case in which a factory in [redacted] (a country in the Near East) was reduced to over 50%. In another case in [redacted] (a country), a factory dropped below 35% of the entire factory capacity that was actually built. A three-digit million Euro sum was then invested (in addition to the prior investment which was larger). The buildings were kept, but the production facilities were completely exchanged to produce other products. IP2 stated that 'no one needs it today'. IP2 also presented details of another case in [redacted] (a country). This interviewee argued that it was said by the strategists that the factory is required in 20[redacted], as there will be a boom. People want the old [redacted] (product models and types), as the new ones will be more expensive from 20[redacted] (one year later) onwards, as there will be new [redacted] requirements (governmental requirements). We built like crazy and what was – a crisis in 20[redacted] (the same year as before). In addition, IP2 talked about a case in [redacted] (a country) in which a factory with a low vertical integration and only one section should have been developed in [redacted] (more than 5 but less than 12) steps to a complete factory with all factory sections. This interviewee said that these steps will never come as they were assumed. Moreover, IP2 delivered information about another case in [redacted] (a continent) in which a product 'model a' was dropped and replaced by another product 'model b'. 'Model b' was also planned from the beginning but increased in capacity. The consequence was a three-shift production from the start and that the [redacted] (a production section) has already reached its limit at the end of the Greenfield project. Furthermore, the [redacted] (another production section) of 'model a' was not appropriate for 'model b'. In addition, the first factory [redacted] (a BFPC) took place a short time after the SOP. The affected production sections were neither prepared for the changes which occurred during the Greenfield nor for the changes which occurred during the Brownfield. Furthermore, a newly constructed supplier factory has been closed, as parts of the dropped product would have been produced by this supplier. (This real-world case has been adapted in order to protect the interviewee. The real-world factory involves more product models, and more sections were affected.) IP5 described a Brownfield which has been completely cancelled after the point of no return. This led to the loss of a large investment. IP2 argued that it was problematic to change a [redacted] ('product a') plant into a [redacted] ('product b') plant. IP8 reported on a project in which finally about 20% of the originally planned and implemented factory capacity was required. The market was suddenly lost. Numerous further cases from all over the world (mainly Africa, Asia, Europe, North America and South America) were described by the interviewees. Transformations of OEM plants had in almost every case large impacts on suppliers and their factories.

Cases of SMEs were also described. IP6, for instance, provided details about an SME of which the old site was too small. This led to a new Greenfield at another location, which required three and a half years. Another case was disclosed by IP5. In this case, the area of another SME was too small and led to a BFPC-E of another factory. It emerged from the interviews that such cases happen often.

It was also recognisable that approval processes which are required for land utilisation (land-use plan/construction law) and are normally required in the case of off-site-extensions and other off-site cases often last one year. Agriculturally used areas, for instance, are converted into industrial areas (i.e. farmland is converted into building land), while it also happens that industrial areas are converted into residential areas (IP6). Furthermore, residential and/or commercial areas can be converted into industrial areas. Other cases are possible.

Appendix 6.1.1_06 Changing Transformation Requirements

Changes have not only an impact during the planning/re-planning of a factory. Changing/new transformation requirements impact very often on (partly and completely implemented) physical objects and structures of incompleted factory projects. IP1 argued that the daily practice shows that new transformation requirements impact on already started transformations. This was validated by IP2, who said that it is natural that this happens. IP2 has also used the words 'yes, of course' in this context (in the sense of 'such cases are normal'). Words such as 'of course' and "klar" were often used by the interviewees in this regard. IP2 also said that which applies to a Greenfield applies also to a Brownfield. IP3 revealed a case in which additional and unplanned substitution processes for the technical infrastructure were required. IP3 is one of the interviewees who used the words 'of course' in this regard. IP3 provided furthermore details about a case in which logistics areas were changed into a press shop. This happened several times in one and the same project, which impacted FOs/FSs massively and increased costs and project delays. In another factory, a press shop was changed into a logistics area. The framework conditions of this project were also changed several times. IP3 further stated that it will surely come to new planning changes and demolitions such as column shifts, and wall and ceiling break-throughs. The process planning is still in the concept phase while the factory planning must already perform constructions. In another case, two years at least are required for the re-engineering of a press shop in which new machines including new foundations etc. will be integrated. The problem in this case is that the transformation should be done much faster, which is not possible due to multiple dominos. IP4 and IP5 talked about steady changes which are necessary due to new requirements, e.g. from the sales department. IP5 stated that a building was already done and that a capacity increase was then required. This led to building changes. Furthermore, the takt-time was increased and conveyors were significantly impacted. This led to further impacts, while other impacts occurred. The final solution was far from its optimum. IP6 revealed a case in which a building extension over a road was required and in which the soil bearing capacity was insufficient. IP8 argued that given infrastructures no longer fit the new capacity requirements. You recognise that you need to exchange them or you include additional ones. IP7 talked about a case in which the construction of a new building was cancelled after the detail planning, i.e. after the point of no return. This interviewee stated that the project moved from a green to a red status. IP7 further stated that what was planned to be integrated into the new building must now be integrated within the given buildings. Numerous changes will occur and late decision changes are very problematic. Furthermore, a new (product) model project led to production shifts to suppliers. IP7 argued that this will lead to displacements and higher logistics costs. IP8 stated that premises change after processes have been initiated, when processes are performed and after processes have been completed (physical processes in particular are meant). All possible changes and cases happen. IP2 said that numerous things exist and occur in Greenfield and Brownfield projects. These occurrences inhibit these and other projects after they have been initiated. This leads to unplanned changes. A similar statement was made by IP7. IP1 stated that changes of changes lead to conflicts and overlaps. Increased costs and delayed time schedules are the result. IP5 talked about 'transformations of transformations' within existing structures, additional expenses, and an increased work effort. IP5 further argued that her/his planning team needs to know the requirements as soon as possible so they can use the holiday period for transformations (so as not to disrupt the production). The word 'suddenly' was used by IP5 several times in the context of changing transformation requirements.

Appendix 6.1.1_07 Compromises

IP3 argued that there are differences between what factory planners want and what the process requires. IP8 described in this context continuous transformations (e.g. reconstructions and moves) that are performed by process owners/users mainly after completions of factory projects and have an impact on diverse FOs/FSs, e.g. the s&d infrastructure, conveyor systems, logistics and production facilities, building structures etc. IP1 spoke about surprises, as users make changes, while IP8 stated that numerous systems show first during operation that they must be changed. Through these changes, future plans for factory developments are inhibited and can even be disabled. IP4 talked about lean characteristics of a process which could first be developed during operation, weekends and holiday periods (in BFPS-4). IP7 stated that a checklist for approval processes exists and when changes come up during the implementation of which the governmental authorities have not been informed about, it leads to problems. Because it is unknown when changes occur and which changes, and because changes are also made by process owners/users, governmental authorities cannot be adequately informed. Process owner/user changes emerged from several interviews, and unknown changes from all interviews.

Appendix 6.1.1_08 Impact of Project Durations on Data Reliability

IP1, for instance, argued that project durations have a negative impact on the quality of (factory) planning data. IP8 stated that the longer the project durations, the more uncertain the planning premises become, which were once assumed. Not all premises survive. IP2 said that the more one wants to look into the future, the more difficult it becomes. Similar statements were made by IP3 and IP6. Both IP3 and IP4 said that the data quality gets better over time. IP5 stated that the longer the project duration, the more changes and transformations occur. IP7 stated that no project is carried out as originally planned, as changing transformation requirements always occur. IP7 further argued that this impacts negatively on the time and costs. The longer you go back in time, the more considerable is the gap between what is actually implemented and what was planned. This is normal and the exception proves the rule.

Appendix 6.1.1_09 Right becomes Wrong

IP5 stated that the general structure is not ideal at all. (This interviewee talked in this context about the arrangement and linking of buildings.) [redacted] (a number of) halls for [redacted] (a number of) [redacted] (specific) vehicles were constructed, which was very expensive. One year later, the requirements changed completely. In another case, the factory lacked areas, which led to several rented halls outside the factory. First, IP5 claimed that this was a management mistake or in other words, a wrong decision, but it became evident that the taken decision (i.e. to rent halls) was probably the best option against the backdrop of what was possible. Nevertheless, IP5 argued that the decision led to high logistics costs and that the solution was not lean at all. IP5 further stated that this will surely be changed again due to cost reasons. IP6 talked about constructed FOs/FSs which are no longer required. This interviewee also stated that roads are constructed and not even six months later these roads are opened to include s&d infrastructures. IP4 said that it is not that nice if you construct a building for several million (Euro) and realise that its functions, dimensions, and location are not required anymore, as the requirements have changed. This interviewee stated that this leads to the worst case: You need to demolish the building. (These sentences were recounted based on a real-world case.) IP2 said that if one has no possibility to extend a factory, she/he can only dream: 'If I had done it in a different way, I could now have/would now be able to...'. This interviewee provided details of a case in which a [redacted] painting (for a specific product structure) was positioned in the [redacted] (a position) of a factory which was, according to IP2, once reasonable. Over the years, transformations were done around this object. This made the factory less efficient. IP3 stated that it is the classic case to look back and to say: 'We should have done it differently'. IP2 used the words: '...if it is not considered and you say: We should have considered it'. A similar statement was made by IP5. The mistake to position toilets and other social rooms in the middle of a building is done again and again, and on top of this building are transformers, which are connected to and required for the supply of the entire factory. This was stated by IP2. However, it emerged from the interviews that this is not a recurring mistake, but rather in the nature of things. Blue-collar workers in OEM plants must meet defined timeframes, e.g. to eat and to go to the toilet. What was previously done would not have been done if it would not have been (assumed to be) appropriate at the point in time when it was planned and/or done. Thus, the right becomes wrong over time.

Appendix 6.1.2_01 Routine Operation in Factory Planning

All answers to the question about a routine operation in factory planning led in one direction and showed that there is no routine operation in factory planning, as there are continuous changes which are the only routine. The most important statements of the interviewees in this regard are the following ones: IP1 said that factories are being repeatedly modified to meet new product requirements. IP4 stated that reactions to frequent changes or, in other words, changing premises are the routine operation in factory planning. IP2 said that changes of premises could amount a routine operation in factory planning. IP3 described that there are never clear assignments about how a building should look. This applies mainly to production sections. IP8 said that there is no routine, as the market changes permanently. The statements of the other interviewees underline that continuous changes occur and dominate the routine in factory planning. It also emerged from the interviews that as the more time passes by, the more changes occur. This, on the one hand, is logical. On the other hand, this has not been sufficiently considered in factory planning – particularly against the backdrop of today’s factories, their developments, and the development of their characteristics and capabilities, e.g. their transformability.

Appendix 6.1.2_02 Statistical Intervals

Prediction intervals become wider as one moves further from the available data. Changing developments or in other words, changes of data over time are the reason why such statistical intervals were, are and will be developed. These intervals are, for instance, used in the pharmaceutical industry (Wiles, 2013b). A small amount of data can be better handled than a large one. Simple interrelations can be better handled than complex ones. Shorter durations can be better handled than longer ones, e.g. developments in 6 months can be better prognosticated than developments in 2 or more years. General explanations about statistical intervals are provided by Barrow (2013, p. 276) and Wiles (2013a, 2013b). A pharmaceutical product is usually less complex than an automobile, which does not mean that this is always the case or that pharmaceutical products are not complex. Moreover, production and logistics processes for a final product are as a whole usually simpler and involve fewer objects and structures in the pharmaceutical industry than in the automobile industry, which does not mean that processes and raw-material compositions in the pharmaceutical industry are simple. In addition, production networks and supply chains are usually less complex, while the automotive industry comprises rather more competitors. Thus, it is rather possible to forecast product- and production-related demands for, for instance, a headache pill than for an automobile. To define relevant factors, links and impacts between these factors is simpler for such a pill due to a smaller amount of data which is less complex as a whole. Furthermore, a shorter time period must normally be considered than in the case of automobiles (consider the product, process and factory planning for Greenfields and Brownfields). Moreover, changes of the factory environment are usually not as negative for products and factory structures of drug producers as for those of automotive OEMs.

Forecasts for market developments and trends for drugs are already complex, although historical developments and data, past experiences/experience values and statistical analyses (besides others) can be used under consideration of, for instance, the population growth, competitors and their developments, and further factors. Nevertheless, forecasts(/anticipations) can be relatively exactly determined. In contrast, forecasts(/anticipations) for automobiles, which finally determine required factory characteristics, are much more difficult because more relevant factors are involved and because the most links and impacts between these factors are more complex. Furthermore, longer timeframes must be considered. This makes scenarios in the factory planning for automotive OEM plants less reliable. Already by considering prediction intervals or scenario funnels of product models and types and of production figures (see, for instance, Wemhöner, 2005, pp. 115–119), which are far not all relevant ones and lack further appropriate considerations (which are described in the following sentences in subsection 6.1.2), difficulties are recognisable. Further required planning data are based on forecasts (see, for instance, Schenk, Wirth and Müller, 2010, p. 23), but far not sufficient to indicate the complexity faced by product, process and factory planners in the automotive industry today.

Appendix 6.1.2_03 Incomplete, Subjective and Reduced Data

The aim of scenarios is not to predict the future but to pre-think alternative possibilities or, in other words, alternative future scenarios of 'what could be' in order to get to better decisions (Fink, 2002b, p. 297). Nevertheless, one must prognosticate alternative futures to enable such pre-thinking. Fink (2002b, p. 312) uses the words "Blick in die Zukunft" which can be translated as 'a view into the future'. To what extent these statements are contradictory (the same as statements of other authors) can be assessed by the reader. It must in any case be considered that market research faces different difficulties and has limitations. To acquire reliable data can be problematic (Buber and Holzmüller, 2007; Furnham, 2012). Furthermore, market research opens up a considerable scope for interpretation (Hoffmann, 2007). Thus, market research results are questionable since they are not only based on hard facts. Furthermore, the selection of the right scenario technique/approach is difficult, as many of them exist (Hambach and Albrecht, 2014). Scenario techniques are in between facts and speculations (Dönitz, 2009, p. 7). Therefore, the effectiveness of these techniques is highly questionable against the backdrop of the complex and continuously changing factory and work environment, which is challenging. Suggestions about how the use of scenario techniques can be improved (Dönitz, 2009; Hambach and Albrecht, 2014) are also open to question. Moreover, when the data is processed further, other problems occur (e.g. problems with regard to the point in time when data has been acquired and/or data which has not been provided, and problems with regard to the definition of values) (Bangsow, 2011), which aggravates the situation. These sources validate the contents of this appendix and validate the main body of text. Furthermore, it is conceivable that managers, planners and/or other persons take decisions based on their past experiences which were once right but can be actually wrong for a new situation (consider also the line of least resistance attitude). On the one hand, scenario techniques appear highly scientific in the factory planning literature. On the other hand, they are based on the intuition of scenario planners (Fink, 2002a, p. 205) and are subjective (Fink, 2002b, p. 312), not to mention a special feel of factory planning experts or participants for future factory developments (Heger, 2006, p. 106).

It is also important in the context of scenarios that the steerable and non-steerable key factors of Hernández (2002, p. 119), which are also shown by Wiendahl, Reichardt and Nyhuis (2015, p. 380), require a revision (the same as the use of scenarios in factory planning). According to Hernández (2002, p. 119) and Wiendahl, Reichardt and Nyhuis (2015, p. 380), steerable key factors are the production depth (vertical integration), product prices, building lifecycles, and the location of the production (just to mention a few examples). These prices and lifecycles as well as the location are in fact steerable, but this steerability leads to no advantages if products cannot be sold or if buildings are inappropriate to encompass required processes. Planning premises and finally factory characteristics must meet the requirements of the factory environment, e.g. of the market. (It can be an exception if an enterprise and its product(s) dominate the market.) Therefore, market and other requirements decide about these key factors. Furthermore, it cannot be claimed that the production depth is always steerable, as, for instance, a supplier can refuse to produce parts or become bankrupt. That these cases happen emerged from the interviews.

Appendix 6.1.2_04 Cynefin Framework

Hester and Adams (2014 pp. 180–194) (and other authors such as Snowden, 2002) discuss the 'Cynefin framework' and different domains which are included in this framework. 'Complex', which is one domain, means that "the relationship between cause and effect can only be perceived in retrospect, but not in advance. The approach is to probe, sense and respond." (p. 181). 'Chaotic', which is another domain, means that "there is no relationship between cause and effect at the systems level [(it can at least not be determined in advance)]. The approach is to act, sense, and respond." 'Disorder' is a further domain and means that causality is unknown (p. 182).

Factory Planning in the 1980s was already complex. Today, factory planning is mainly at the interface between the complex domain and the chaotic domain, while even the disorder domain can occur, which emerged from the interviews. It can be claimed that throughout the BFPSs, a factory passes through the complex domain (mainly BFPS-1 and BFPS-2) and the chaotic domain and can even reach the disorder domain. Disorder can be reached when both the 'to be'-status and the 'as is'-status of a factory cannot be defined. This can happen in factory planning. That several domains can be reached at the same time must be considered. Thus, not only scenario planning but also factory planning can face the chaotic and disorder domain.

Appendix 6.1.4_01 Rapid Implementations and Transformations

Factories should be efficient, green and transformable. Furthermore, factories should be clearly structured and involve short flows. A crossing of flows should be avoided. An optimal arrangement and connection of FOs/FSs should be enabled over time, which is only possible if the general structure is transformable. This was highlighted by all interviewees and is in line with the general factory requirements which are described in subsection 2.1.2. Transformability makes high investments future-robust. It was repeatedly stressed by all interviewees that it is required to perform factory implementations and transformations rapidly and without production stops. This shows the importance of the transformability and of the implementation and transformation velocity of factories.

Appendix 6.1.4_02 Exchange Areas (1 of 2)

IP5 argued that if no exchange area is available, holiday works can help if the duration of the required transformation is not too long. Substitution processes can be another option. IP7 stated that available extension areas, exchange areas, and building volumes are very sensible, as one can bypass many problems. IP3 made a comparable statement about exchange areas. IP5 said that the body shop requires a complete change in the case of a product model change and thus a complete exchange area. Operational sequences, production flows, and logistic flows change. IP5 talked furthermore about difficulties which occur if no exchange areas are available. This applies to the assembly shop including end-of-line due to the rain test and other fixed points. IP5 also stated that exchange areas are very important.

This interviewee argued that transformations within buildings are required if exchange areas are not available and that this makes transformations difficult, if these are possible at all. IP2 said that exchange areas can be required for paint shops, as the largest product determines the characteristics of this section (see also the eBFPC 'product model change' in subsection 6.1.7). According to this interviewee, free extension and exchange areas should be located between buildings. However, IP2 also stated that such areas also lead to problems such as longer distances. IP8 said that exchange areas increase transformability and that if one does not have them, she/he needs to do a patchwork and extend single separated areas as required. IP8 used in this context the expression UHP, the same as IP3. IP3 argued that transformations (e.g. a BFPC-B) are very expensive and often not possible, and that the use of exchange areas is preferred. IP3 stated that, in the case of a product model change, different machines and machine arrangements are required in the body shop. Therefore, exchange areas are required. IP6 stated that exchange areas are very important, as they lead to transformability and enable transformations which without these areas are not possible at all.

It also emerged from the interviews that the pre-production of parts* and substitution processes are not always possible and/or reasonable, and that holiday works are not always sufficient to meet transformation requirements and/or to perform transformations in time. *(When the words 'pre-production of parts', 'pre-produce parts' or 'pre-produced parts' are used, not necessarily and/or not only parts are meant. Systems, subsystems, automobile bodies, assemblies, subassemblies and other objects and structures can be meant. It is also necessary to store pre-produced parts (etc.).) Furthermore, it is not always possible and/or reasonable to perform outsourcing. In the case of press shops, parts can be pre-produced. Substitution processes are possible, but appropriate machines (e.g. presses) are required. Outsourcing can be an option. In the case of body shops, single welded assemblies/units can be pre-produced, while the pre-production of automobile bodies is limited. The pre-production of automobile bodies is normally limited to buffer and storage area sizes, while free areas can also be used. Substitution processes can help, the same as outsourcing (at least partly). In the case of paint shops, substitution processes are rather not possible, and pre-production (pre-painting) and outsourcing are hardly possible and/or reasonable (mainly due to connected flows and the general requirement to paint parts of an automobile body together (the exception proves the rule)). In the case of assembly shops, substitution processes can help. To pre-produce (pre-assemble) automobiles partly is rather difficult, particularly if one considers their disintegration from and reintegration into the line, required logistics equipment etc. and storage areas (meant is not to produce finished automobiles and to park them afterwards). Nevertheless, outsourcing of separable assembly shop works is partly possible, the same as the pre-production of parts which are the outcome of such processes (consider only JIT/JIS). These circumstances will not always be mentioned. This emerged from the interviews. What must be considered are entire flows, e.g. production flows. Substitution processes, the pre-production of parts and outsourcing can lead to difficulties. Possibilities with regard to substitution processes, pre-production and/or outsourcing must be reflected against the backdrop of these flows and their transformability (i.e. the level to which these flows are transformable), while other FOs/FSs must be considered, as these can be impacted too (consider difficulty factors such as domino effects). Outsourcing is furthermore generally a question of a company’s attitude. In the case of automotive OEMs, it is often not only reasonable to keep press shop-, body shop-, paint shop- and assembly shop-related works and processes in-house for flow-related reasons, but also for reasons with regard to know-how. This emerged from the interviews, but depends on the specific case. Exchange areas are, in the case of a product model change, particularly required for body shops, but also for other sections. This emerged from the interviews. Subsections 6.1.7 and 6.1.10 involve further information in this regard and further information about substitution processes, the pre-production of parts and outsourcing.

Appendix 6.1.4_03 Exchange Areas (2 of 2)

IP4 argued that sufficient areas for the production, employees, goods and inbound and outbound logistics are required, and explained that exchange areas are often required in the case of transformations. IP6 stated that transformations can be disabled without exchange areas. IP6 also stated that it would be best if one could make a real area exchange, but on land – on the fixed floor – this is hardly possible. According to IP5, exchange areas are required to pre-test the production. IP5 found furthermore that a new construction at an exchange area is preferred in factory planning rather than having a transformation, e.g. a BFPC-B. This interviewee stated that it is more difficult to perform transformations without exchange areas. IP3 claimed that an optimal factory is a factory in which one has huge areas and alternative or, in other words, exchange areas. A Brownfield without exchange areas means that transformations must be done within given structures which make transformations more difficult and partly not possible. If exchange areas are available one can implement a new production and demolish the old one afterwards. The statements of IP5 and IP3 were also validated by IP8, who claimed that if one has no exchange areas, it is necessary to make add-ons, attachments, and patchworks everywhere. Subsection 6.1.7 contains further information about exchange areas.

Appendix 6.1.4_04 Key Influencing Factors

The implementation of new building technologies and sustainable solutions such as solar and photovoltaics can lead to extensions (IP3) (such sustainable solutions were not often mentioned), the same as new road surfaces to reduce noise (e.g. due to traffic diversions) and changing/new [redacted] (fluids) for automobiles, as additional process facilities and infrastructures can be required (IP5). IP4 expressed that when machines become so old that spare parts are not available, exchange areas can be required. IP8 described numerous technological changes which impacted a paint shop and other sections, while new/changing standards were also reasons for transformations which required additional areas. Similar cases were described by IP3 and IP7.

Causes which lead to transformations are mostly product-related. This emerged from the interviews. IP3, for instance, argued that continuously developed products are the main cause for permanent transformation requirements towards buildings and building structures. (It also emerged from all interviews that transformations of building contents are performed continuously (see also the eBFPC product model change).) This statement was strengthened and extended by IP5 and IP8, who argued that product changes impact continuously on a factory. Product changes were explicitly identified and described by IP1, IP2, IP3, IP4, IP5 and IP8 as the main reason for capacity-unrelated area extensions. This was furthermore validated by several statements of IP6 and IP7. It emerged from all interviews that capacity-unrelated area extensions occur by reason of products. Examples of changes which come along with changing and/or new products are: changing/new materials (IP4 and IP8); changing/new production technologies (IP6, IP4 and IP7); methods and processes (IP4 and IP8); changing forms/dimensions (IP2 and IP5). These factors can also be reasons for product changes. IP1, IP4, IP5 and IP7 mentioned electric automobiles in this regard. IP4 stated furthermore that new modern production plants require often higher buildings and wider spacings between columns. Deep-drawing/stamping presses are designed for larger forces and are therefore larger, the same as their tools.

Distributions of product models, types and/or variants change (e.g. 20% type ‘a’, 35% type ‘b’ and 45% type ‘c’ change to...). It emerged from the interviews that a change of these distributions leads in most cases to area extensions (if the overall capacity is not reduced, but this can even then occur). It emerged furthermore from the interviews that the overall capacity of a factory and product dimensions normally grow (all interviewees). Both a capacity increase and growing product dimensions lead to the requirement to have additional areas*. Furthermore, new and/or additional functions (e.g. air conditioning, media interfaces, new safety technologies etc.) (IP2) can have an influence on product dimensions and require additional facilities etc. which, in turn, lead to the requirement to have additional areas* (production lines become wider and/or longer because of product dimensions and not only because of additional facilities etc.) *if these areas were not considered upfront; to consider these areas is almost impossible or impossible from a long-term perspective. This means that the complexity in factory planning is much greater than the complexity which can be indicated through the contents of subsection 6.1.4 and this thesis.

Appendix 6.1.4_05 Breathing Factory (including Displacements)

IP8 said that transformability is important for all production sections, for buffers, and for connecting conveyor bridges. IP4 stated that transformability is important for areas, buildings, technical infrastructures and for production lines and facilities, as they are reduced, extended and otherwise transformed in many different ways. This interviewee talked in this context about areas, building structures, roads, walkways, supply networks, production lines, and machines. IP4 further stated that a factory development is concerned with the question of how a factory can be made fit for new products and how the arrangement of areas and buildings, and connections between buildings must be transformed over time. There are influencing factors (in the case of a product model change) which have an impact on the number of stations, conveyor systems, and a retroactive effect on the building (meant is a mediate impact of a transformation).

IP7 argued that production flows change massively. Most dynamic are production and logistics processes. There are changes that must be done permanently. Changes occur permanently. Processes influence buildings and areas. IP7 further argued that the production sequence and flow must always be maintained and that this impacts on the extent of relocations and moves. This sequence is changing. The definition of products has an impact on facilities etc. Requirements change and domino effects occur again. IP5 claimed that with a model change, flows change completely. IP8 stated that each model has a different production structure and with each successor model (car) a completely different production system. IP4 used the word ‘granularity’ in this regard. IP2 said that production facilities should be relocatable. This was validated by IP7. IP4 said that the (production) line and the process facilities should be able to breathe by reason of their changing interplay. The question is also how long my production stops are when I take something out and shift objects together. This is normally not done, as facilities and conveyor systems impact on buildings. IP4 mentioned this several times during the interview. IP5 provided information about a case of a building in which permanent transformations took place over a period of four years: production lines were extended while others were relocated (within this building). Furthermore, new overhead conveyors were installed, while a great amount of steelworks was required. Product quantities changed and assembly lines of a phased out product model were disassembled and removed, while assembly stations from another building were integrated instead in order to be closer to the production and therefore more efficient. IP6 said that if a press shop is replaced by 3D printing, large printers are required. The raw material differs and is also supplied differently, e.g. raw material tanks instead of coils. The volume of raw material increases. Thus, more areas are required and logistic flows change. Furthermore, finished parts can no longer be stacked as before. Special load carriers with intermediate layers are required. IP8 disclosed other logistics changes, while IP7 stated that the logistics change permanently. IP5 recounted a case in which a road has been widened, while IP6 discussed a case of an SME in which wider roads would be sensible but impossible to be implemented due to several restrictions. IP3 revealed a required drainage extension (which means primarily its width) after a groundwater level rise. This interviewee argued that it is still unclear how this requirement should be implemented (an OEM factory in [redacted] (a country)). Larger energy canals and sewers can also lead to (off-site) transformations of the external infrastructure (IP4). Furthermore, the interviewees were asked if it can happen that overarching structures need to be transformed. The statements of the interviewees led in one direction. IP6, for instance, argued that this is the rule with each larger intervention. IP8 stated that this is often the case. This is in line with the statement of IP3. IP8 described several real-world cases in which overarching networks and systems were transformed. IP5 also described several of such cases. This interviewee explained different cases in which objects and structures of main supply networks were displaced. Furthermore, different superstructures were constructed on top of a media canal, which led to the requirement to reinforce this substructure. IP5 stated that buildings, building contents, the technical infrastructure, conveyor systems and steelworks are mainly impacted in the case of Brownfield projects.

IP4 said that it would be desirable that the assembly shop can be implemented where the body shop is. Furthermore, it would be desirable to change it into a press shop. The reality is that exchange areas are required. Buildings are pushed away (i.e. displaced) by other buildings. I extend the body shop and reduce the assembly shop or vice versa. This means that I need more body shop areas and that I reduce assembly shop areas or vice versa. The production depth must be decreased, or I change logistics into assembly areas. IP4 recounted a case of a suboptimal building which was a body shop and a pure logistics building in which parts of the [redacted] (a production section) were integrated. Today, it is [redacted] (a production section) with logistics. IP2 stated that changes of uses happen and that sections grow into others. Assembly areas, for instance, grow into logistics areas. IP2 presented details of a further case in which a building had a history of change and which should again be transformed. IP5 talked about 'permanent Brownfields'. Buildings involve not only many different tasks during their lifecycle – these tasks change over time. IP3 argued that [redacted] (a production section) and logistics areas are changed into assembly areas if the assembly shop is too small.

It emerged from the interviews that factory sections grow not only towards extension areas (outside buildings), but also out of themselves. This means that their extension takes place, roughly speaking, out from their centre towards one or several directions. It also emerged from the interviews that production is mainly prioritised and not indirect areas/functions. Moreover, it emerged from the interviews that indirect functions are often displaced by direct ones. Direct areas and buildings displace indirect ones. IP1 stated that the core grows to the periphery while non-production parts are displaced to the outside of the factory/plant boundary. All interviewees disclosed several cases in which buildings including several building contents and other FOs/FSs were displaced. This means that buildings are not only extended, but are also displaced through other buildings. Numerous real-world displacement cases were outlined by the interviewees. IP5 used the designation 'outstretching of factories'. Furthermore, IP5 argued that building demolitions do not only happen because buildings are too old, but also because more areas and spaces are required for buildings that are newly constructed and extended. All interviewees have confirmed that positions and dimensions of buildings change over time (which does not mean that they can be moved). It emerged from the interviews that this often happens. IP5 further stated that the core grows to the periphery. This is in line with the statement of IP1. IP7 said that it would be sensible if factory objects and structures that are larger than containers were movable, especially as different departments and sections change. Consequently, it would be nice if we could generate free areas in the middle (of the factory). IP1 argued that (if buildings were movable) one could shift a building to the periphery, and instead, put more important ones in the middle. IP4 stated that positionings of objects are a problem because if indirect ones (e.g. office buildings) are positioned at the periphery, growth is disabled; if they are positioned in the centre, they disturb connections between production sections. Factories should be able to breathe. Most of these statements mainly apply to OEM factories that have reached BFPS-4, while it emerged from the interviews that displacements of buildings and other FOs/FSs happen also within factories that have achieved BFPS-3, and even earlier. Building displacements are on the daily agenda within many factories that have reached BFPS-4, while those within BFPS-3 are rather concerned with the displacement of smaller FOs/FSs – but building displacements also happen in BFPS-3 (see particularly subsections 6.1.7, 6.1.10 and 6.2.4 for further information about displacements).

Relevant in this regard are also other indirect and supporting functions. IP4 argued that the relocatability of objects and structures is desirable. Indirect functions should be close, but if more areas are required, they should be movable so that they can be shifted away. Other objects and structures must be close. Canteens must be reached within a certain timeframe and must therefore be located within a certain radius; the same applies to factory fire brigades. This was validated by other interviewees. IP5 said that canteens, sanitary and health facilities should be located in such a way that workers must walk as little as possible. This interviewee talked furthermore about rules and regulations for rescue and emergency escape routes which, for instance, must be located every [redacted]0 or [redacted]0 meters. IP3 also talked about canteen planning and that the ways to these objects should not be too far. A fire brigade and car parks were also mentioned in this context. It also emerged from the interviews that fixed points exist (e.g. different s&d plants) which are not displaced, as the efforts are huge (see appendix 6.2.1_02 for further information in this regard).

Despite the existence of fixed points, several designations were used by the interviewees, which indicate that factories are comparable with living organisms. IP4 used the word “Tetris”. This interviewee talked about building and area Tetris, Tetris within buildings and technical infrastructure Tetris. “Lego” was used by IP4 and IP8, and ‘mosaic’ by IP7 (always in the context of changes and transformations). The designation ‘breathing factory’ was used by several interviewees and it was also stated several times that factories should be able to breathe.

Appendix 6.1.4_06 Amount of Area Works (Brownfield)

According to IP4, in Brownfield projects, there are always smaller area works, e.g. floor screed works and/or smaller drillings. In over 50% of the (Brownfield) cases, large interventions take place, such as adaptations of large pits which, for instance, can be caused by the reduction or extension of production lines. The statement of IP4 is comparable with the information provided by IP5, who stated that in half of all Brownfield projects large area works are required. IP5 further argued that heavy machinery is often required and that these require free spaces. This interviewee also stated that substructures are often transformed. IP7 said that area works are required in 70% of all Brownfield cases while 60% to 70% of these Brownfield cases are concerned with changes of uses and require large area and substructure works. Numerous changes of uses and displacements (e.g. of buildings) were disclosed by the interviewees. IP1 said that the question is whether the building shell, substructures and the energy and media supply are appropriate if an object is moved. IP8 stated in this context that, as a rule, appropriate framework conditions, especially those of substructures, are not given at the location of installation. This interviewee further stated that numerous free areas were heavily built-up with diverse objects and structures which were afterwards demolished to construct something new. This happened repeateadly over the years in which this interviewee was responsible for a certain factory, besides many others.

Appendix 6.1.5_01 Heterogeneity of Factories

IP5, for instance, argued that a press shop normally remains a press shop due to totally different building characteristics compared to other factory sections. This interviewee further stated that a press shop is as deep as high which does not apply to other factory sections. This statement has been validated by IP8, who argued that these characteristics are not appropriate for an assembly shop. IP7 said that it would be inefficient and senseless to align a press and an assembly shop. It would mean that an assembly shop must be as high as a press shop and have the same floor loads and substructures. The term senseless was also used by IP8, who further argued that a press shop and a paint shop involve structures other than a simple assembly shop. IP2 said one cannot make an assembly shop out of a paint shop and asserted that it would make no sense to unify different sections.

Appendix 6.1.5_02 Terrestrial Areas are Taken for Granted

It emerged from the interviews that terrestrial areas are taken for granted. IP7, for instance, said about substructures that ‘one can not even see them’. That ‘factory planners think in fixed structures’ is a further statement of IP7, who argued that smaller relocations are possible, while buildings cannot be moved. IP4, IP5 and IP8 said that building moves are not possible. IP4 stated furthermore that it is difficult to imagine building moves. IP2 said that it is normal to change substructures. IP4 stated that transformations ‘naturally’ lead to infrastructure transformations. IP8 argued that it would be beneficial if structures could be flexibly integrated into the substructure, but that she/he cannot imagine how this can look. Further statements of IP5 and other interviewees showed that the world of factory planning is largely accepted as it is and not questioned. IP7 said that it would be sensible if entire buildings were movable. This was validated by all other interviewees. IP5 answered the follow-up question ‘How important is the mobility of large production facilities?’ as follows: The mobility is not important for large deep-drawing presses, as they are since many decades located where they are. This also shows that the existing problems in factory planning are not always recognised as such and in a way that allows always explicit statements about these problems and how they can be solved. Both 'many problems in factory planning' and 'terrestrial areas' are taken for granted. Nevertheless, the entirety of interview statements speaks a common language. IP5 also stated that it would be sensible if such FOs could be moved, and that this is logical. This interviewee further stated that it would be very good if buildings could be moved together with all their robots and other machines, but that she/he does not know how this can be made real (see also the other interview statements above). The number and quality of interview statements provide a clear picture which shows that the area-mobility and different MASs are required.

Appendix 6.1.5_03 Heterogeneous Transformations and Growth

IP8 talked about a real-world factory and stated that when she/he started to work there, this factory had [redacted] (more than 30%) of its current size and [redacted]% (about 40%) of the maximum employees that ever worked in this factory. This statement also shows that different objects and structures in a factory grow heterogeneously. IP6 stated that a factory grows heterogeneously per section and that one needs to do more in certain sections and less in other ones. IP2 also stated that each production section changes differently. IP3 made a similar statement and further argued that factory sections and departments change differently, building-wise and process-wise. This interviewee highlighted that sections are specific and that this can lead to difficulties if one wants to transform them. IP4 claimed that when a paint shop has reached its limit, a new paint shop is required, as one cannot just extend it due to the technical processes and the process chain involved. According to IP4, an assembly shop can rather be extended. IP1 said that buffers between sections differ. This implies that they change differently. IP4 stated that countervailing effects can occur. A certain object can require more energy and another one less. IP4 further stated that this shows the requirement to have a transformable infrastructure. IP6 described that coupled lines and pipes in the ground can be used to a certain limit and grow afterwards stepwise. This means that such structures must be exchanged when their limit has been reached. Another option can be to leave these structures in the ground and install additional ones. Both options can be required. The same applies to a system. When an existing system has reached its limit, it must be exchanged or extended through additional structures and/or objects or, in other words, system elements. Many further statements were made which emphasised the heterogeneity of factories and heterogeneous transformations and growth. IP5 described roads which were widened and required demolitions of adjacent objects and structures (even of buildings). Similar and further cases were described by several interviewees. The following paragraphs were developed based on all interview statements.

A capacity increase leads to an extension/dimensional increase of objects and/or structures (this can also occur through an exchange of FOs/FSs) and/or to the implementation of additional objects and/or structures. This is in line with Bracht, Geckler and Wenzel (2011, p. 33), who argue that, in addition to collision checks, it is examined if supply lines are sufficient to supply the required amounts, e.g. of water and/or pressurised air.

Different FOs/FSs grow heterogeneously. This applies to all factory structure levels down to smallest elements such as water pipes and ventilation shafts. A process facility, for instance, requires roughly said (a) different types and (b) different quantities of energy and media (inputs), and generates (c) different types and (d) different quantities of energy and media (outputs). Furthermore, (e) different types and (f) different quantities of inputs for the direct process (e.g. raw materials, parts and/or semi-finished products) are required, while (g) different types and (h) different quantities of outputs (e.g. finished parts) are produced. In addition, (i) kinds/types and (j) the number of required employees, tools, devices, racks, logistics equipment etc. can differ ((e), (f), (g), (h), (i) and (j) are not depicted in figure 74, which visualises these circumstances; relations between areas and FOs/FSs are also not depicted).

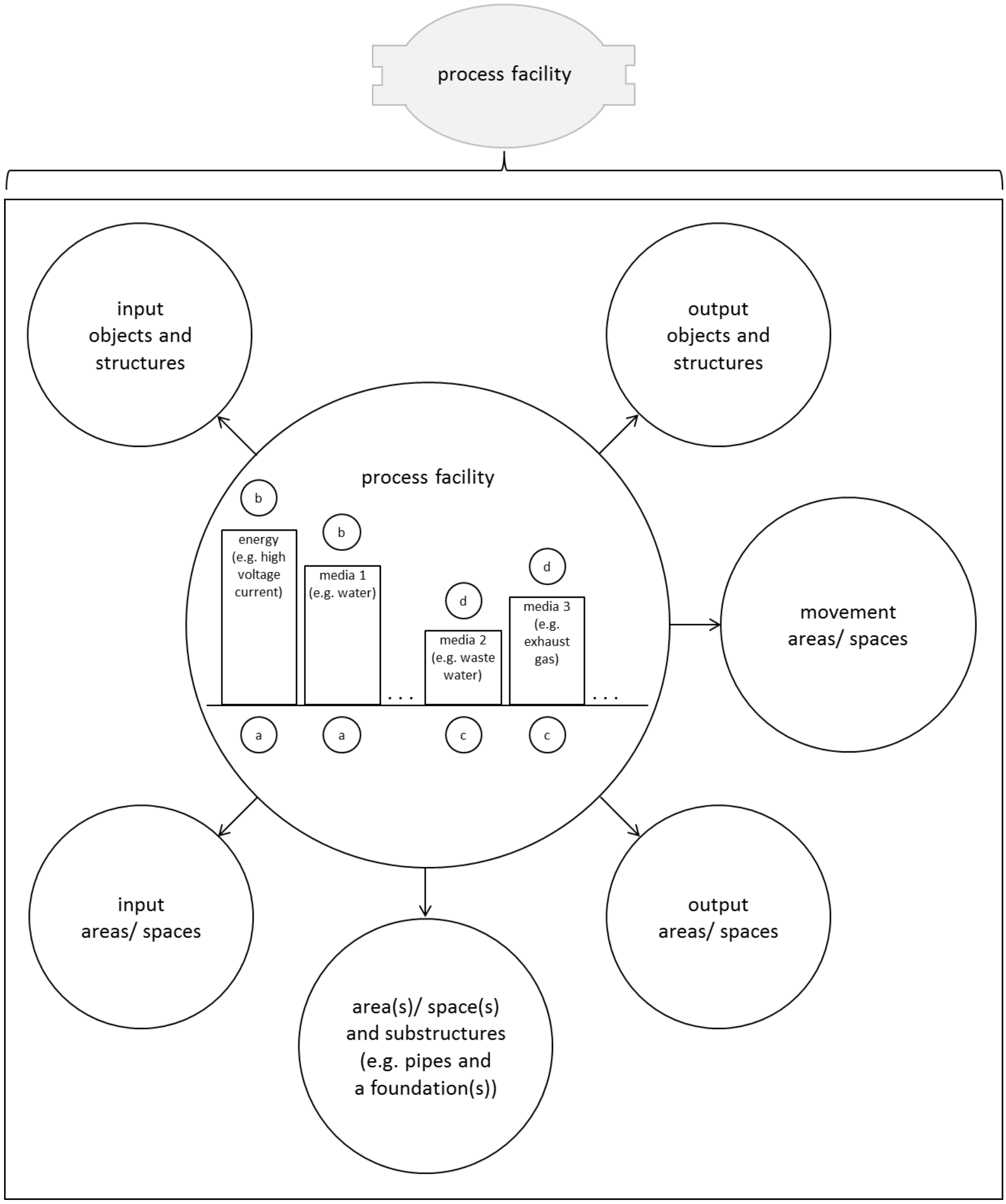
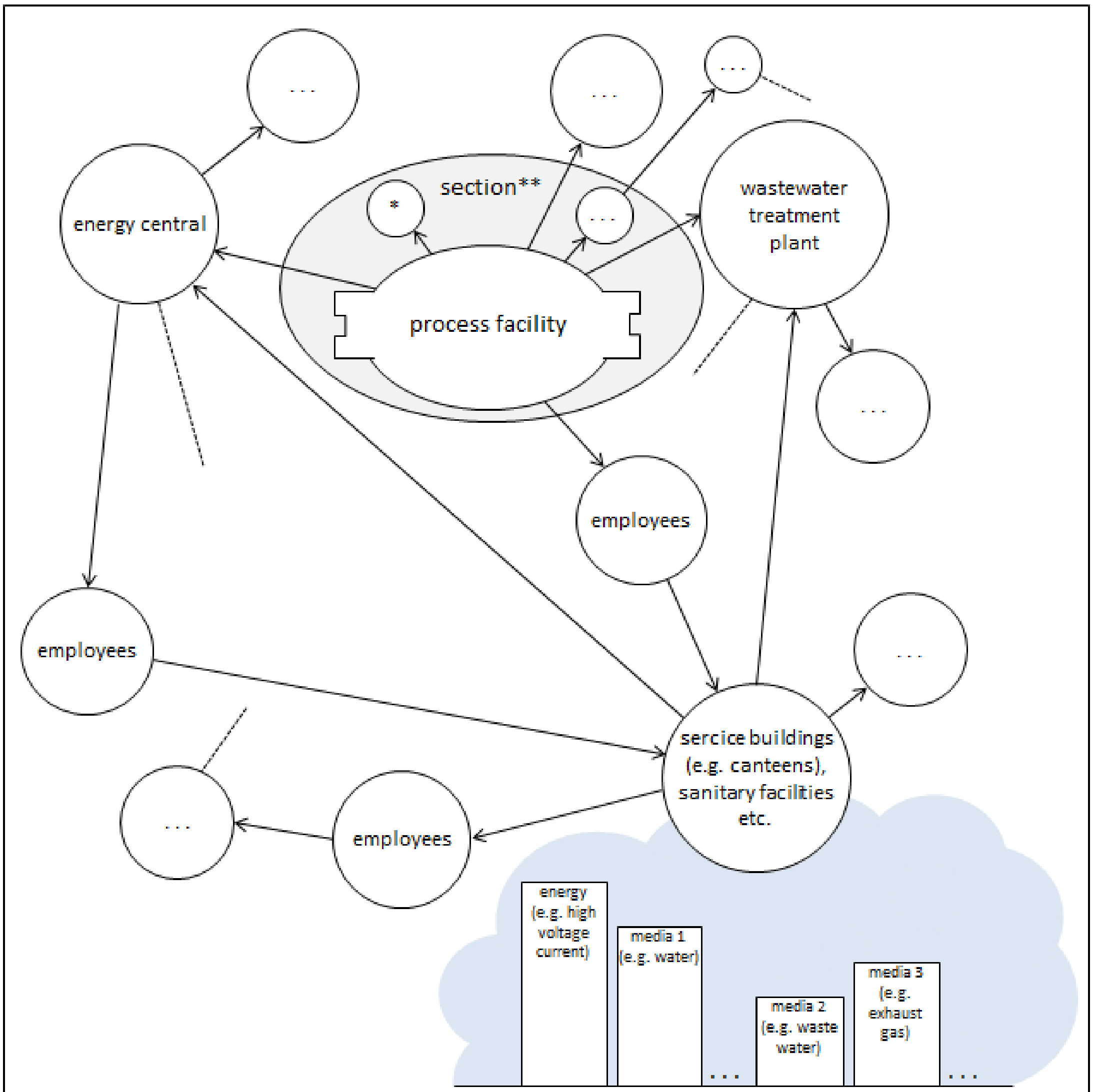


Figure 74: Impacts of a process facility

Racks, equipment and the like can have a further impact on the required energy and media. In sum, this has an impact on required input and output objects and structures (e.g. pipes), input and output areas/spaces, and on movement areas/spaces around the process facility. A change (e.g. when a process facility is exchanged through another process facility) impacts differently on these FOs/FSs and areas/spaces. Thus, a capacity change (e.g. a capacity increase) of one FO/FS (i.e. FO or FS) is consequently, as a rule, not proportional to its dimensional change with regard to its size, shape/form (e.g. footprint), and (e.g. technical) contents. An additional object can possibly be installed instead of transforming or exchanging an object. This depends on the circumstances and has, as a general rule, also an impact on FOs/FSs.

Not only can the required number of blue-collar workers, maintenance staff etc. be impacted, but also the required number of white-collar workers and office employees. Furthermore, such a change can evoke different requirements towards s&d plants and overarching networks and systems, and lead to further domino effects (figure 75).



* direct impact on adjacent objects and structures
** Interfaces and impacts of the section are not depicted, the same as impacts on the section (e.g. on a production line/ group that could be involved as structure level between the process facility and the section (i.e. when the process facility would belong to this line/ group).

Figure 75: Process facility as a trigger for a domino effect

(The exchange of a process facility can also lead to a reduction of employees. Blanket statements are therefore hardly possible, as it always depends on the specific case in hand. Nevertheless, the previously described patterns occur repeatedly.) This means that not only directly connected and/or adjacent FOs/FSs (e.g. water and wastewater pipes, equipment etc.) can be impacted through a transformation, but also other FOs/FSs, which is often not directly recognisable without deeper analyses. Domino effects and further difficulty factors must be considered in this regard.

Heterogeneous transformations within a factory section are depicted in figure 76. Each of these transformations can significantly impact on numerous other FOs/FSs and employees. This is self-explanatory if one considers the abovementioned circumstances.

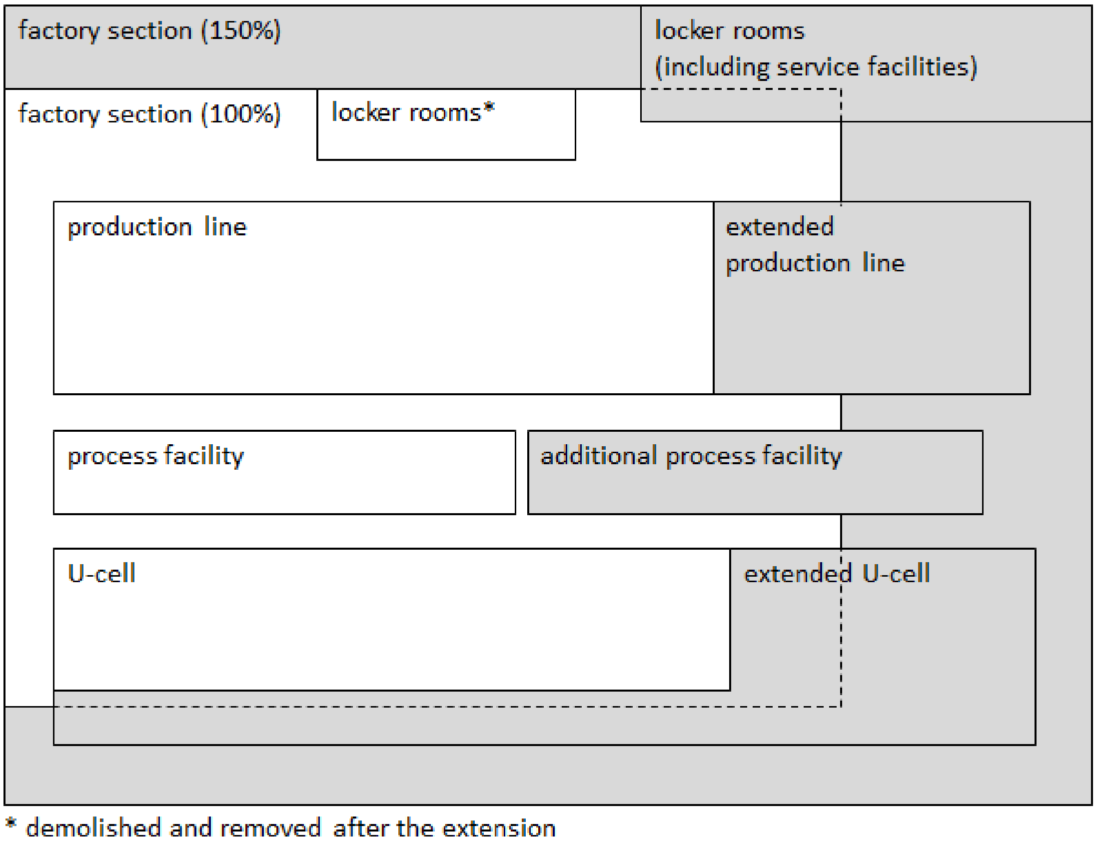


Figure 76: Extension of a factory section

Not only can process facilities be exchanged. Many other transformations occur, as visible in figure 76. Not all possibilities are depicted. The eBFPCs, for instance, involve further possible transformation scopes. This makes one understand heterogeneous transformations and growth of factory sections (figure 77), and consequently of factories.

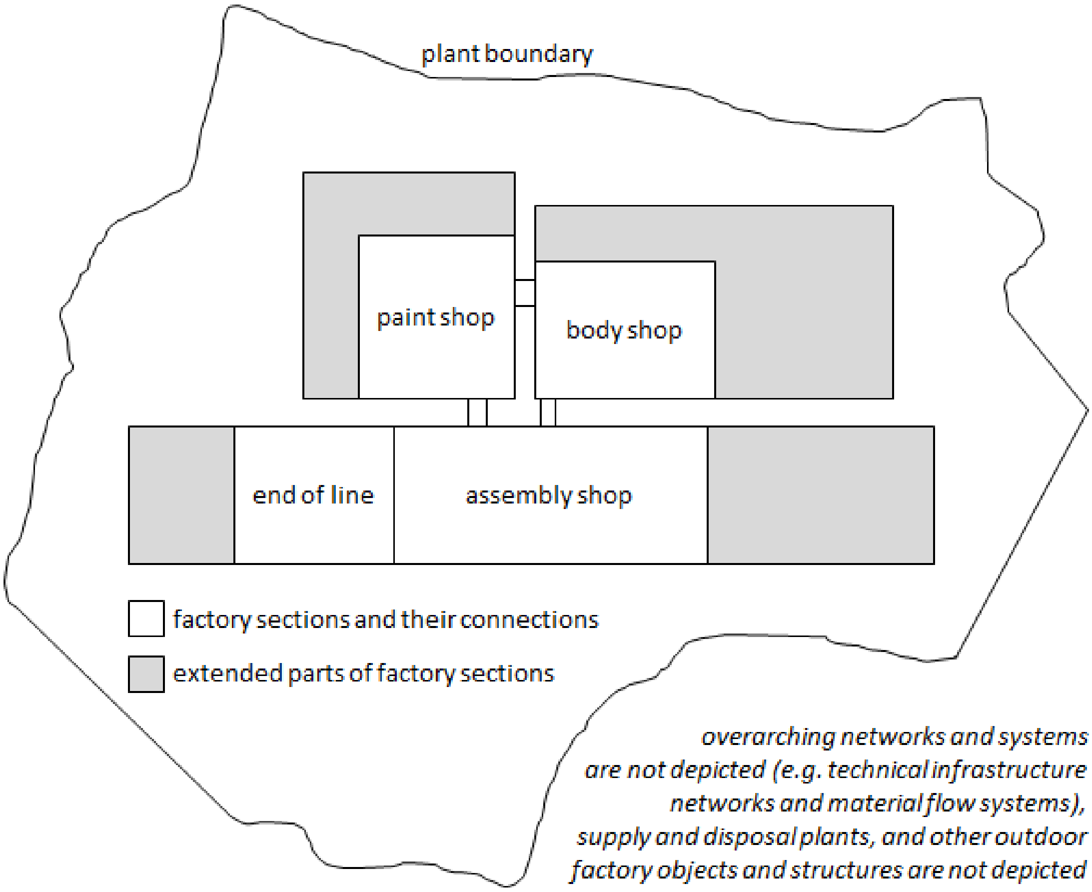


Figure 77: Heterogeneous growth of factory sections

Figure 77 depicts building shapes of factory sections and connections between them. Other interfaces for inputs and outputs (e.g. truck unloading) are not visible, the same as building contents. Furthermore, no parking places etc. are depicted. Other limitations are described in the figure. Not all limitations of such figures will be mentioned in future – especially if these limitations are obvious, as in the case of the previously mentioned limitations. It must be considered that in the case of today's factories, not all section extensions can be performed easily and that they can differ, which depends on the circumstances (see the eBFPCs for further information and details).

In order to make the real complexity of the described circumstances to this point understandable more fully, it must be considered that an object normally cannot be transformed or exchanged according to its transformation requirement. One reason for this is that only a limited number of standard FOs/FSs exist, while it is often simpler to install an additional FO(s)/FS(s) (interfaces must also be considered).

Furthermore, an object ‘a’ (e.g. a pipe) changes differently than an object ‘b’ (e.g. an air duct). This is the case as different fluids, solids and/or gases can lead to different requirements and change differently, e.g. depending on the volume flow and/or temperature. Such micro level aspects must be considered for all described FO/FS changes. Moreover, it is for some FOs/FSs better to be exchanged, while it is for some other FOs/FSs better that additional FOs/FSs are installed. Both options can occur, and it is also possible that one or both of these options are not possible. This depends on the specific case and circumstances.

To conclude, what applies to a process facility applies in a similar manner to larger FOs/FSs or, in other words, higher factory structure levels, while smaller FOs/FSs involve further characteristics which impact on their heterogeneity and heterogeneous transformations and growth. Different factory capacities require different FO/FS dimensions (e.g. building volumes, road widths and pipe diameters) over defined distances (e.g. road and pipe lengths). Capacity changes of different FOs/FSs lead to heterogeneous changes of these dimensions and distances, e.g. between FOs. A capacity change of a factory leads consequently to different dimensional changes of different FOs/FSs, and to different changes of related distances. One transformation requirement can evoke further transformation requirements. More employees, for instance, require more sanitary rooms while more sanitary rooms require more water and the like. FOs/FSs grow out of themselves which means that their extension takes place, roughly speaking, out from their centre towards one or several directions. Different movements/ relocations are also possible. Heterogeneous ‘effective transformation and/or movement directions’ are one outcome. In sum, these are system characteristics of a factory which lead to the circumstance that a transformation requirement cannot only lead to huge efforts, but also to inappropriate actions and even a disaster, which is explained in section 6.2, while the aspects that are described in the previous and next subsections must be considered, and are considered, e.g. through the transitions.

Appendix 6.1.7_01 Product Model Change

IP5 said that five to six years are required to transform a factory for a new product model and that one always has new requirements, even if the drive technology remains the same. Transformations start three years before the SOP and go on up to three years after it, while transformations for the then following model must be partly prepared in parallel. This is in line with IP8.

IP1 and IP8 stated that a body shop and an assembly shop including end-of-line require exchange areas and that these can also be required for all other sections. IP8 argued that changing and new materials/material technologies, production methods and processes make buildings change. A body shop requires the implementation of a completely new production system, as steel changes to aluminium and as sheet thicknesses change. Other changes occur. This is a change in use from an area perspective. Such a quantum leap happens in the automotive industry generally with each new product model (car). What applies to a body shop applies in a similar form to an assembly shop. IP8 said that the rain test must be transformed with each product model change. The same applies to the marriage and numerous other objects and structures. I invest in the case of a product model change several million (Euro) for the assembly shop (IP8 talked in this context about a three-digit million Euro sum; the management view of this interviewee demonstrated several times that almost everything is possible from a financial perspective and also that almost everything is done if it can benefit the enterprise). IP5 argued that in the case of a new automobile model (car) (i.e. a product model change), new buildings are required. In assembly shops are production lines and single workplaces rearranged. In the case of a product model change, the body shop requires a complete change and thus a complete exchange area. Operational sequences, production flows, and logistic flows change. Many other changes occur. Product sizes increase. Movable robot cells cannot be used in the entire body shop. Several robots and other objects are fixed. This cannot be changed. These objects are hardly relocatable. If there is no exchange area it leads to vast difficulties in the body shop (which was validated by all other interviewees) and also in the assembly shop (the rain test and several conveyors were mentioned in this context). The paint shop can also require an exchange area. IP5 stated that changing automobile models can lead to transformations, as these models involve different dimensions. IP2 said that the largest product is decisive for the paint shop. This interviewee talked about the dimensions of a structure of a specific high-volume series product and argued that it is therefore impossible to use the current paint shop. Furthermore, (quasi-)exceptional cases occur. IP7 stated that the legislation in [redacted] (a country in Asia) requests in 2017 that [redacted]0% (more than 20%) of the new registrations are electric cars. This interviewee further stated that the occurrence of new and changing product models, types and variants is normal. It is also normal, that additional areas are required.

IP5 argued that a product model change is rather mishmash than a pure BFPC-B or a pure BFPC-C. A product model change can also be perceived as a programme. This should not (necessarily) be confused with a 'factory structure recovery programme' (please consider the following text in subsection 6.1.7). IP8 argued that programmes are required in order to meet new requirements with regard to new models, types and variants. This interviewee claimed that this has been in a plant that has reached BFPS-4 over [redacted]0 years (several decades) on the daily agenda. Further relevant information for the product model change can be found in the following appendix.

Appendix 6.1.7_02 Constant Switch

In the case of today's factories and the subsequent development of new product models, a constant switch between an old and a new body shop building (i.e. one can transform and use the old body shop for the next product model and so forth) is only possible without extensive demolitions and growth if at least the following requirements are completely fulfilled:

- similar number and distribution of models (types and variants not necessarily), i.e. not only a similar factory/production capacity
- product dimensions remain largely the same (and thus dimensions of FOs/FSs), the same as product materials

- no additional product technologies/functions and/or production technologies (methods and/or processes) and thus additional FOs/FSs are implemented
- dimensional (and other) requirements (e.g. the required area size) must be similar in the case of a functional or technological (ex)change
- no production depth increase

These five points can also be relevant for other sections in the case of a product model change. The four last points in particular can impact press shops, paint shops and assembly shops if these occur differently than described (even though production depth changes (point five) are normally not relevant for paint shops, while press shops can often solve dimensional product changes by means of new or changed tools, which is not always possible). Press shops and paint shops are rather not impacted by variants/changes of variants (first point), while assembly shops can be impacted. It must be considered that the viewing distance determines the validity of such statements. Other sections (e.g. sections for the production of engines) can also be reflected against the backdrop of these points, which is not done in this document.

It is even conceivable that a product model change could happen in one and the same building if these requirements in sum were fulfilled, as production stops could be decreased to a minimum, while it would be necessary to perform these and other transformations rapidly, e.g. replacements/exchanges, technical modernisations and renewals. Nevertheless, this is unrealistic due to numerous requirements that change over time. Factories cannot survive if market requirements are not met, as competitors will meet them at least partly, which will indeed lead to UHPs (i.e. their factories become UHPs), but also to their survival. Thus, factories are forced to implement transformation requirements as good and as rapid as possible to stay competitive and to be able to survive, which leads to UHPs. A factory with a pure monopoly can be an exception, which is rather not the case with automotive OEM plants. Niche products can also lead to exceptions. Even if a constant switch between an old and a new body shop could be done, additional models, types and variants which will be produced, and synergy effects which will be taken by competitors will lead to competitive advantages for these competitors. It is evidenced in the interviews that it is critical if the ability to supply is low. There is no other chance than to go with new requirements. Thus, UHPs are unavoidable over long factory lifecycles. This emerged from the interviews. Different project cases occur over time and fully destroy the nice idea of a constant switch between an old and a new body shop.

A building with sufficiently large and otherwise appropriate areas within this building (i.e. a building with exchange areas) is not considered in this appendix. Nevertheless, it is unlikely to have such a building, and the five abovementioned points are also relevant in this regard (consider also the previous appendix).

Appendix 6.1.7_03 Production Depth Change

IP8 stated that internal logistic flows and areas change in the case of a production depth change. IP4 described that production areas turn into logistics areas or vice versa when the production depth changes. This interviewee further stated that the infrastructure all around ‘naturally’ must be adapted. If the production depth is reduced, more parts will be supplied. IP6 said that the production depth depends on demanded production output figures. This interviewee also stated that factories grow weaker when more parts are bought from suppliers. Nevertheless, as further stated by IP6, the opposite case is also possible, which means that with increased sales of a product it is more economical to produce these parts in-house. A certain quantity decides about whether an in-house production or outsourcing will be done. IP6 further stated that the optimum of fixed and variable costs changes continuously. The interview with IP6 showed that framework conditions (e.g. the market) can hardly be forecasted and that a change between in-house production and outsourcing often happens and is common practice. Other reasons such as the availability of raw materials can also lead to the requirement to outsource a production. There are different factors that play a role in this regard. IP2 stated that the production depth impacts the supply of parts, inbound and outbound logistics, running costs, and the supply of products. IP4 explained against the backdrop of an ending production (i.e. the production of a product of which production figures decrease at the end of its lifecycle) that they will rent an off-site building to outsource a storage area of approximately [redacted]0,000 m² (less than 300,000 m²). Thus, they will receive some areas for the new product (model change). Nevertheless, these areas are far not sufficient for the product model change and are also not in appropriate positions to create a combined production flow. IP4 further argued that the old body shop of [redacted] (a certain automobile model (car)) lacks areas and involves many interfering contours. The time that would be required before outsourcing can be done is too long. Therefore, the required area cannot be used as it is not available at the right time. Outsourcing is therefore not possible. IP5 stated that a very large off-site building complex was bought and transformed in order to displace an in-house production. The wish was to keep it inside which was not possible. Other contents were also outsourced. A much larger area would have been required to keep these contents in-house. This was not possible. Furthermore, other contents were insourced. IP1 stated that outsourcing is sometimes an option for factories and argued that this means for suppliers often difficulties, as they have a weaker position to solve problems. This is in line with IP2, who argued that new on-site areas were generated through the shift of extensive production and transformation requirements to suppliers – particularly variant-related production requirements that require large areas. IP6 said that a factory without areas rents off-site buildings and reduces its production depth. It performs outsourcing. This situation changes when rental and logistical costs are too high (e.g. when the throughput/output increases) and when it is more cost-effective to create a new and connected structure, as the logistics costs decrease – and this finally leads to lower total costs. IP6 also stated that rented buildings are not ideal at all for company purposes (e.g. from an efficiency-related perspective), but that these buildings can eliminate bottlenecks. IP5 argued that their strategy is not always right, but that they must do the best out of what is there. Nevertheless, rentals and relocations are not always sensible. It emerged from the interviews that areas which were won through decreased production depth/outsourcing are used for other purposes. This leads to position changes of FOs/FSs in the own factory, to

FPPs (e.g. diverse demolitions and area and substructure works), and to difficulties such as displacements. Insourcing leads either to larger displacements (and/)or to less efficient processes* if these processes are far away from their optimum position *(compared to the optimal solution). Nevertheless, insourced processes can be more efficient and sustainable than outsourced processes (e.g. due to a more effective factory configuration). This depends on several factors such as required process facilities and transportations (see the following appendix and subsection 6.1.10 for further information).

Appendix 6.1.7_04 Dilutive Effect (BFPS-3 and BFPS-4)

The grey zone/dilutive effect between BFPS-3 and BFPS-4, and circumstances in which effects of BFPSs are different and/or in which particularly negative effects of BFPSs are postponed (i.e. model exceptions), are explained in this appendix.

As long as the structuredness of a factory can be maintained and is not discarded, and as long as appropriate areas (i.e. free terrestrial areas or areas and substructures which already involve required characteristics) are available in appropriate layout positions (or in X, Y and Z within the space of a factory), efficient process flows, a good utilisation of synergies, and green factory characteristics can be largely maintained (figure 78).

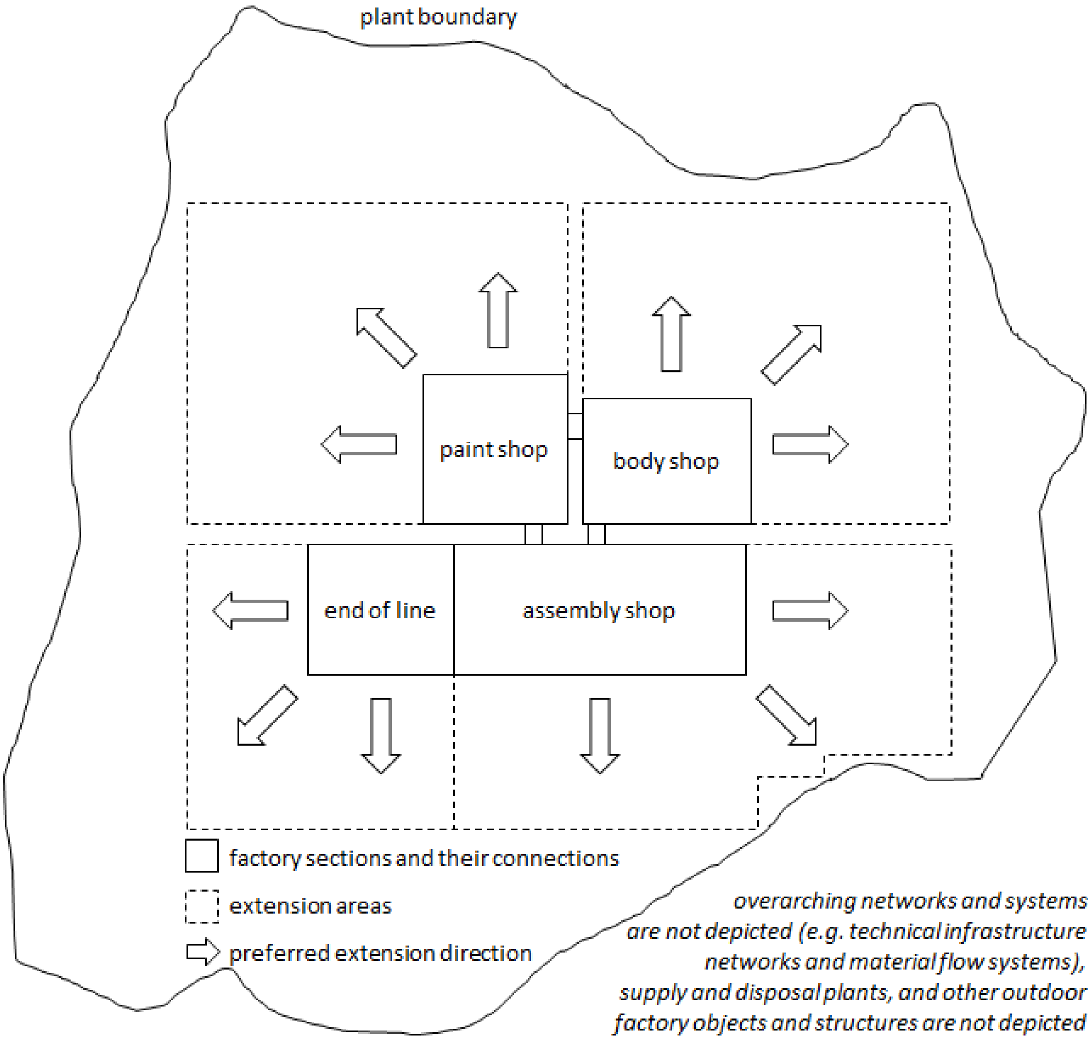


Figure 78: Structuredness of a factory

This figure shows how sections, which involve in this simplified example an optimal arrangement, would optimally develop throughout the BFPSs if only extensions would occur (changes of connections between sections are not depicted and process flows are not considered). Smaller displacements can occur, e.g. in the case of extensions of sections. *(It must be considered that this is just a simplified example of the reality. To have all sections beside one another could also be optimal. Furthermore, the number of different product models, types and variants could decide about an optimal factory layout. Moreover, an optimal factory layout changes over time. Thus, this example is used to explain generally valid patterns. It is just an example in which other FOs/FSs than the depicted sections are excluded.*

In the case of a capacity-related section extension, the optimal solution from a section-related perspective is largely equivalent to the optimal solution from an entire factory-related perspective. The original building remains at its original position and is extended to its preferred extension direction(s), while appropriate flows are generated. In the case of a product model change, the optimal solution from a section-related perspective is equivalent to the optimal solution from an entire factory-related perspective. The section remains at its original location (always on condition that the original location is the optimal location). The most appropriate position for a production depth increase (from a production flow perspective) is at the closest point to where the insourced production scope is required (of course, other flows must be considered). In the case of today's factories, it is hardly possible or impossible to maintain an effective factory structure. This is particularly the case when different cases occur over time. This is what takes place in the real world.)

The more this structuredness has been left – which means the more nested/intertwined a factory becomes – the more FOs/FSs are generally impacted in the case of a transformation, and the larger are displacements. Furthermore, the larger a factory is, the more FOs/FSs are normally involved in a transformation. The size and structuredness/unstructuredness of a factory consequently determine its complexity, while the size and structure and thus the complexity are furthermore influenced by other factors such as the number of produced product models, types and variants, and their characteristics. The higher this complexity – particularly the unstructuredness – the worse the situation and the more disastrous are impacts of transformations. Once the structuredness is being discarded, large displacements occur more frequently (this depends, of course, on the transformation requirement and how this requirement is processed, but this statement is generally valid). A development towards a UHP is consequently hardly avoidable, as transformations last too long (see section 6.2 for details about what 'too long' means in this context and to what such durations lead). The inner/core of a factory becomes in most cases earlier intertwined than its periphery. This emerged from the interviews.

The problem is that factories are much more complex than depicted in figure 78. The complexity of automotive OEM plants is rather recognisable in figure 79, which is still too simple to depict their real complexity if they involve all objects and structures that are required to produce an automobile, e.g. s&d plants.

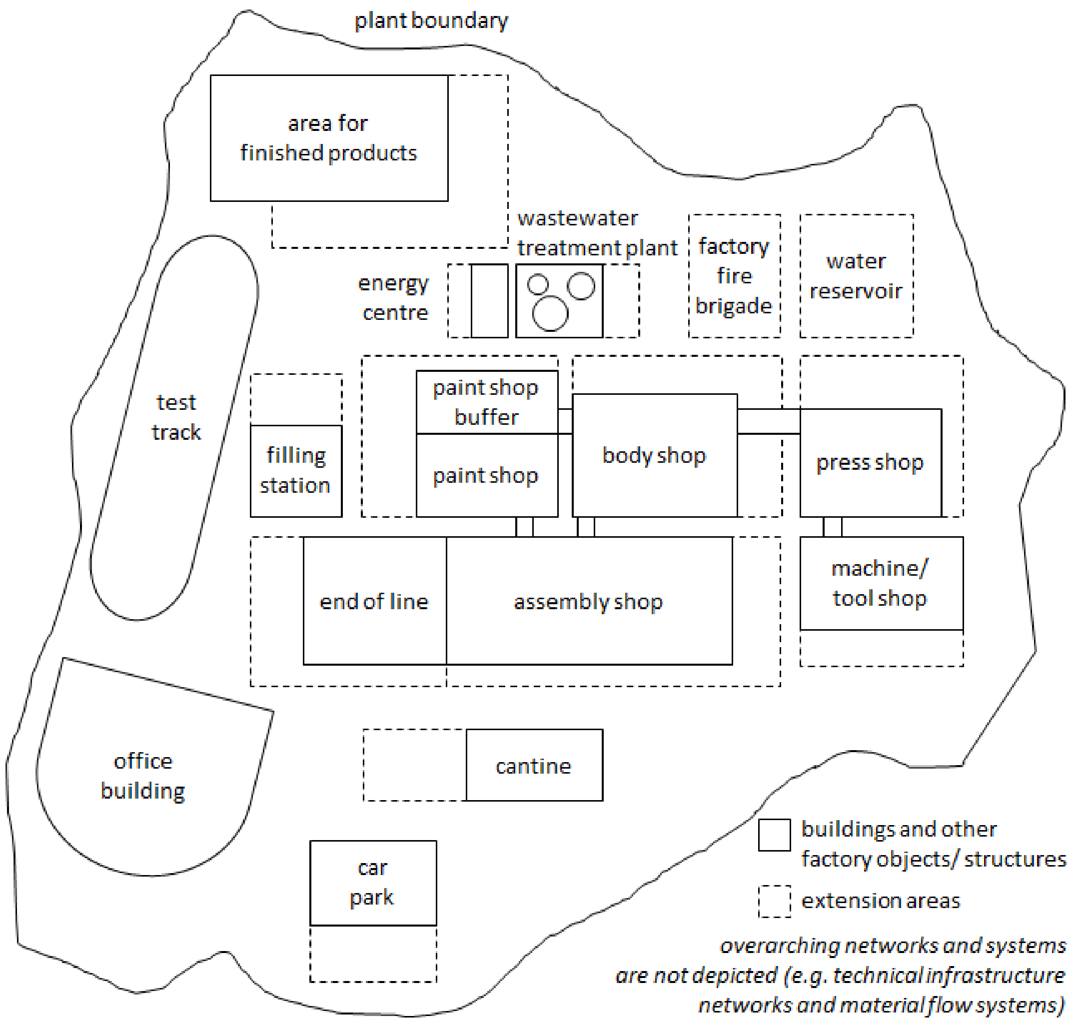


Figure 79: Possible complexity of an OEM plant

Hence, it is understandable why only (approximately) one to two factory extensions can be performed without large displacements. This emerged from the interviews. A further problem is that not only capacity-related extensions occur (while such extensions lead normally anyhow to intertwinings, at least within buildings), but also other factory project cases/eBFPCs, and mixed cases. An optimal factory starting configuration can be different than the depicted one, but this does not change the problems which are faced by current factories. It is furthermore often unclear which starting configuration is an appropriate one, particularly if changing factory/transformation requirements occur during a Greenfield, and if further changes which occur over the years and require different factory configurations are considered. This emerged from the interviews.

Thus, despite the availability of extension areas, chaotic statuses and large efforts (such as building displacements) can occur, as differently occurring transformation requirements (e.g. a considerable dimensional growth of a product model that replaces another model) can lead to completely different transformations within different factory sections etc., while their corresponding extension- and other transformation-factors involve different ratios. This means that an assembly shop might require 20% additional areas, while a body shop might require more. Furthermore, their building contents require different transformations. In addition, it emerged from the interviews that exchange areas are at least required for (entire) body shops in the case of a product model change. The same can apply to other sections, depending on the transformation requirements or in other words, required transformations. That further transformation requirements such as the need to produce additional product models, types and/or variants can occur must also be considered, the same as required transformations of indirect areas and other FOs/FSs, e.g. canteens etc. The inner/core of a factory becomes in most cases earlier intertwined than its periphery. This emerged from the interviews. Intertwinings occur even if the core of a factory is only used for sections and also if it is furthermore largely kept free for extensions and other transformations, while free areas cannot be kept free throughout a factory's lifecycle. Furthermore, energy and media etc. from the FOs/FSs at the periphery must be brought to the sections, while disposals etc. must also be considered. Such solutions lead to a lower competitiveness compared to a factory solution in which distances are kept short. Furthermore, such factories also become unstructured over time. It emerged from the interviews that today's factories develop in any case into UHPs if their lifecycles are long enough. This is inherent in the system. 'Factory structure recovery programmes' can recover the structuredness of these factories, but this is not always the case. Further information about why today's factories develop into UHPs and why this is hardly avoidable can be found in subsection 6.1.10, appendix 4.3.1, appendix 4.3.2, appendix 6.1.10_02, and appendix 6.1.10_03, while further information about UHPs is comprised in the following text and appendices of subsection 6.1.7.

The developed model of this thesis is only a model of the reality. This applies especially to the BFPSs. It is thinkable that a factory is implemented, reaches directly BFPS-4, and that this factory is structured. Nevertheless, the same factory will earlier reach an unstructured status (if it stays in BFPS-4) than the same factory which would previously be in BFPS-3, i.e. with a larger area from the beginning. Admittedly, a BFPS-4-factory can again reach BFPS-3 through the purchase of adjacent off-site extension areas (which requires time), while a factory which was once in BFPS-3 and got after BFPS-4 back to BFPS-3 will hardly be as structured as in its first BFPS-3 (see appendix 4.3.1 and the following pages of this thesis for further information in this regard).

A BFPS-3-factory is consequently inappropriate if unstructured (and/)or if free areas are in wrong positions (which can be the same but does not necessarily have to be the same). It is at least less appropriate than a structured BFPS-3-factory which involves appropriate areas. A BFPS-4-factory is, as a general rule, unstructured if it developed from BFPS-3 or, in other words, if BFPS-3 has been previously passed through. Latest after new transformation requirements a BFPS-4-factory becomes unstructured. In this context, it must be considered that, for instance, more product models, types and/or variants lead to a more complex factory. Thus, a BFPS-3-factory can be more complex than a BFPS-4-factory, e.g. a BFPS-4-factory with only one model.

SMEs normally do not have the financial background to buy large extension areas from the start. These factories reach normally directly BFPS-4, but are normally also less complex than automotive OEM plants. Furthermore, new transformation requirements can often be more easily absorbed. This emerged from the interviews. IP6, for instance, argued that a routine operation can at the soonest be reached by a regional SME, at least rather than in the case of a global company. IP2 said that areas which are purchased require between 20% and 40% of a construction sum – if doubling areas are purchased even more (it can happen that areas are provided at no charge, particularly in the case of OEM plants). It is often not possible to buy doubling areas in the case of SMEs, as it impacts on the product price which can lead to a loss of competitiveness. This generally applies to the first factory of an SME.

It also should be considered that a new OEM plant in an emerging market which is small at the beginning and involves no extension areas (e.g. due to risk reasons and a small market) would have a great chance to be structured in BFPS-4 (it would in most cases at least be more structured than a BFPS-4-factory that passed through BFPS-3), but would sooner or later develop into a UHP due to different transformation requirements which occur over time. Nevertheless, such a factory would normally develop slower into a UHP than a large BFPS-4-factory, particularly if fewer and less complex product models, types and variants are produced. In any case, it must be considered that unknown (quasi-)exceptional changes and cases can occur (see appendix 6.2.6_03 for further information about the dilutive effect between BFPS-3 and BFPS-4).

Appendix 6.1.7_05 UHPs

The common understanding in factory planning practice is that factories become so-called ‘Vereinte Hüttenwerke’ or ‘Vereinigte Hüttenwerke’, which can be translated as ‘united huts plants’ (UHPs). All eight interviewees knew this designation. IP8 claimed that this designation is used since 30 years. Reasons why factories develop into UHPs were disclosed. IP3 argued that the expression UHP exists, as only things were done in the past, which were really required, where numerous different small areas were implemented which the process (planners) really wanted (based on the real process requirements to date). As a result, as further argued by IP3, different building structures have been developed alongside each other, which led finally to the UHP. IP8 argued that factories develop into UHPs, because small transformations which were necessary at these points in time were always planned and carried out. IP8 also stated that this will not change in the future. IP4 said that huts are constructed again and again in several places of a factory. These huts are numerous provisional arrangements which were originally intended for diverse single functions or extensions and which have in different constellations a number of different common functions which have nothing to do with their original function. There are numerous small and nested functions, also indirect ones, which are fixed. The factory is dominated by interfering structures which cannot be relocated due to limited areas. You have an office building right in the middle of the factory which for any reason cannot be removed. Interfering contours, objects and/or structures are words which were often used by the interviewees. IP5 stated in the context of UHPs that production sections are linked and that buildings and flows change over time. Extensions and adaptations are made and little by little turns a factory into the status of a UHP. In other words, the factory becomes a UHP or reaches the status of a UHP. IP2 said that an unstructured development leads to UHPs. A hut is added there, something is demolished there, something is moved there, and this leads finally to a total (factory) nesting. This is in line with IP1, who argued that the designation UHP is a pejorative designation for a totally nested factory, while IP7 found that transformations lead to this status. IP4 also said that a lack of available areas leads to UHPs. This is in line with IP1, IP2, IP6 and IP8. IP6, for instance, argued that all factories sooner or later become UHPs and that area-scarcity and different factory developments lead to this development, as single sections are extended over time. IP1 stated that UHPs develop where areas are limited and where continuous transformations occur within building and process facilities. This is in line with IP2, IP4, IP6 and IP8. IP3, IP5 and IP6 made further statements which demonstrated that a lack of areas leads to UHPs. It emerged from all interviews that areas are the main reason why factories develop into UHPs. IP1 further stated in the context of UHPs that structural connections can only be sensibly changed if one makes one step and demolishes them (see the following appendix for further information in this regard, and appendix 6.2.6_06 for real-world UHPs, while further information about UHPs can be found in appendix 6.1.10_03).

Appendix 6.1.7_06 Factory Structure Recovery Programme

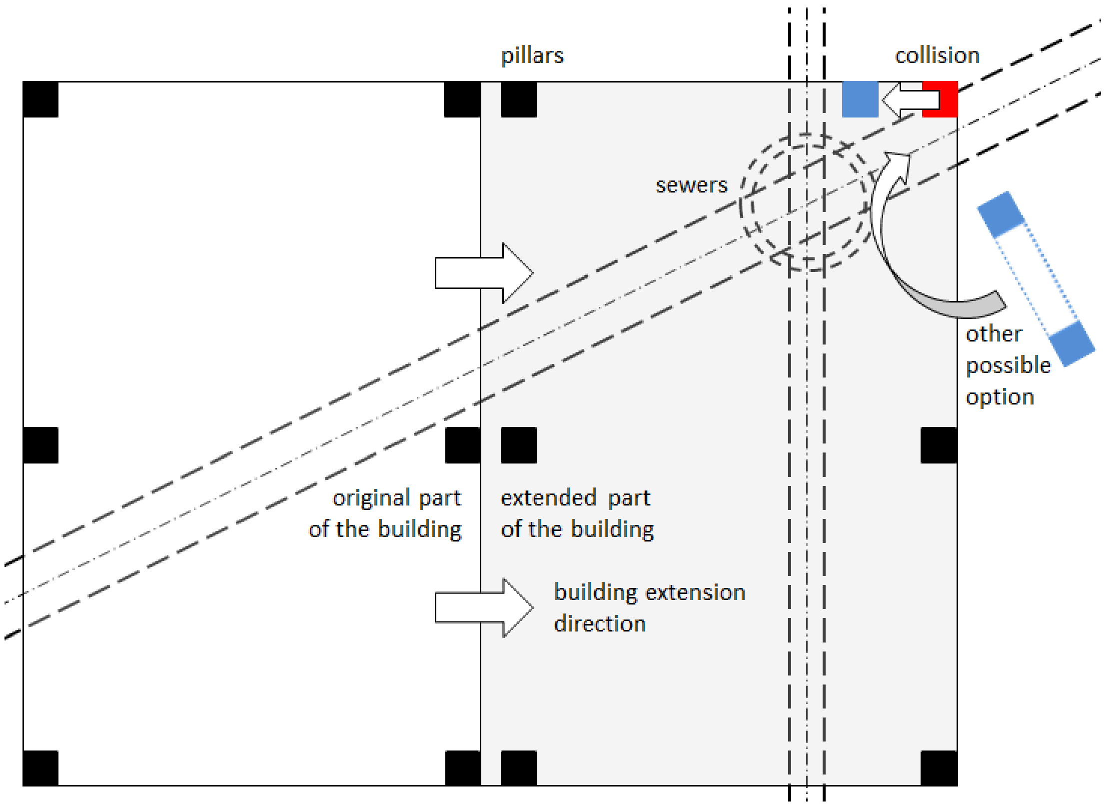
IP5 argued in the context of programmes in BFPS-3 and BFPS-4 that a proper factory structure is essential – it is the Alpha and the Omega ("...eine richtige Fabrikstruktur ist das A und das O"). IP7 stated that large projects are always required over time. IP2 argued that ten to fifteen years ago her/his former boss said that all seven to ten years the future development of all plants needs to be reflected and planned conceptually (or, in other words, roughly) for the next ten to twenty years. For these locations, a strategy needs to be developed and is partly developed. IP1 answered a question about the reasons that led to a certain factory programme as follows: The aim was to strengthen the location against the backdrop of new framework conditions. This programme is required, as meanwhile numerous issues dammed up which were not carried out in the past. It is an alignment and adaptation of the location towards new requirements. Without such a programme you would not free yourself from overlaps and changes which occur during the already started implementation or in other words, physical transformation phase. It is better to make a cut as it was done and defined with this programme (in this BFPS-4-factory). IP8 argued that one must ask herself/himself particularly in the case of grown structures: 'Where do I want to get to?' ("Wo will ich denn hin?"). IP4 stated that people in strategy departments think about factory structure recovery programmes and that these programmes can but must not necessarily be sensible. IP6 argued in the context of factory structure recovery programmes that demolitions and the development of a new entire structure are required when optimisations are not sufficient. IP6 stated that programmes can be sensible but are often neglected due to cost reasons. This validates the short-term thinking in factory planning or, in other words, short return on investment periods in factory planning. IP3 stated that factory structure recovery programmes are in any case required, but it is an economic efficiency calculation whether it is better to build a new factory. IP2 made a similar statement. IP3 said furthermore about a BFPS-4-factory that it is meanwhile a UHP with such a status that it should be completely demolished and newly constructed. In the context of exchange areas, IP3 argued about another real-world factory that it is a UHP which should be demolished and newly constructed. Transformations are too expensive. We must construct something new and demolish this UHP. IP8 stated that factory structure recovery programmes were initiated for all factories (of a specific OEM). IP8 also said that one can see what became of the plant '[redacted]' (a specific BFPS-4-factory) through the patchwork. Now we must invest [redacted].[redacted] billion ([redacted]) (one of the world's strongest currencies) – I do not want to say to bring the plant to a new production system, this cannot be done at all within a grown structure – to make it to some degree capable of surviving. For [redacted].[redacted] billion ([redacted]) (one of the world's strongest currencies) I would have implemented a plant with the latest factory technology in a green field. This would even be possible with a smaller budget. Thus, it would not be necessary to invest now twice as much. IP8 answered the question about why this programme is still or, in other words, despite this done. This interviewee stated that there are many political reasons, as a location such as '[redacted]' cannot be closed just like that. Furthermore, the areas in '[redacted]' (a country) are limited. (The following was said out loud:) Where can you find at one go an area of [redacted] km^2 – first of all, you need to find it. Based on the way IP8 made this statement it became evident that it is hardly possible to find such a location. This is in line with the other interviewees.

Appendix 6.1.10_01a Collisions and Optional Outcomes

Information about collisions, decisions and optional outcomes is provided in the following. Despite the fact that collisions should be avoided (Grundig, 2015), collisions of objects and/or structures were recurrently disclosed by all interviewees.

interview partner (IP)	IP3	To have collisions is normal. . . . Two years at least are required for the re-engineering of this press shop. New machines and new foundations will be integrated, and conveyors for the sheet cut and scrap. The problem, in this case, is that the transformation should be performed much faster, which is not possible at all due to several dominos . . . You cannot disconnect it just like that. First, the production must be ensured. I do not know yet if this can be done in our factory. . . . First, we have implemented these routes over the building. Afterwards, the routes in front of the building could be demolished and the building extended. Finally, we have implemented new routes and removed the routes on top of the building.
	IP4	Overlaps and collisions occur in Greenfields and the more the Brownfield, the stronger they become. . . . There are often collisions with structures that are already integrated there, e.g. with the conveyor technology. . . . The strongest collisions occur between conveyor technology and ventilation systems.
	IP5	Air ducts and conveyor technology lead in the most cases to collisions. *Information: IP5 has described several real-world cases in which collisions between air ducts and conveyors occurred. These were partly very complex and led to different domino effects. The following pages of this subsection provide information about such cases.*
	IP7	Requirements change and domino effects occur again. . . . a new (product) model project led to production shifts to suppliers. This will lead to displacements . . . It comes often to collisions.
	Please consider that collisions lead (roughly said) either to intertwinings/intertwined structures or to displacements. These issues are explained next.	

Furthermore, foundations and canals in the ground can collide, which leads often to stopgap solutions (figure 80; this figure depicts a simplified real-world case).



overarching networks and systems are not completely depicted
(e.g. the transportation infrastructure and material flow systems),
building contents are not depicted

Figure 80: Stopgap solutions after collisions

To achieve a perfect solution in this real-world case is hardly possible, as the building and sewers can hardly be repositioned. This example illustrates that collisions generally lead either (a) to displacements (and consequently to dismantlements/disassemblies and assemblies (if possible) and/or demolitions and new constructions (if required and/or obviously more sensible than intertwinings)) or (b) to intertwinings (if possible). (It is also possible that both a displacement(s) and an intertwined structure(s) are the outcomes of a transformation requirement. More complex/wide-ranging projects lead to such circumstances.)

It emerged from the interviews that areas and substructures are often impacted in the case of transformations, but people can impede or promote such works, depending on the framework conditions (e.g. project scope, inhibitors, and budget), and their influence on decisions, their interest and their attitude, i.e. if they want a solution which requires less works, which means that they follow a 'line of least resistance'. In the case of today's factories, structured and efficient solutions generally require transformations which last longer, while more rapid transformations lead rather to intertwined FOs/FSs and less efficient processes. It is seldom the case that the most rapid transformation leads to an optimal solution/flows. *(New constructions and extensions of buildings in which flows of old buildings/original parts of buildings do not change and in which appropriate areas are in appropriate positions can be effected relatively quickly and involve good flows. Such cases are the exception and are excluded in this evaluation. Nevertheless, in these cases transformations are also mainly performed as simply, as effortlessly and as quickly as possible (see the following pages for further aspects which must be considered in this regard). Cases which also lead to flow changes require increased durations. Extensions in which flows change within original parts of buildings also require rather more areas for optimal flows compared to the most rapid transformations, which lead rather to more intertwinings (this is not necessarily always the case). BFPSs must be considered in this regard.)* Thus, from an extreme point of view, transformations are either performed with the aim ('option a') to achieve (again) an effective structure and preferably efficient processes or ('option b') to retain given FOs/FSs as they are and perform transformations around them (if possible) (figure 81). To keep it simple and to focus on the most important transformability-aspects, next, only an optimal solution/flows and the shortest transformation time are considered, even though other factors can impact on decisions, which can have negative consequences for an actual transformation requirement(s) (appendix 6.1.10_01b).

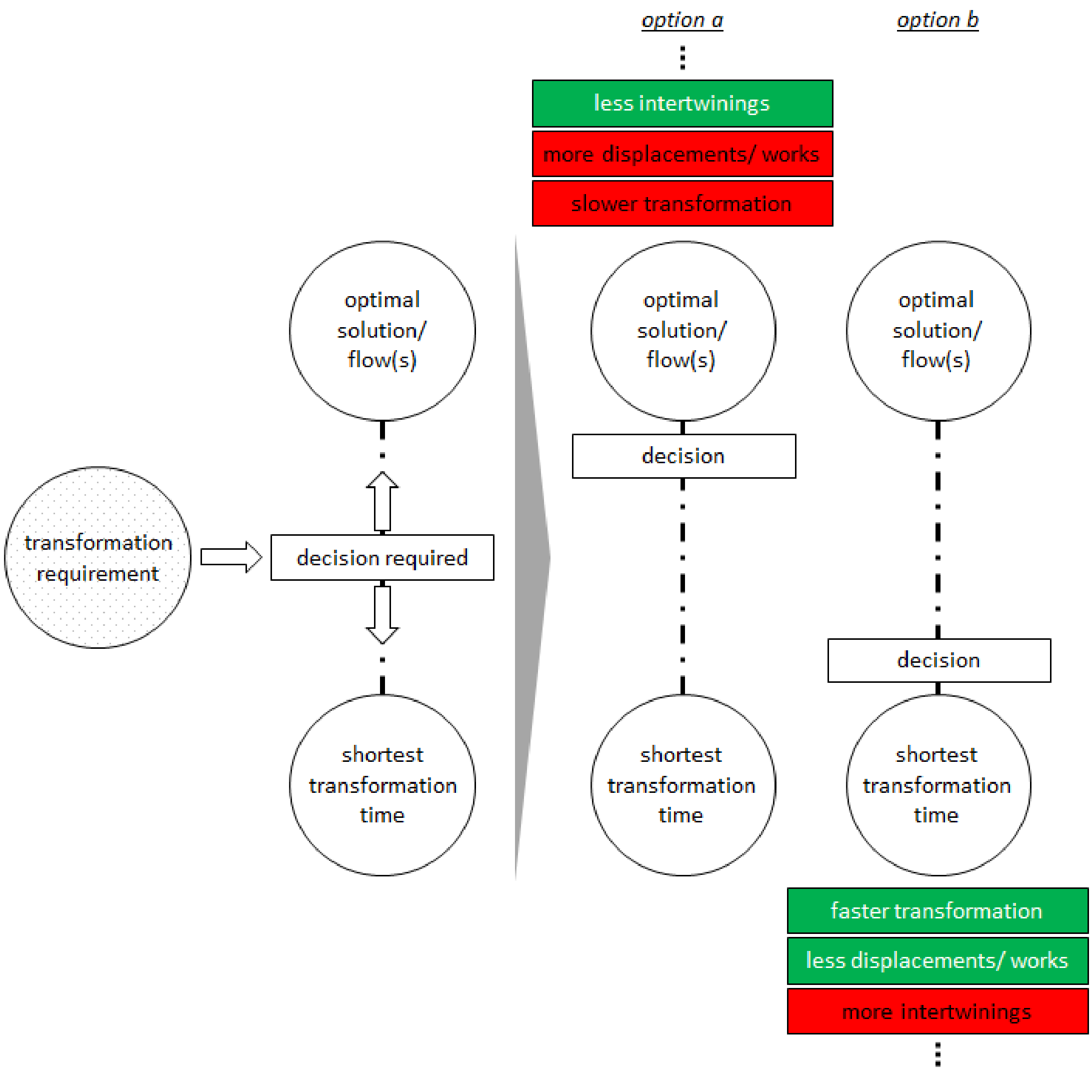


Figure 81: Optional outcome

It emerged from the interviews that the reality in today's factories lies in between these extremes, but that transformations are rather determined by an attitude of the line of least resistance (i.e. the simplest/most effortless) and tough timelines. Thus, transformations are performed as simply, as effortlessly and as quickly as possible, but this depends on the specific case, on the decision(s), and on the processed tasks. Fast transformations are prioritised in order to enable an earlier re-SOP; the objective is to avoid halts in production. Thus, one is tempted to implement transformation requirements around given FOs/FSs ('option b') in order to avoid immediate and (in most cases) greater effort, and longer durations. This is especially the case if it is not known whether greater effort etc. will ever lead to advantages, e.g. to disassemble air ducts to later enable a more structured solution, in comparison constructing pipes around air ducts. The likelihood that transformations will be performed in this way is very high if there are no other clear decisions, as at this point displacements cause dismantlements/disassemblies and/or demolitions. Thus, in practice, displacements and other difficulties are rather avoided as long as possible, which leads earlier to intertwinings. Thus, buildings become intertwined as far as possible, which means that free areas outside buildings are kept free for as long as possible. First, when there is no other option or when transformation requirements can supposedly be accomplished more simply and/or rapidly, buildings are extended and/or new buildings constructed in free areas if appropriate areas are available, instead of transforming given buildings (consider the contents of subsection 6.1.7).

This means that over time 'option b' leads to intertwinings within buildings (i.e. displacements within buildings can be initially avoided, while this leads later to more difficult displacements) and to intertwinings from an entire factory-related perspective (through extended and/or new buildings, which become large inhibitors over time), even if the latter can be postponed (outdoor FOs/FSs must also be considered). Finally, when there is no other option, building displacements occur. Factory structure recovery programmes are also rather avoided for as long as possible, while intertwinings also occur in new buildings (appendix 6.1.10_02). It emerged from the interviews that in any case, today's factories sooner or later become UHPs if their lifecycles are long enough, independently of which optional approach transformations are performed (appendix 6.1.10_03). This is particularly the case if real transformation requirements are implemented in a factory, and if not only those tasks are performed which can be possibly simply accomplished against the backdrop of a current factory configuration and status (consider also subsection 6.1.7, particularly what was said about the need to meet transformation requirements, about UHPs, and about the fact that it is hardly possible to define what is reasonable to be achieved, especially from a long-term perspective).

The possibility to perform fast transformations with today's factories decreases throughout the BFPSs. Project durations increase as 'more numerous' and 'larger' inhibitors, displacements and demolitions occur, while flows become worse and the factory becomes less efficient. If one stays with a design freeze, flows do not necessarily get worse. Nevertheless, this can lead to a loss of competitiveness if requirements are not met.

Appendix 6.1.10_01b Decision Influencing Factors and Aspects

It emerged from the interviews that an organisational change can have extreme impacts on physical FOs/FSs. Centralisations and decentralisations often impact on FOs/FSs – the higher the reached BFPS the larger are the impacts of one and the same requirement. IP5 described that it can lead to organisational and consequently to building changes when a product changes. IP4 argued that it changes which department or division dominates other departments and divisions, i.e. the power to push decisions through. Sometimes finance has the upper hand and sometimes quality. This changes constantly and leads to factory transformations. IP[redacted] stated that [redacted] (a specific object which is not at all required for the operation of a factory and has nothing to do with sections or departments) was implemented in the centre of a factory and that this was very disadvantageous for production and other flows. IP[redacted] also said that departments are preserved where they should be demolished. Many other interviewee statements led in the same direction. Figure 82 shows which influencing factors and aspects can impact on a factory.

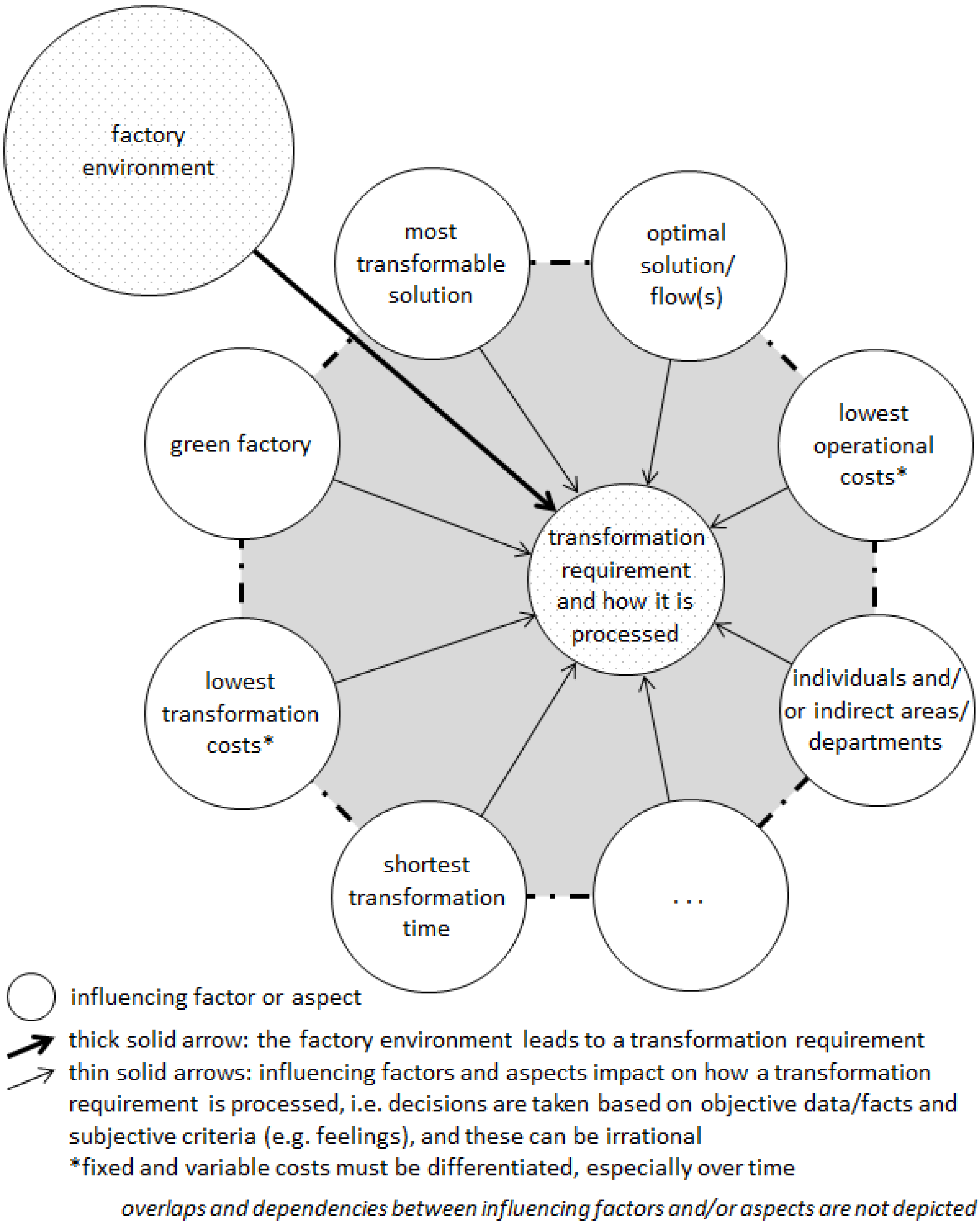


Figure 82: Optional outcome (advanced)

It is possible that through influencing factors and/or aspects a transformation requirement is processed in a way that the real requirement cannot be met partly or completely (not depicted). It is also possible that one or more influencing factors and/or aspects lead to processes which disturb or even disable an appropriate processing of a transformation requirement (not depicted). Further relevant information in this regard can be found in appendix 6.2.6_07.

Appendix 6.1.10_02 Line of Least Resistance

IP2 argued that a building that must be relocated is a problem. This interviewee said furthermore about an object in a factory: 'This is a fixed point and transformations are performed around it'. Moreover, IP2 talked about a pain that is strong enough to perform a transformation. This means that the transformation would not be performed if this pain would not be strong enough. IP2 provided details about a case in which transformations were performed over 30 years around an object which will be done until a point when one says: 'It is no longer possible, we must remove it'. IP2 further stated that it is simpler to install something in a free area than to displace something – the simplest is done. There are areas which are not impacted, not transformed; such points are also there where the most connections are. When a transformation occurs, it goes in a direction which has all degrees of freedom and not in a direction where a building is. The most rapid transformation is done. Similar statements were made by other interviewees. IP7, for instance, talked about a new construction of a building, described in this context a connecting bridge between two buildings, and argued that transformations are performed around this bridge. IP7 stated that this is the simplest solution. IP5 revealed a case in which an exchange area was used instead of performing a BFPC-B, as it was simpler and more rapid. Several similar cases were presented by the interviewees. IP5 further argued that she/he would in most cases build new instead of transforming within given structures. IP5 further stated that exchange areas are very important. It is not good when a transformation is required and one has no areas left. A new construction is in most cases cheaper than a transformation if one has too many interfering contours. IP5 mentioned in this context UHPs. IP3 said in the context of exchange areas: The factory is now a UHP; now, transformations are too expensive; now I must construct something new and demolish this part of the UHP before new constructions can take place. IP3 also argued that every couple of years a large re-engineering factory programme (i.e. a factory structure recovery programme) is in any case required, but that it is an economic efficiency calculation whether it is better to build a new factory before one performs gigantic measures. This is validated by IP2, IP5, IP6 and IP8, who made similar statements. IP4 stated that structures should be demolished but are used further because of the timeline. This interviewee said that the second-best solution is followed. Further interviewee statements go in the same direction.

The discussed line of least resistance attitude, the requirement to perform transformations as rapid as possible, and compromises (appendix 6.1.1_07) validate these statements. These statements are also underpinned by the following data: IP3, for instance, argued that the older a factory building, the higher the roof and floor loads, as more contents are integrated. This interviewee further stated that UHP structures occur within buildings. IP1 argued that transformability is limited where areas are limited and where through permanent transformations within buildings and facilities the development went towards UHPs so that one is only able to perform future transformations through exorbitant costs. IP5 said that it comes definitely to a UHP when all areas are occupied. This interviewee further stated that this is the same development as in the case of [redacted] (a real-world UHP). Details of other factories and factory developments emerged from the interviews and underpin the information in this appendix. Many real-world UHPs were discussed (see appendix 6.2.6_06).

Appendix 6.1.10_03 UHPs in Any Case

It is hardly possible to make generally valid statements and recommendations about how a today's factory should be developed, as it always depends on the specific case and circumstances. Nevertheless, the following can be said ((quasi-)exceptional cases are initially not taken into account, and s&d plants and other outdoor FOs/FSs are not considered in order to keep it as simple as possible):

(1) To keep areas free as long as possible so that BFPS-4 is avoided as long as possible generally makes sense, as one does not know what will be required, where, and when. Free areas enable one to perform transformations in a simpler way than would be possible if these areas were occupied/covered/heavily built-up, but required. The existence of free areas ensures that high degrees of freedom are retained. This means that it is better to implement vast transformation requirements at free areas than to perform a building

transformation (if possible) or to demolish a building and to construct a new one instead.

(2) To maintain the structuredness of a factory as long as possible – which means to keep areas and buildings with their building contents structured – also makes generally sense, as future transformations can be performed simpler. Transformation requirements which cannot be done within given buildings, require in any case additional areas or must be done by other factories, which also require areas (keywords: pre-produced parts, substitution processes, and outsourcing).

(1) and (2) exclude one another at least partly. The following aspects must be considered: If transformation requirements are implemented as fast as possible within a given building (i.e. with a line of least resistance attitude), this normally leads to a more rapid first transformation(s) and earlier to more inhibitors and intertwinings within this building. Thus, this leads to higher building complexity (and in the case of later transformations within this building therefore to more works/efforts, displacements, other difficulty factors, and longer durations) compared to the approach described in the following paragraph, but there is a chance to keep areas outside this building longer free which means that there are for a longer period of time fewer large inhibitors, i.e. the point in time when an additional building(s) is required can be postponed. Nevertheless, there is the risk that a (e.g. extensive) transformation requirement occurs which cannot be depicted anymore within the given and then strongly intertwined building(s). If this risk occurs, it leads to the case that further areas and/or buildings are required. Thus, areas become occupied (BFPS-4) (in any case, extension areas are sooner or later occupied), while the old buildings are largely intertwined, which can increase the difficulty of future transformations, e.g. when these buildings are used as exchange objects/areas. Thus, transformations within given buildings in BFPS-3 and later in BFPS-4 are more difficult compared to the case that the structuredness in these buildings would have been maintained, but areas can thus be kept free for a longer period of time (see also the following text in subsection 6.1.10 and section 6.2, e.g.

about vicious cycles). It emerged from the interviews that this is normally intuitively done today by Europeans (see appendix 6.1.10_02 and below).

If one retains the structuredness of buildings within the first transformation(s) (even if larger efforts are required for that), later transformations can be simplified in these buildings compared to the case that they are strongly intertwined. Nevertheless, this approach involves the risk that free areas are earlier occupied (BFPS-4) through larger inhibitors (e.g. extended and new buildings), while these larger inhibitors can be more easily transformed compared to the case that these are completely intertwined. In the case of extensive transformation requirements, this approach can lead to more disadvantages than the one in the previous paragraph. It always depends on numerous circumstances.

Thus, it depends on the specific case and circumstances with which approach off-site areas and/or cases are earlier required. It is hardly possible to make generally valid recommendations about which approach is better for today's factories, as this also depends on the specific case and circumstances. There is nothing better to say, particularly if today's factories are concerned. What is more sensible cannot be known upfront, as the future is unknown. This means that it is unknown which future developments of the factory environment and therefore, which future factory configurations are the most appropriate ones. Nevertheless, it is sure that today's factories sooner or later develop into UHPs if their lifecycles are long enough, independently of which of these two general approaches is taken (see subsection 6.2.6 and particularly appendix 6.2.6_06).

Extensive transformation requirements already occur with everyday cases. Project durations can thus lead to a vicious cycle (see subsection 6.2.6). In BFPS-3, areas can be used, but in BFPS-4 problems occur in any case. The abovementioned risks must be considered in this regard. Thus, it cannot be generally said that it should be tried to avoid BFPS-4 as long as possible, e.g. to avoid BFPS-4 because project durations generally increase. It depends on the specific case and circumstances. Nevertheless, if BFPS-4 has been reached, permanent exchange areas (e.g. in buildings) and/or objects (e.g. buildings) should be available. This is difficult, as their positions and characteristics are decisive, and these change, as do transformation requirements.

Furthermore, (quasi-)exceptional cases occur in any case over time (e.g. booms and/or vast technological changes), and these make the statement that today’s factories become UHPs indisputable, independently of which BFPS has been reached.

Thus, today’s factories are in any case not suitable to meet today’s transformation requirements, which is not always recognisable, as all companies use the same factory concepts (today’s factories) and face the same general problems. This means that competitors also use today’s factories. Furthermore, one cannot see the complete outreach of the limited transformability of today’s factories. This is because normally it is not possible for 100% of the occurring transformation requirements to be implemented (what is meant here are those 100% which would be reasonable to be implemented if each relevant transformation requirement could be implemented), and particularly not fully. If these 100% would always be implemented, today’s factories would develop even sooner into UHPs. Today, what is rather implemented is what is reasonable to be implemented against the backdrop of the given factory configuration and transformability. This means that a factory is defined against the backdrop of anticipated and most recent requirements, and these requirements are implemented as well as possible, or at least attempts are made to implement these requirements as well as possible against the backdrop of the given factory configuration and transformability. This applies to Greenfield and Brownfield projects and ends often in compromise solutions, while it can occur that real transformation requirements cannot be implemented at all. The line of least resistance must also be taken into account. Furthermore, transformation requirements are often shifted to other (horizontally and/or vertically integrated) factories which must also be considered in this context. Moreover, it must be considered that this shifting leads to UHPs and UHP structures in these factories, while the own factory is also impacted through diverse requirements which come up through these shiftings (see, for instance, appendix 6.1.7_03).

Vicious cycles and the possible circumstance that not even the ‘as is’-factory status can be defined, reinforce, besides other aspects in subsection 6.2.6, the statement that today’s factories develop into UHPs if their lifecycles are long enough. Such aspects can lead to the case that free areas (e.g. extension and exchange areas) are earlier used and/or required, e.g. when the complexity within intertwined buildings cannot be handled anymore, which can also be the case if these aspects do not occur. These aspects are substantiated throughout the main body of text.

Appendix 6.1.10_04 Domino Effects

An initial transformation requirement can trigger further transformation requirements and different domino effects at different factory structure levels. Capacity-related (not only caused by the eBFPC capacity increase), particularly capacity increase-related domino effects occur. In the case of a capacity increase, initial, direct/primary or mainly obvious transformation requirements occur, which means that more employees, machines, areas, roads, walkways, s&d infrastructure elements etc. can be required. This does not necessarily have to be perceived as a domino effect, as the border between obvious and non-obvious impacts of a transformation requirement is often indefinable. This depends on the specific definition, and on how and when impacts of a transformation requirement can be perceived. This is relevant for direct/primary impacts and for indirect impacts (i.e. secondary, tertiary etc. impacts). It is recognisable in Schenk, Wirth and Müller (2010, p. 361) that such circumstances are manageable to a certain extent.

A factory’s transformation requirement can in sum lead to numerous different transformation requirements which impact on numerous different FOs/FSs, e.g. a displacement can lead to a domino effect. These requirements are not obvious if nature-related, physical/chemical and/or human-related processes dominate transformations (particularly not in late BFPSs).

Domino effects can lead to displacements (if sufficient areas/spaces are not available in appropriate positions) and other difficulty factors which can require substitution processes etc. It emerged from the interviews that the impacts of factory projects were often not completely known by the interviewees (neither explicitly nor implicitly). Many in-depth questions about these impacts could not be answered. Why this was the case is recognisable more fully when the information in sections 6.1 and 6.2 is absorbed. FOs/FSs impact on other FOs/FSs and partly on one another. That this can occur over a whole plant is superficially depicted in figure 83.

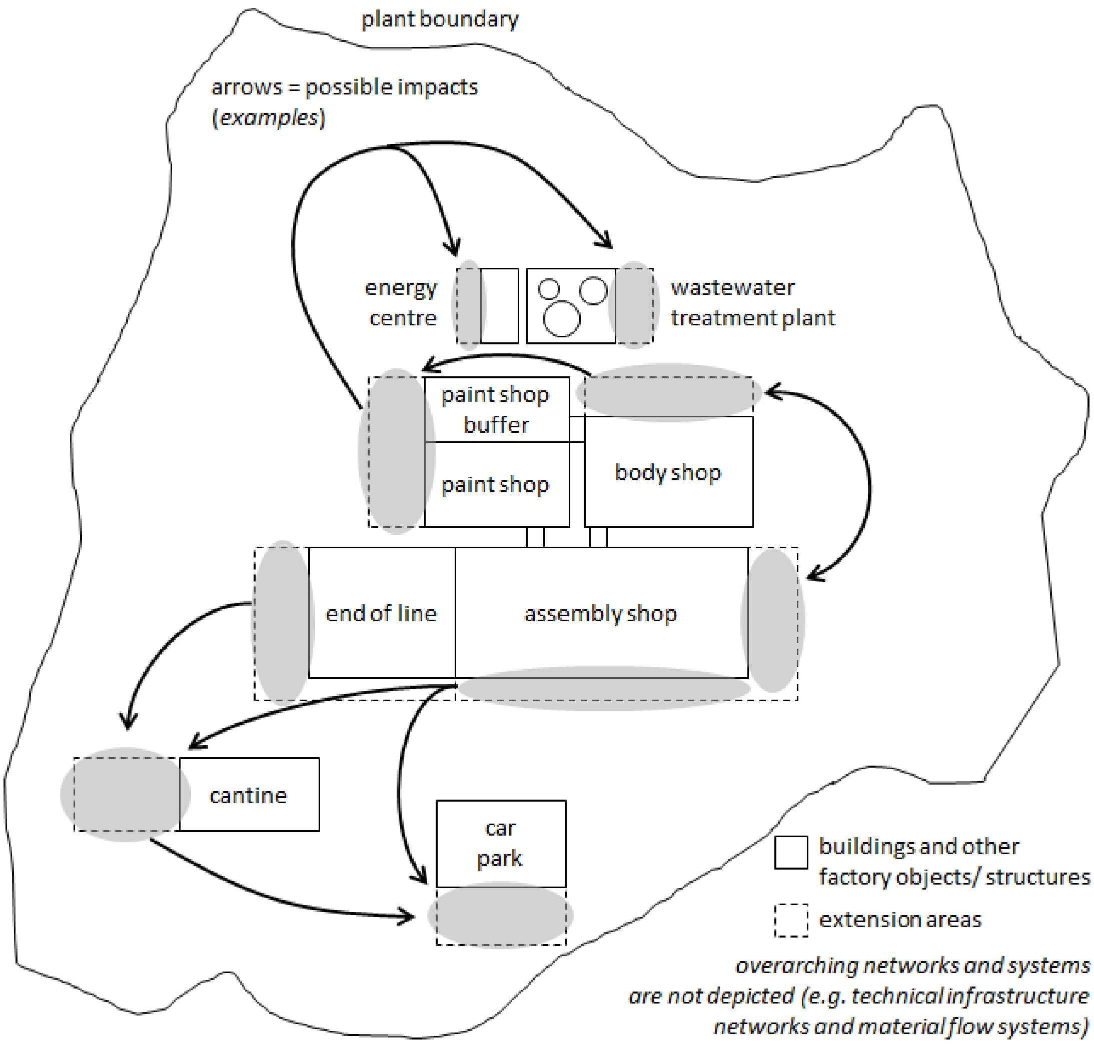


Figure 83: Capacity-related domino effects

Heterogeneous transformations and growth of mainly heterogeneous FOs/FSs can also lead to displacements etc. and domino effects (e.g. chainings), and further increase the difficulty in factory planning (consider appendix 6.1.5_03). These aspects are relevant for most difficulty factors. Displacements, substitution processes, the pre-production and storage of parts, other factors, and related domino effects can be similarly mapped. If these maps are overlapped, the complexity in factory planning is partly perceivable.

Appendix 6.1.10_05 Chaining Examples

The following 'chainings', besides others, are possible:

chaining type 1	a transformation requirement can lead to displacements if no appropriate areas are available at appropriate positions
chaining type 2	a displacement can cause another displacement(s) and/or lead to a substitution process(es)
chaining type 3	a substitution process can lead to a capacity-related domino effect and/or to a displacement (which, in turn, can lead to further substitution processes, displacements and so forth)
chaining type 4	capacity-related domino effects can lead to displacements and to substitution processes (the same as heterogeneous transformations and growth)
. . .	. . .
chaining type n	. . .

Table 27: Chaining types

Possible chainings are depicted in figure 84.

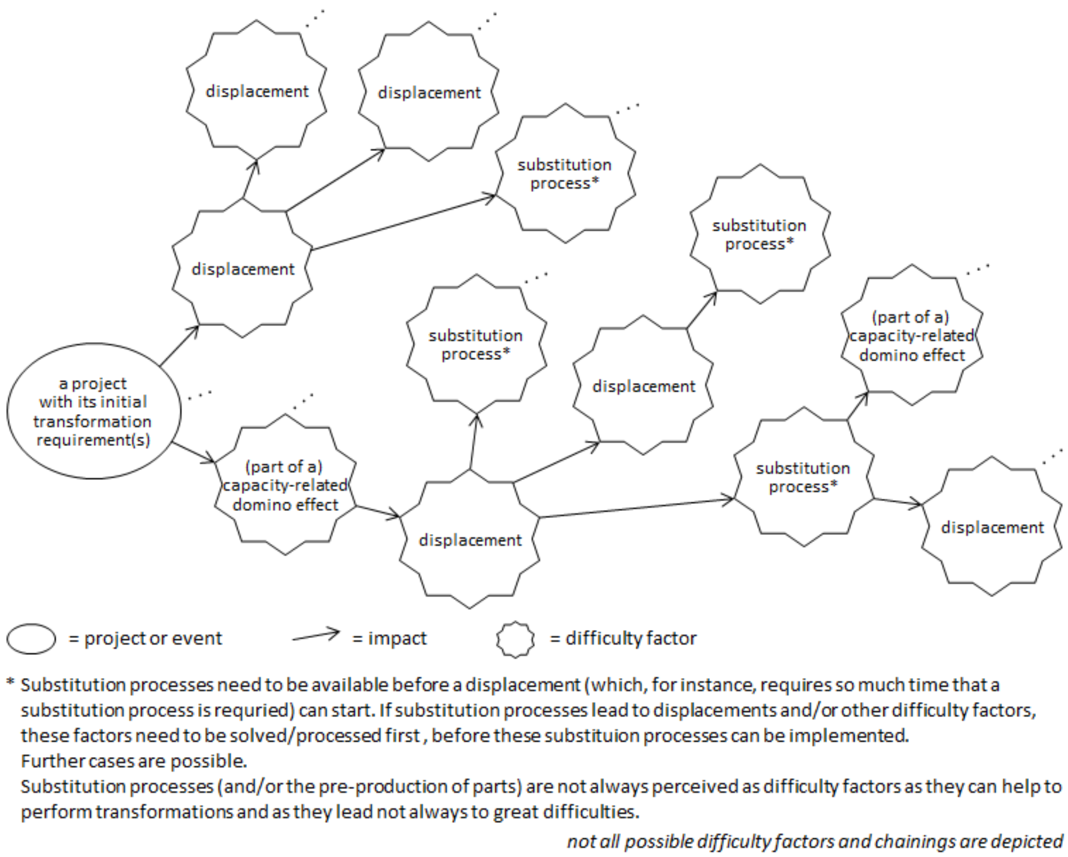


Figure 84: Chainings

Depending on the circumstances (e.g. the achieved BFPS) and depending on which FOs/FSs are impacted, different impacts are the outcome. Relatively simple examples (compared to real-world cases) describe possible chainings in tables 28 and 29. No other than direct/primary and secondary impacts were differentiated. Tertiary and further indirect impacts are possible.

example 1: replacement/exchange of a machine (the new machine has a larger footprint and requires a larger foundation)	
process step 1	interrupt/cut-off the supply
process step 2	disconnect and disassemble the old machine (scrap it or move it to a new location (which can lead to area works, displacements etc. at the new location))
process step 3	perform approval processes which can be required
process step 4	change impacted areas and substructures (e.g. foundation(s); displacements are possible through the use of heavy (construction) machinery/equipment and larger foundations)
process step 5	change impacted s&d infrastructures and roof structures if required (displacements are possible)
process step 6	install the new machine and connect it to the s&d infrastructure (capacity domino effect that can lead to further impacts)
process step 7	prepare larger logistics areas which can be required (and can lead to further displacements)
. . .	. . .
possible chainings (i.e. difficulty factors in sum): capacity-related and displacement domino effects can directly happen, substitution processes are possible, further capacity-related and displacement domino effects can appear indirectly/mediately, the same as further substitution processes (other and further impacts are thinkable)	

Table 28: Chaining example 1 of 2

example 2: implementation of an additional machine	
process step 1	perform approval processes which can be required
process step 2	prepare required area(s) and substructures
process step 3	install required s&d infrastructures and change roof structures if required
process step 4	install the additional machine and connect it to the s&d infrastructure
process step 5	prepare logistics areas which can be (and are normally) required (and can lead to further displacements)
. . .	. . .
possible chainings: capacity-related and displacement domino effects can directly happen, substitution processes are possible for given infrastructures (of other machines etc.) and can furthermore occur indirectly/mediately (e.g. if, for instance, another process facility needs to be relocated first to free required areas and spaces which can lead to further displacement domino effects and substitution processes) (other and further impacts are thinkable)	

Table 29: Chaining example 2 of 2

Appendix 6.1.10_06 Project Changes and Multiple Projects

The following occurrences can be reviewed based on figure 85. Hence, one can understand more fully why displacements, chainings etc. occur.

(a)	The changing factory environment can evoke project changes in one and the same project.
(b) (depicted with (b1) and (b2))	Furthermore, new factory projects/eBFPCs emerge over time and have impacts on incompleted/unfinalised projects (e.g. on already implemented objects and/or structures of incompleted/unfinalised projects).
(b1)	Spatial project overlaps can lead to changing transformation requirements of incompleted/unfinalised projects, which normally leads to a direct/immediate impact(s). An indirect/mediate impact(s) can also occur (not depicted).
(b2)	Furthermore, direct and/or indirect impacts can occur, even if there is no spatial project overlap.
not depicted	Moreover, it is possible that not only one but two or more projects impact on an (third) FO/FS (e.g. an s&d plant), e.g. through capacity-related domino effects which are not the only possible initiators of such a happening.

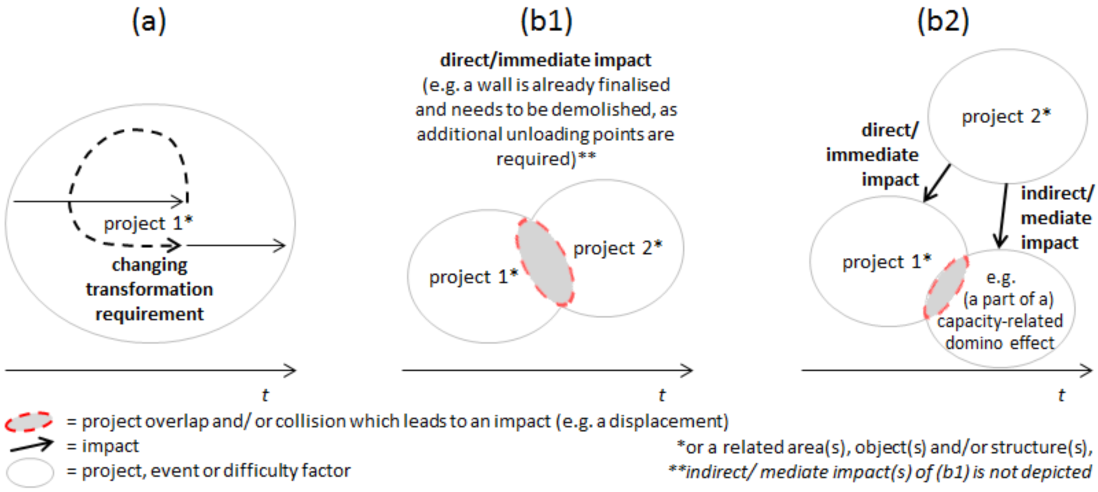


Figure 85: Possible impacts of project changes and simultaneous projects

A direct project overlap (b1), for instance, can lead to collisions, displacements, and chainings. Figure 86 depicts how this can appear in combination.

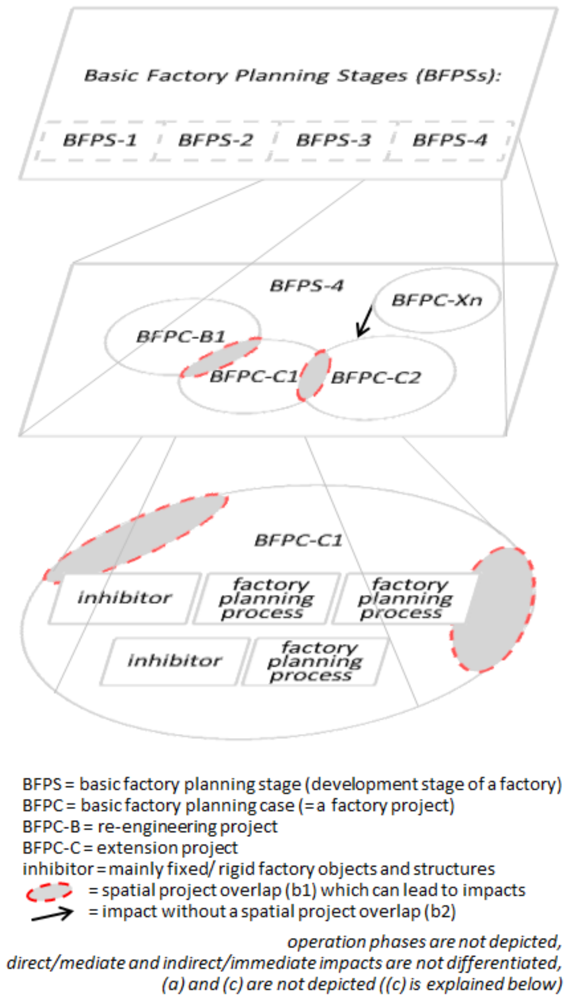


Figure 86: Possible impacts of projects in BFPS-4

Durations also depend on difficulty factors (e.g. chainings), but depend essentially on inhibitors and possible FPPs, which in turn depend on the specific factory concept. Generally, more inhibitors are involved in BFPS-4 than in BFPS-3 (the dilutive effect between BFPS-3 and BFPS-4 must be considered). Furthermore, the risk for (a), (b1) and (b2) is higher the longer the project durations. (a), (b1) and (b2) occur if the implementation or transformation velocity is too low and project durations are increased as a result.

As shown in figure 87, different transformation requirements emerge over time in any case, independently of project changes and impacts of simultaneous projects. This can have a direct and/or indirect impact on FOs/FSs that are the outcome of completed projects. *Future inhibitors are completed after project completion. The more inhibitors have been implemented or completed, the more they inhibit later transformations. This means that in an incompleted project, changes can normally be better implemented than after a completed one – at least from a purely physical perspective. In both cases, physical inhibitors represent efforts in terms of time as well as cost, work effort and other resources (e.g. materials) which are demolished or otherwise stripped off and removed.* Each new project impacts on what has previously taken place and/or what is given. Figure 87 depicts this from a project-related perspective (possible impacts on untouched areas etc. and not depicted).

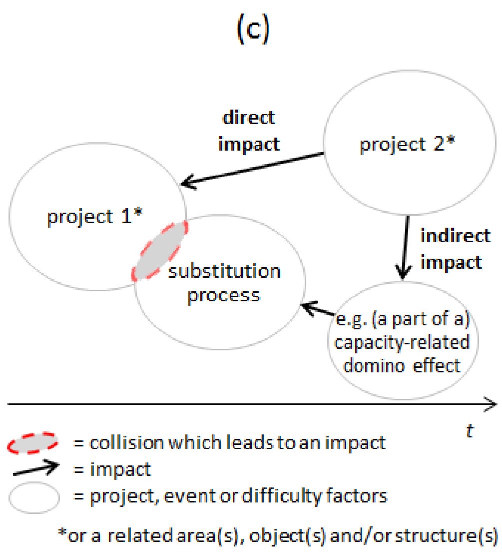


Figure 87: Possible impacts of new projects on completed projects

Figure 88 provides a building-related perspective of the described circumstances. In the case of one and the same building, (c) is the case when an operation phase is in between a Greenfield and a Brownfield or in between two Brownfields ((c) can also have other impacts). Figure 88 also depicts what single difficulty factors, chainings, project changes and simultaneous projects can lead to, at least to some extent.

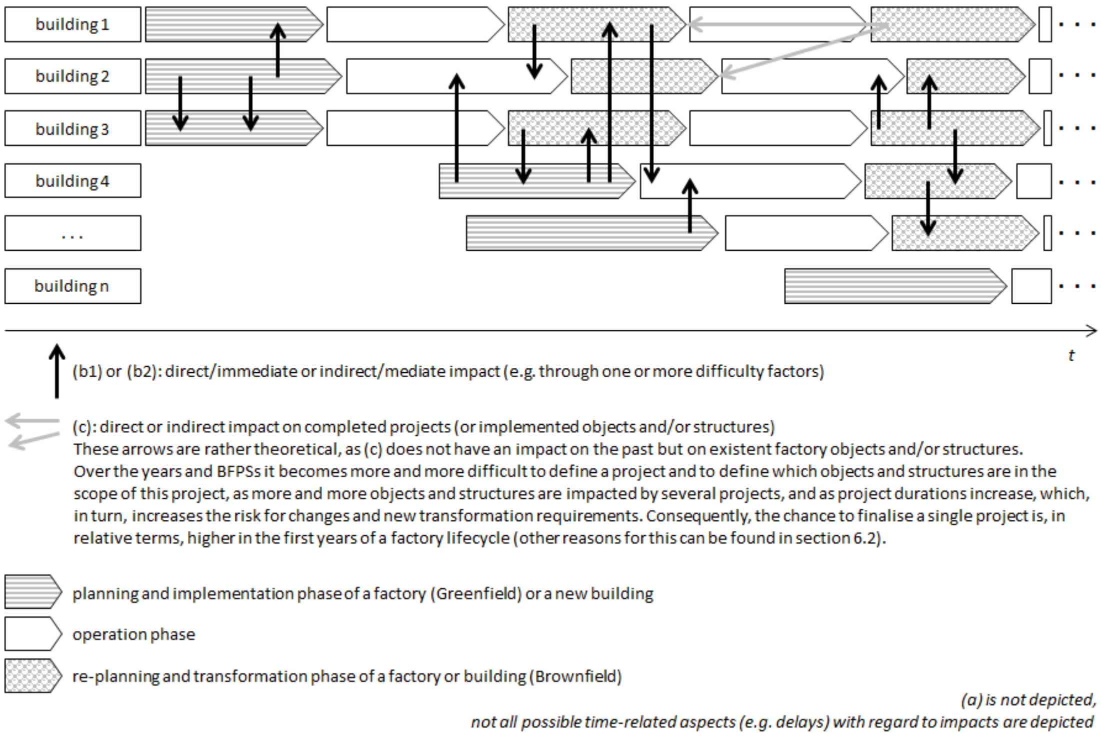


Figure 88: Possible project impacts from a building-related perspective

Figure 89 provides a layout-related perspective about these circumstances.

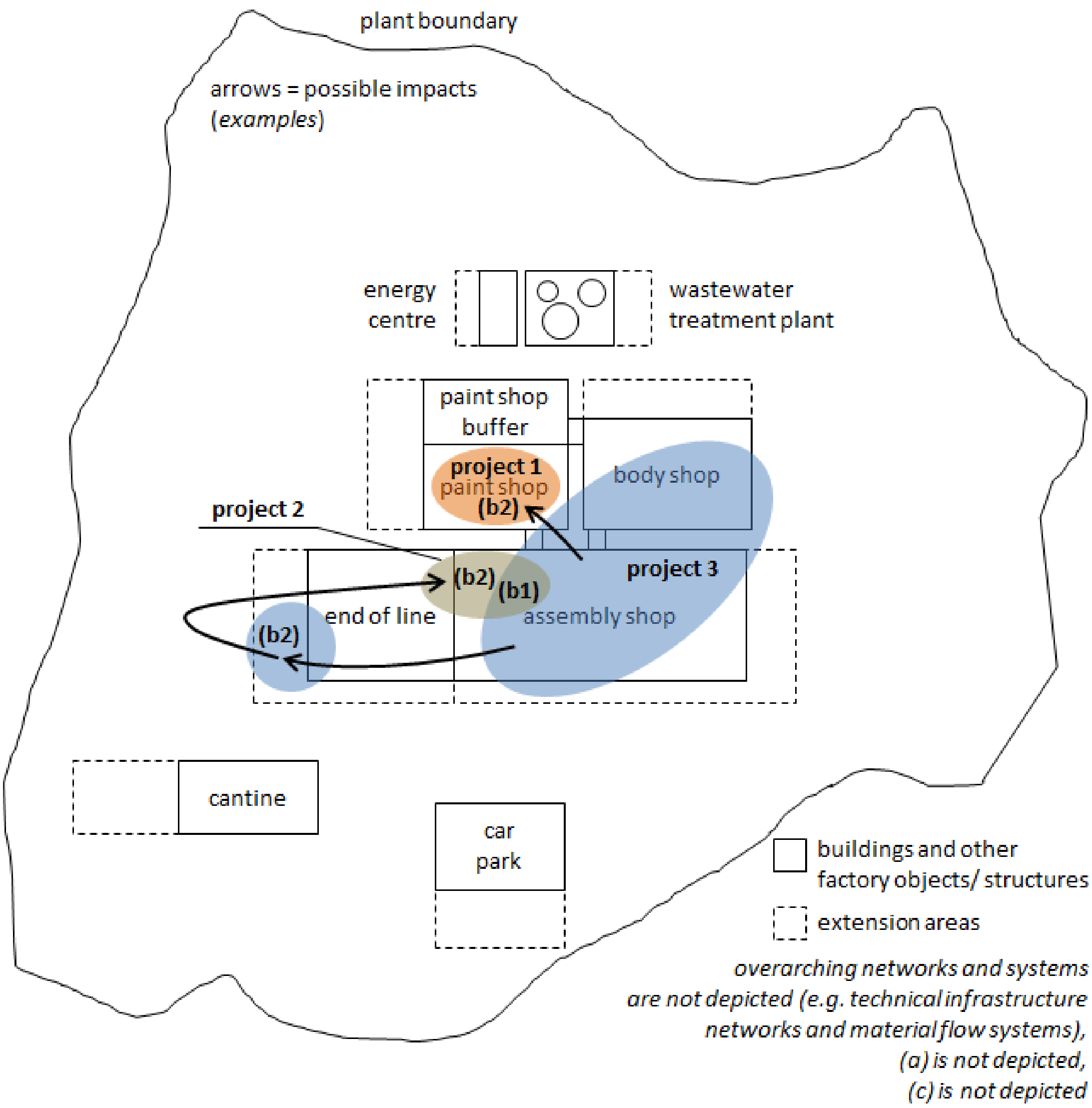


Figure 89: Impacts of projects on one another

Numerous reasons why the depicted projects impact on one another are conceivable. (b2) in the paint shop, for instance, must not necessarily emerge from a capacity-related domino effect (which can also occur and impact on project 1). Many other impacts are conceivable, particularly if one considers that OEM plants involve more FOs/FSs and are much more complex than the depicted one. Not only buildings and building contents, but also areas and other FOs/FSs can be impacted.

Appendix 6.2.1_01 Fixed in Soil (Basements, Tunnels etc.)

The interviewees were asked what impact it does have on the transformability of an object/structure if this object/structure is positioned in the area/ground. All answers to this question led in the same direction. IP4 argued that it considerably limits the transformability if an object is positioned in the area. IP2 stated that these objects and structures can hardly be transformed non-destructively and that they should be located where one does not plan to build a building. This interviewee argued that facilities exist which one cannot and does not want to relocate, especially if they go deep into the ground. IP5 also stated that the transformability of objects and structures in the ground is limited and that demolitions are normally required in the case of their transformation. IP5 further stated that canals within areas are not transformable. IP7 said that a foundation remains as it is and that a reuse is rather difficult. The same applies to a water pipe. It is in the area. IP3 argued that the more is overbuilt or the more an object or structure is overbuilt, the lower the transformability of factories. According to IP1, the dimensions and function of an object, and how deep it is positioned in the ground are decisive for its transformability. Furthermore, a transformation of an energy canal leads to delayed processes and higher costs. IP8 said that it is restrictive if an object is positioned in the ground. Some of these statements indicate the importance of short project durations and rapid transformations (also against the backdrop of substitution processes). The question was not asked to IP6, as this interviewee explained on her/his own that pipe systems that are buried in the area are always fixed. According to IP6, it would be best if one could make a real area exchange, but on land – on the fixed floor – this is hardly possible. IP1 argued later during the interview that objects and structures are firmly anchored within terrestrial areas. This interviewee further stated that buildings are constructed on solid ground with solid foundations and that buildings cannot be moved (consider subsection 6.1.7 in this context and in the context of exchange areas/an exchange of areas (i.e. area exchange).

The transformability of substructures is consequently disabled, except within basements, tunnels and other spaces within the ground. One IQ was whether comprehensively implemented basements would lead to advantages. It emerged from the interviews that such solutions can be temporarily advantageous, but sooner or later become inhibitors. IP1, for instance, argued that canals can absolutely inhibit transformations. IP6 made a similar statement and went a step further. This interviewee stated that a second installation layer would be rather beneficial if it is a flexibly connectable solution with an integrated infrastructure to enable the rerouting of given cables and the integration of new ones. This would make it possible to bring a structured cabling to each workplace. That different areas and substructures inhibit transformations emerged frequently from all interviews. IP5, for instance, stated that tunnels and ducts inhibit transformations quite often. A similar statement was made by IP2, who further stated that everything that one brings into the area should be assembled or buried in a way that does not inhibit future transformations. The information in the previous sections must also be considered in this context, e.g. substitution processes etc. Modular, movable and combinable foundation elements also do not lead to considerable advantages, as they require earthworks and are limitedly movable and otherwise transformable. Moreover, the need for substitution processes and/or structures is highly probable in the case of their relocation, as their transformation velocity is low. A further problem is that large foundation elements can hardly be moved. Furthermore, to move foundation elements together with FOs/FSs is often hardly possible or impossible.

One could argue that it is still possible to construct multi-storey buildings. IP4 argued that this is done if one lacks areas. IP4 further argued that one would go rather into the widths (if possible) instead of having several conveyor system layers. IP5 asserted that, due to cost reasons and multi-storey building regulations, one would never go into additional floors if sufficient areas were available, but that this is an option if one lacks space. IP1 said that it is more difficult to perform transformations over several floors, while IP2 stated that several storeys should even be avoided, as it is always simpler to change things in two dimensions than in three. IP4 underpinned these statements, as she/he argued that huge problems occur. They are ranging from building structures (e.g. infrastructure) over process facilities and up to conveyor systems if multi-storey buildings are used. This interviewee further stated that huge efforts are required in the case of a transformation and described real-world cases in which lifter holes were relocated. This interviewee talked in this context about massive impacts in buildings. IP4 also stated that it is not always possible to go into a second floor because of safety reasons, floor loads, roof loads and heights. To locate huge loads on upper floors is also often disabled. In addition, the accessibility requires spaces and escape routes etc. Moreover, a multi-storey building requires a stronger substructure. Single-storey buildings have a better accessibility, a more filigree roof structure, and daylight.

An increased difficulty to perform transformations within several dimensions can be seen as counterarguments to TASs, but are clearly related to today's factories, as if multi-storey buildings and/or their structures become inhibitors, great measures and efforts are required to neutralise them. Unlike today's factories, which have a fixed ground with foundations, TASs are not fixed. This means that the area-mobility is enabled, while TASs involve an inner transformability. As regards higher costs, the argumentation is valid that if TASs were serial/series products, their costs would decrease. In this context, further advantages provided by TFCs with regard to efficient processes, decreased transportation costs (e.g. through decreased distances between suppliers and OEMs), improved utilisation of synergies, increased transformability and green production must be considered. Further positive, but also negative aspects are discussed throughout this thesis.

Appendix 6.2.1_02 Fixed Sections, Objects and Structures

It emerged from the interviews that sections and departments are fixed. This is also valid for all other objects and structures in this appendix. IP3 argued that when a press or a paint shop is implemented in a Greenfield, it is fixed. IP1 stated that these sections cannot be relocated, while IP5 said that a press shop stays a press shop. IP1 used in this context the word 'static', as did IP7. IP1 further stated that buildings cannot be moved. This has been validated by all other interviewees. Building superstructures are not the main problem, but rather their substructures and those of diverse fixed objects and structures (see the next but one paragraph), besides further objects and structures which inhibit transformations. IP2, for instance, said that buildings stand solidly on the ground and on foundations, and sometimes on 20 m deep poles. This interviewee added that they cannot be moved, while IP8 expressed that all production sections are fixed today. That residential buildings are fixed points has been added by IP4. Furthermore, connecting conveyor bridges between sections are fixed. This has been stated by IP3, IP4 and IP7.

The transformation potential of TBSs, of which substructures are currently fixed and heterogeneous, is limited, the same as the transformation potential of possibly comprised second installation layers. In the case of a building displacement (in which a TBS is displaced/moved/relocated), for instance, TBSs and such layers do not lead to considerable advantages, as one needs first a new location for the displaced building and its contents. Furthermore, it is in most cases required to free and prepare the space at the target location and to construct required substructures before a relocation of a TBS can happen. To transform a given building (i.e. a TBS) could also be an option (particularly if its substructures would not require a reconstruction). Nevertheless, already a relatively simple transformation of a TBS without substructure works can cause problems and require additional areas, e.g. when a building height must to be increased. Therefore, TBSs are hardly favourable without the ability of a transformable (e.g. mobile) area/substructure. It emerged from the interviews that areas and substructures are often impacted in the case of transformations. This must be considered in this context.

Other fixed objects and structures within buildings additionally increase the rigidity of today's (factory buildings and) factories or, in other words, decrease their transformability. IP7 said that objects that are encased in concrete are rigid and that their dimensions remain the same. This interviewee further argued that such objects would not be well constructed if they would change. This means that they must be solid and robust. IP7 also stated that objects and structures are statically arranged, and that the presence of a large number of these objects and structures will inhibit transformations when a production flow changes. IP2 said that in buildings are naturally also facilities which cannot be relocated – especially if they are deep in the ground. Object dimensions and weights were also mentioned in this context, the same as building and gate heights. IP2 added that objects exist that one does not want to move at all due to a huge effort. A [redacted] (an object) in [redacted] (a real-world factory) which is over 120 m long, 12 m high and requires 8 m deep pits was only one example that was provided by this interviewee (the values were slightly adapted). IP2 added that a [redacted] (an object) in [redacted] (a building in a real-world factory) disturbs transformations and prevents efficient flows since decades. Both IP2 and IP7 argued that production facilities should be relocatable, which is often not possible today.

IP4 stated that canteens, factory fire brigade departments, gas (stations), and combined heat and power stations are fixed points, while these stations were also discussed by IP3 in this regard. IP3 claimed that if locations for such objects have been defined, they should remain there, especially if tanks are positioned in the ground. IP4 stated that she/he really does not want to talk about a case in which, based on a management decision, a [redacted] (a specific s&d) plant with all feed-ins and feed-outs should have been relocated (as this is currently hardly possible). IP4 said in this context that the speech is about certain fixed points in factory planning. According to IP4, the energy centre, which is often located beside the paint shop (which is often the most powerful consumer), is a further fixed point. Such and diverse other s&d plants (e.g. power plants) were also identified as fixed points, e.g. by IP1 and IP5. IP2 argued that even smaller transformer stations require foundations and other structures which are also in the ground. This is in line with IP3. Many other examples with regard to technical infrastructures were described (see, for instance, the following paragraph). Another example of a fixed object is a car wash (IP5), besides many others.

The technical infrastructure in or under the soil is also fixed. IP4 described in this context large energy canals and sewers, while IP3 characterised diverse infrastructures for the s&d of wastewater and rainwater as fixed, e.g. drainages. IP6 mentioned in this regard different networks (e.g. pipe networks), whereas IP2 said that infrastructure elements are fixed if these are in the area, under roads, or beside roads. This means that besides infrastructures under soil and in tunnels etc., which can become large inhibitors, there is another solution: pipes etc. can be mounted on trusses. Nevertheless, such a solution requires areas and spaces which are normally anyway limited and can represent or become an inhibitor in the case of a transformation. It must also be considered that transportation infrastructures change, and that these must be opened or demolished. It emerged from the interviews that this takes place quite often. IP5 described demolitions when roads were widened. Similar cases were described by several interviewees, while IP4 stated that also railway lines and loading areas are fixed and can lead to problems in the case of a transformation.

Appendix 6.2.1_03 Basic Area Works

It emerged from the interviews that contaminations of areas are not only a problem for factories which have outlasted wars and/or have been in contact with asbestos. All interviewees described different real-world cases in which contamination of areas either was or still is a problem. IP[redacted] disclosed a real-world case in which the area has been polluted through ore mining (Middle Ages) and additionally through agriculture, which led to lots of m³ of contaminated material. IP5 stated that a lot of contaminated material is removed. IP[redacted] disclosed that a former [redacted] (a specific area) could not be used as a location. IP7 described a BFPC-E in which a building of an SME has been bought (for an OEM) and of which the area has been contaminated through the previous use ([redacted] industry). This interviewee argued that the demolition and reinstatement costs were very high. Archeological villages (IP[redacted]) and dinosaur bones (IP[redacted]) were other problems which led to project delays. Who knows what the future will bring. Asbestos, for instance, was used for a long time, despite the fact that it is harmful. Other harmful substances may be identified in future, e.g. through new technologies and methods.

Further negative area characteristics were disclosed: Swamp areas, expanding loam and flood areas were described by IP2, and swampland and flood zones by IP4, while inhibitors in the area (e.g. rocks) and insufficient soil bearing capacity were mentioned several times by all interviewees. Furthermore, fluent liquids (e.g. water) can damage objects and structures in the area (IP7). Huge efforts (e.g. through land levelling) until the site is appropriate for use are normal for Greenfield projects. IP2 talked about enormous masses if one wants to level more than one km² with a height difference of more than one meter; many hundreds of thousands of truckloads and tours (i.e. drive away from the site (e.g. to an earth dump) and drive back to the site) were required over a period of one year. IP3 provided information about a case in which [redacted]0 hectares (approximately 200 hectares) land were levelled which required [redacted] (more than six) months. IP4 said that over 1.[redacted] million m³ were moved and that this is possible in the case of huge and angled terrains. Three real-world cases were described by IP8. IP8 said that a hill was levelled and talked about tremendous masses. Furthermore, height differences of 1[redacted] meters were levelled. In another case, [redacted] (large natural objects) were removed, a village relocated, and a river aligned.

Massive earthworks are not only required in Greenfields. IP6 argued that normally no area is available to store the soil on site (which does not make sense in all cases). IP1 said that it was required to excavate and remove a lot of soil. IP7 disclosed two cases and used the words 'umpteen thousand m³'. IP[redacted] said that ca. [redacted],000 m³ (approximately 650,000 m³) were removed for the land levelling and the preparation and excavation of pits and trenches. If each truck loads 1[redacted] m³, [redacted],000 tours (approximately 70,000 tours) are required which are in 100 days [redacted]0 tours per day (approximately 700 tours per day). IP5 presented information about a further example in which over [redacted],000 m³ (approximately 450,000 m³) soil were removed, and in which [redacted] tours per day (approximately 470 tours per day) were required. IP4 stated that the absorption capacity of landfills is limited. This is in line with IP6, who said that there are often problems with landfills. Furthermore, objects and structures can be damaged by heavy equipment or machines such as excavators which require space. Free spaces for machines etc. can also be required in buildings when large FOs/FSs must be transformed. Only the land levelling can require for Greenfields six months and much more than that. The interviewees described several cases in which one year or more were required. Partly over 7[redacted]0 tours per day and over 1 million m³ of moved material were required. Brownfield projects can require similar values (the values were slightly adapted).

IP5 stated that a sufficient soil bearing capacity is a prerequisite. It is, for instance, required for foundations. If you do not have it, projects become very expensive and time-consuming. IP6 talked in this context about increased efforts and costs, and about additional construction works which require extra time. IP8 stated that it can lead to high investments to remove and to reinforce soil (besides high investments that are furthermore required for the land levelling). IP8 also talked about unclear soil conditions, the same as IP2 and IP5. Several real-world cases with unclear soil conditions were described by the interviewees. IP5 provided details about a case in which the soil settled. Furthermore, IP8 talked about the area quality and soil bearing capacity which is often insufficient. Moreover, IP8 discussed inhibiting structures in the area and also talked about inappropriate floor load capacities. Information about inhibitors in the area/ground/soil was provided numerous times by several interviewees. Thus, the area quality is often a problem. IP1 talked about level differences in a Brownfield, the same as IP3, who said that these must be levelled. IP5 disclosed a Brownfield case in which different heights of an area were levelled. IP4 also stated that there are often level differences in the case of Brownfields and not only in the case of Greenfields. IP2 talked in this context about slopes. IP7 stated that the soil condition is essential, as it decides about what can and what cannot be done, e.g. foundation works. This interviewee stated that the depth of foundations must be increased due to soil conditions. IP7 also talked about waters and rock layers in this regard. Furthermore, there are several surroundings. This interviewee further argued that everything that can be removed will be removed. IP3 talked about a rising groundwater level after a few years (BFPS-3-factory), and about a required but hardly implementable transformation (i.e. widening and extension) of a drainage. IP2 also described cases in which the groundwater increased.

Appendix 6.2.2 Industry 4.0

Küpper *et al.* (2016, p. 5) describe the structure of future factories. Driverless transport(ation) systems (DTSs) “guided by a laser scanner and radio frequency identification technology in the floor” are future factory solutions, while “[Toyota] will use a modular conveyor, which is built on the factory floor instead of a pit, giving workers greater flexibility in changing the length of the line and in moving the line-side equipment.”

Automated guided vehicle systems (AGVSs)/DTSs and other solutions (e.g. movable robot cells) can increase transformability, but their use is not everywhere possible. Furthermore, material flows are required which can hardly be solved with AGVSs/DTSs, e.g. overhead conveyors. Moreover, fixed objects are required for these systems, while handover points also require RFOs/RFSs. New scanners (e.g. instead of other guiding and measuring equipment) can be used, but the belonging technology and/or s&d infrastructure often requires fixed objects/structures. This emerged from the interviews. Many other modern solutions exist and are in use, and new ones emerge. IP6 argued that large 3D printers have specific area and substructure requirements. It is obvious that different types and sizes of these printers will be required if this technology should be widely implemented in OEM plants and/or supplier factories. This also applies to other solutions and will also have an impact on process flows. Even if movable robot cells and other TFOs/TFSs are used, area and substructure requirements at new positions must be appropriate, e.g. footprints and floor loads. An s&d infrastructure(s) is in most cases also required for TFOs. Thus, RFOs/RFSs which often inhibit future transformations, as well as other FOs/FSs which can inhibit future transformations are required (all interviewees). Moreover, (direct) process inputs and outputs must be considered. Which RFOs/RFSs (of which currently not all can be replaced or substituted by modern solutions) are required in OEM plants is recognisable in appendix 6.2.1_02. Meant are particularly FOs/FSs which have fixed substructures and those which are rigidly bound with the ground, e.g. FOs/FSs which are buried/below ground level. Furthermore, it must be considered that almost all FOs/FSs which have points of contact below ground level normally cannot be moved/relocated without area and/or substructure works. This can be required in old and new positions. Industry 4.0 does not only focus on transformable solutions, but these aspects must be considered. Many transformation requirements such as those that are presented throughout this thesis cannot be adequately solved without transformable areas/TASs. Real-world factory developments must be considered in this regard.

Appendix 6.2.4 Approval Processes

The information in this appendix is generally valid for today's factories, but can vary per country and land. IP7 argued that approval processes are everywhere similar. An equivalent statement has been made by IP1, who is a further specialist for approval processes.

Reasons why approval processes exist have been stated by IP6, who argued that regions can be impacted with each construction (e.g. the overall water supply) and that this can lead to an impact on the given infrastructure network, at least partly. Furthermore, the region provides additional services (e.g. garbage trucks), employees, living spaces and public infrastructure. This, in turn, leads to additional requirements for the infrastructure etc.

Approval processes are normally required in/for the following cases (higher-level perspective):

- new construction (e.g. of buildings)
- extension (e.g. of buildings)
- demolition (e.g. of buildings)
- change in use (e.g. when a logistics area turns into a production area or when a machine is exchanged through another machine with higher emissions and/or floor loads)
- environmental aspects/emissions change (e.g. when the environment can be polluted or otherwise negatively impacted which, for instance, can occur through additional machines and/or noise)
- safety issues (e.g. when people can be jeopardised which, for instance, can occur through pollution, noise and/or instable building structures)

In the case of earthworks/area, sub- and superstructure works, and different transformations (e.g. building works and works with regard to building contents), the specific case decides about required approval processes and their durations. Moves of TFOs, for instance, normally do not require approvals if areas are not impacted. Small foundation works often also do not require approvals. Nevertheless, if the building static and/or people (also people who live beside the factory) are negatively impacted, approval processed might be required. Larger earthworks and/or substructure works require approval processes. Approval processes require in general 3 to 6 months and can be done in parallel to one another. Building applications can require 6 or more months until their permission/approval, e.g. when the public must be involved and/or if water(s) is impacted. Exceptions are possible.

An additional upfront approval process for earthmoving works is required if a certain limit (m^3) has been exceeded (IP7). The same applies to special cases with regard to groundwater (IP1). Special permissions are required for special processes (which can furthermore require special structures, e.g. waterproof foundations) due to safety and/or environmental issues and are only permitted in a certain area which leads to further (quasi-)fixed points, particularly in the case of today's factories. IP6, for instance, argued that special processes such as galvanisation are only permitted in a certain area due to emissions and environmental protection, and that these processes require special approval processes. Basic requirements in such a case are a waterproof foundation and an additional pipe system. IP3 described a case in which a water resources act led to additional area requirements (surface coating/floor surfacing) which are required in the case of a fire and because of polluting substances, e.g. leaking fluids. This interviewee argued that there are numerous special permits. This was validated through further cases. IP7 stated that special permits are also required for areas that require high loads and/or where high objects are going to be assembled. Furthermore, energy canals (IP7) and tunnels require special approvals, especially if these are accessible and walkable (IP1).

Appendix 6.2.5 Programme Challenges

The interviewees were asked if large projects are challenging and if so, why. IP4 answered that it is challenging to assume the premises and to handle the different interests of the different departments and sections, indirect and direct ones.

Displacements and spatial breathing occur due to organisational changes. IP2 argued that it is challenging to make forecasts. The market, market developments, required capacities, product models etc. Do I need a transformation, an extension, a new location, or will I restructure the factory completely. These are questions which emerge in this context. IP3 talked about unexpected changes. IP1 said that programmes are very, very challenging. Changes and overlaps always happen. New projects come up steadily. IP5 argued that it is challenging to perform a programme in time. This interviewee said about a real-world programme: I thank god that I am not involved that much (in this programme). Chaotic. A large number of projects. The coordination is bad. Not only ten people sit together. There are lots more. IP7 said: Time, money, project overlaps – one always has overlaps and programmes become always critical. Programmes are a big challenge and a big problem, also from a logistics perspective. Production supply and the transport and removal of construction material and of other things are required. Numerous incoming and outgoing trucks are required and numerous difficulties occur. IP3 mentioned logistics and site logistics in this regard. IP6 talked about time delays and increased costs. Different domino effects and unplanned impacts on sections and departments were described. IP8 provided information about a programme and stated that disruptions of the ongoing production are the major problem, and the given infrastructures which require an adaptation. The work associated with these structures disrupts ongoing processes. Substitution processes such as traffic diversions are also required. IP3 said that it is tried not to interrupt the ongoing production. This requires time and money. Furthermore, IP3 stated that the whole organisation is challenging. This corresponds to the statement of IP5. IP7 said about programmes that it is known that several overlaps will occur, but that this does not mean that these overlaps can be handled. IP4 stated that it is difficult to conceive programmes. IP8 said about a programme in a BFPS-4-factory that far over one billion [redacted] (one of the world's strongest currencies) are required to bring the factory to a new production system level, not possible at all, in the grown structure, but to make it to some extent survivable. (The author has kept the translation of this sentence very close to the original statement.)

Several interviewees made very critical statements about different cases in BFPS-4-factories, highly questionable management decisions (whereas the question is if these could have been done much better), and a planning inability. It emerged from the interviews that the planning of factory projects in some BFPS-3-factories and particularly in BFPS-4-factories is more than challenging, even if a reliable project management (which can but must not necessarily be based on a project management system) is implemented. Not only changing and new projects and project scopes are decisive in this regard, but also and already the factory complexity which lets the involved planning teams struggle and require the involvement of more and more people, even if there is no new or simultaneous project (regardless of whether or not several projects are handled through a programme(s)).

It emerged from the interviews that the total effect/impact of a 'factory structure recovery programme' (which is performed to reach again an effective factory structure and efficient factory processes) is unknown in factory planning practice and that this effect/impact cannot be known, as such projects are only processible step by step. Furthermore, it is known in factory planning practice that wide-ranging programmes must be performed from time to time. Reasons for these programmes are also known, e.g. to get back to an effective factory structure and thus to efficient factory processes.

Appendix 6.2.6_01 BFPS-1 – Site Selection

IP6, for instance, stated that site selection is decisive for the development of a factory, while IP1 argued that a new factory should be implemented where the lowest labour and raw material costs are, and where the highest subventions and incentives can be received. The statement of IP1 complies with the statement of IP6, who added 'lowest construction costs' and 'most customers' to the list of requirements of a good location and argued that the probability to find such a location is extremely low. Lowest labour and raw material costs were also stated by IP1 and IP7, who added product costs. IP2 said that site selection is one of the most important managerial decisions, as a factory cannot be relocated completely once implemented at a wrong location.

The question about whether a location can be wrongly selected has been answered very unitarily by all interviewees: either with 'yes', 'of course', or 'definitely'. Numerous real-world cases which took place all around the world were described by the interviewees. IP1, for instance, provided information about a case in [redacted] (a continent) in which the location was not at all appropriate. This led to a factory closure. Similar cases in South Eastern Europe and [redacted] (a continent) were disclosed by IP2. IP5 provided details about a case in which different heights of the area led to vast area works and to the question if the location should be changed. Further cases of plants which cannot be revealed (current OEM strategy) have been presented by IP4 and IP8. Other cases were previously described (e.g. in appendix 6.1.1_05), while many further ones were outlined by the interviewees. IP6 argued based on a real-world case that if a factory is done and the market changes, a factory closure can be the consequence if the total costs are too high. A further case of site selection occurred after a BFPC-E and was recounted by IP7. According to IP7, it was required to transform a former factory of a company in [redacted] (compass direction) Europe. This factory was left by the previous owner. Several buildings had to be demolished which were not at all suitable for the purposes of the OEM. Furthermore, it was required to construct new buildings and to reconstruct others. Moreover, areas were [redacted] (not appropriate). This shows that site selection is also relevant for off-site cases/Brownfield projects. Different cases which impacted supplier factories were also described. IP[redacted], for instance, disclosed a case in [redacted] (a country) in which a supplier factory was built and never used, as the OEM made a decision change.

Appendix 6.2.6_02 BFPS-1 – Required Areas Sizes

IP8 stated that it is difficult to find huge areas. Furthermore, it is always problematic, as there are problems with private properties. This interviewee said that even today factories exist in which areas belong to private individuals. Details about a project in [redacted] (a continent) were provided by IP2. [redacted] (more than

50) different owners wanted more and more money and it was not possible to find an alternative area. Furthermore, IP2 talked about prices in Southeast Asia (an emerging market) which are as high as in Central Europe. Thus, it was not possible to buy huge areas as is possible in some regions in North and South America where one receives incentives. Thus, it was required to make the factory narrow and tight, as [redacted]00 million USD were required at once. IP2 presented details about another case in [redacted] (an emerging market) in which the area shape was inappropriate and not good for a use. Diverse property issues led finally to changes of the emerging factory. As a result, the positions of buildings and diverse flows were suboptimal, besides other disadvantages. Numerous cases were recounted by IP3. In two cases, a deal was cancelled, as the seller wanted always more and more money. This is in line with other cases of other interviewees. Three further cases were described in which delays and suboptimal layouts were the consequence.

One IQ was how easy it is to find large enough areas in the right region. IP5 said that it is not simple. A Greenfield requires connections to rails, roads, electricity and water, and must be close to a city, as workers are required and as their ways to the factory should be short. IP6 talked about a case in South America and stated that a continuing shortage of space occurs within the related factory. This interviewee said that it is more simple to find huge areas in the countryside and more difficult in urban areas. IP8 said that it is not simple to find huge areas – in [redacted] (a continent) definitely not. It is rather possible in [redacted] (a country) and [redacted] (a country). IP1 used in this context the word difficult. IP2 said that one goes there where as much supplier industry as possible is located, where as many people as possible live so that one has the required workforce, but simultaneously one wants to have a large free area, that cannot be found in such regions. This leads to the problem that one wants both but cannot find both. You can find one of these factors, but not the other factors.

Thus, terrestrial areas are subject to restrictions in size and shape. Huge areas with appropriate characteristics are rare and more and more unavailable.

Another IQ is: 'How sensible is it to purchase doubling areas or larger areas (i.e. area reserves of additional 100% and more)?' IP5 said that such areas are very important to enable an outstretching of the factory. IP2 said that it is always sensible (see below for further information). IP3 stated that it is very sensible and added that a Brownfield without exchange areas is problematic, as transformations must be performed within UHPs which must be demolished first. IP7 argued that extension areas and building volumes are naturally very sensible, as one can bypass many problems. A comparable statement was made by IP3. IP8 said that it is first expensive but afterwards sensible to enable extensions and factory duplications. IP4 stated that it is a cost factor but a sensible one. According to IP4, at least doubling areas should be bought. IP6 said that it is not sensible to buy doubling areas as it is uneconomic. IP6 further stated that this is rather possible for automotive OEMs, but not for SMEs. IP1 said that it can be sensible, but that it is always a risk. IP2 stated that, due to cost reasons, one builds only what is required. Nevertheless, there is often no other option, as these additional areas are required. IP3, IP4 and IP8 made comparable statements. IP7 argued that it is a problem if one has purchased a doubling area which is not required as it is static.

Appendix 6.2.6_03 BFPS-3-Factories

The following cases and information are related to BFPS-3-factories. IP3 disclosed a case in [redacted] (a continent) in which an unplanned building extension led to an extensive shift of large media routes. Routes were provided over a building (as a substitution process) to enable the workers to demolish the routes in front of this building. Afterwards, the building could be extended and new routes were constructed. It was then possible to remove the substitute routes. IP7 provided information about a real-world case in which a building extension led to a drainage displacement. IP5 presented details about a project in which the roof structure could not be used for a transformation. New foundations, chip conveyors and media ducts were required to be brought into the floor. The floor was dug up which was, according to IP5, very laborious and expensive. Several displacements occurred. IP5 further argued that it is often the case that new machines are heavier than old ones. This leads to the requirement to construct new foundations or to extend respectively to reinforce old foundations. IP5 also stated that sometimes old foundations are reused, which is a compromise and involves certain risks. Many other cases were provided by the interviewees: foundations were in wrong positions or not appropriate for new requirements; shifts and replacements of columns occurred; new FOs/FSs were integrated, exchanged etc. IP1 said that factories become stopgap solutions after several Brownfield projects. This also emerged from the other data of this and from the data of all other interviewees. The interviews also showed that construction machinery and equipment require spaces and often lead to displacements.

Furthermore, it emerged from the interviews that project overlaps occur in BFPS-3. Nevertheless, IP4 argued that these can be generally more easily solved if one has areas, compared to a factory in which all areas are occupied, i.e. a BFPS-4-factory. IP5 stated that project overlaps occur at all factory structure levels and in each project down to all technical professions. Given structures are being transformed. Changes occur and also changes of changes. IP5 also stated that the management and coordination of a BFPC-B can be extremely difficult, even if extension areas are available, i.e. within a BFPS-3-factory. This interviewee described displacements, substitution processes and different domino effects in this context.

Appendix 6.2.6_04 Characteristics of BFPS-4-Factories

'What are the characteristics of a factory if all extension areas are occupied?' All answers to this IQ led in one direction which is shown by the following exemplary statements. IP1 said that the transformability of factories decreases when all areas are occupied. This interviewee further stated that everything becomes more static when all areas are occupied. IP2 stated that there is no capability to breathe and that no optimal arrangement of areas is possible anymore, as no exchange areas are available to restructure areas. This thing (the factory) languishes ("Das Ding vegetiert vor sich hin"). It can only be transformed in parts and not holistically. IP4 talked about scattered functions and scattered functional areas, and about a lot of conveyors and interfaces. A further statement of this interviewee is that a factory is dominated by long distances which are spread all around. IP6 said that the bottleneck of the entire system is decisive for the entire factory efficiency. The factory output was mentioned in this context, while IP6 described many other bottlenecks that occur. IP7 stated that conveyor bridges are a characteristic of such factories. These brigdes are partly located on top floors of buildings. This interviewee also said that a further characteristic of such factories is that they are built upwards. Further statements of this and other interviewees demonstrated that this leads to later problems and inhibiting structures which make transformations difficult or impossible. IP8 is the interviewee with the longest experience in factory planning. IP8's answer to this question was as simple as it was determinative. IP8 said: 'Then we talk about UHPs.'

Appendix 6.2.6_05 Transformations in BFPS-4

'Which transformations are possible and how if all extension areas are occupied?' IP1 said that outsourcing can be an option. IP2 answered that the production goes on. Thus, one cannot demolish something just like that. Substitution processes are required, particularly for the production and for what is produced at the moment. IP8 stated that transformation possibilities are very limited in such a case. Transformations can be partly only done through demolitions before one can build something new. IP8 further stated that substantial reconstructions are another possibility. IP5 made a comparable statement and talked about massive changes and demolitions. IP3 also said that first one must demolish something before a new construction can be done. IP7 said that demolitions are one option. Demolitions can be the simplest possibility if it is possible at all to perform demolitions. IP6 stated that either demolitions or a new Greenfield is required. IP5 also said that one must buy new areas if possible, or perform outsourcing to suppliers, which is not always possible. Furthermore, IP3 described a real-world case and talked about buildings of a factory which is meanwhile a UHP and should be demolished. Outsourcing can be a possibility if no areas are available, but even then at least logistic flows change. Furthermore, it is unsure if outsourcing is possible at all. IP4 stated that structures should be demolished but are used further because of the timeline. 'We take the second-best solution' is a statement of this interviewee who talked about numerous inhibitors, the same as IP7, who said that it is required to perform constructions around inhibitors such as a conveyor bridge. IP5 described a BFPC-B in BFPS-4 that led to numerous difficulty factors and chainings. IP2 stated that when a factory has reached its capacity and area limitations, there is not much transformability left. IP4 said about conveyor system transformations which require three and more months that these cannot always be broken down and split but must be done non-stop (continuously). According to IP4, holiday works cannot help in this case. IP7 described several building demolitions, extensions and new constructions which took place on a main axis of a factory and of which processes were highly interwoven. All interviewees have disclosed cases in which building displacements occurred and in which complex process chains, domino effects and chainings were involved. IP8 stated that the transformability of areas is not sufficient. IP8 repeated that the transformability of areas does not suffice. This interviewee presented details of two factories and argued afterwards that it can be seen in the living object that this is the case. 'Catastrophic' and 'not viable' are words which were used by IP8 to describe the characteristics of these factories.

It emerged from the interviews that the daily business of factory planners is problematic if OEM plants that have reached BFPS-4 are being transformed. IP4, for instance, said: Which transformation is not problematic?/. This means that all transformations are problematic. IP7 argued about projects in BFPS-4-factories that these are always problematic, while IP5 talked about a real-world case in which permanent transformations happened in a building over a period of four years. Production lines were extended while others were relocated. New conveyors were installed and steelworks were required. Furthermore, transportation sizes and weights are restrictions (in all BFPSs) (particularly IP2, IP3, and IP5). IP3 added limitations of lifting devices, portal sizes and road widths. Curves additionally increase difficulties. It emerged furthermore from the interviews that not only BFPS-4-factories but also BFPS-3-factories can lead to difficult, laborious and expensive transformations, which involve small and large displacements and many other difficulty factors. Further information in this regard can, for instance, be found in appendix 6.2.6_03.

Appendix 6.2.6_06 Real-World UHPs

The interviewees were asked if factories exist which they range into the category UHP. IP2 looked at factory layouts of different BFPS-3- and BFPS-4-factories at the wall: ‘This is such a hut’. If I take a look at these plans (factory layouts) at the wall I see only huts and a hut with some yellow streets in between. Four real-world factories were directly named by IP2, while IP3 named three plants without much thinking (all are BFPS-4-factories). IP8 said that all factories are meanwhile UHPs. Even some new factories are unstructured. A (BFPS-4-)factory, as argued by IP8, became a UHP as only reactions to current requirements took place. The factory was extended and transformed, but there were no thoughts about a new overall structure. The extension steps were too small to justify a factory doubling or a new factory. IP6 argued that UHPs can often be found. The growth of a factory leads to the case that one must rent off-site areas or perform outsourcing. IP5 said about a factory that has reached BFPS-4 that it is a chaotic plant. There is no exchange area, no area to stretch the factory out. IP7 provided a comparable statement. Both IP1 and IP4 talked about factories which have reached BFPS-4 and described programmes, while it became evident that such programmes cannot always help to restructure a factory appropriately. IP3 argued that all factories become UHPs, while IP6 stated that all factories sooner or later become UHPs. Extensions play one role and transformability another role. Furthermore, IP2 talked about a relatively new plant in [redacted] (a country) and claimed that this factory could turn into a UHP. There are already all these sheds and all these small huts which were constructed during the Greenfield for different purposes. This plant is already a UHP and will turn even more into one. Further real-world UHPs were disclosed. IP3 provided information about several UHPs. This interviewee stated that factories turn after twenty years into UHPs. IP6 said that a lot of UHPs exist. A further UHP in [redacted] (a country in South America) was disclosed by IP2. IP2 said about another real-world factory that there are no areas left and that nothing at all can be done, as the structures are intertwined. The interviewees described further cases in which several small and large buildings, besides other FOs/FSs, were demolished and then one or several new buildings constructed (on top of the cleared areas).

Appendix 6.2.6_07 About the Chance to reach an Optimal Factory

It emerged from the interviews that it is hardly possible to maintain lean production in an aging factory – already not in a Greenfield and especially not afterwards, i.e. through Brownfields. IP2 said that the ideal factory is the best compromise. There is no 100% solution but only compromises, as there are so many influencing factors and interests that one can never reach 100% but only compromises. We have an optimal factory when 80% of all single factors of our assessment system are fulfilled. We then have 100%. IP4 stated that everyone wants to have her/his optimal process and argued in this context that no one looks at the factory from a higher level. It is more about who pays what. If everyone optimises her/his project, there is no total optimum. IP2, IP4, IP5, IP6 and IP7 said that there are no ideal factories, i.e. ideal factories do not exist. Nevertheless, it emerged from the interviews that the highest likelihood to achieve an ideal factory is given within a Greenfield project. IP6, for instance, said that if one excludes authority-related processes such as approval processes, and area-related restrictions, it would be basically possible to achieve an optimal factory in a Greenfield. Buildings are not the right ones after years. IP2 argued that you start with a white piece of paper, your Greenfield, with ideal processes, and then you build your adapted buildings over these processes... (the three dots represent a short moment in which the interviewee said nothing). No, you cannot (have ideal processes). If you take a look at the projects at the wall – [redacted] (a continent), [redacted] (a continent), [redacted] (a continent) and [redacted] (a continent). You always deviate from the ideal process and somehow use the existing building structures, areas and sizes, and you adopt them. Thus, one is away from what is ideal. IP7 said that a historically grown factory cannot be an ideal factory, while IP8 stated that transformability is limited wherever spatially and historically grown structures are. Everything leads to UHPs. The factory gets larger and more unstructured and thus more complex. It emerged from the interviews that more and more inhibitors arise throughout the BFPSs and lead to longer project durations. IP7 talked about a surrounded factory and about a case in which it was impossible to increase a logistics centre as required. It was only possible to construct half of the required size. IP6 said that given building structures restrict you and predetermine possibilities. Furthermore, it emerged from the data that factories normally grow and that more products and more projects come up over time. The interviewees provided numerous cases and information which demonstrated that changes occur very often. IP6, for instance, stated that there are always requirements which cannot be expected or forecasted. The interviewees provided information about a lot of cases in which demolitions were required. It also emerged from the interviews that a factory structure recovery programme can help a factory to become a bit more efficient (mainly IP1, IP2, IP4 and IP8), but not much more than that (consider also the risks which accompany such programmes). IP4, for instance, claimed that the processes in an intertwined factory are often aligned in such a way, that she/he doubts that these processes can be much improved through a factory structure recovery programme. This interviewee stated that these processes are not optimal at all. This is in line with several other statements of the interviewees.

Appendix 6.2.6_08 BFPSs and Complexity

It emerged from the interviews that today's factories become more and more intertwined, unstructured and complex over time. It also emerged from the interviews that factory structure recovery programmes cannot always help to recover the structure of a factory.

IP7 stated that influencing factors increase throughout a factory lifecycle, while IP2 said that efforts increase over time. These efforts depend on the factory structure. When the factory is completely covered, it becomes more and more complex to do a restructuring, particularly if no exchange areas are available. Then even for 200 m^2, you need a whole planning team. IP5 stated that factories become more and more built-up and inhibited. IP5 further stated that Brownfields are the most challenging project types and that these projects are much more challenging than Greenfields. This interviewee used the words 'king's class' in relation to this.

IP5 also stated that it is more difficult to perform transformations within given structures than with exchange areas. It became evident that it occurs in several BFPS-3-factories and almost all BFPS-4-factories that it is difficult to perform transformations within given structures and that such areas are not available. BFPS-4-factories can only have such areas within given buildings. Nevertheless, it emerged from the interviews that these areas are normally inappropriate for the demanded FOs/FSs. IP3 described how the transformability of factories develops and stated that it is crystal clear that the more one builds up, the worse becomes transformability. IP6 said that the more a production capacity in a factory increases, the more are the limitations of the infrastructure hit. S&d networks in the ground are a big topic. IP3 stated that the older a factory becomes, the more difficult become transformations, as divisions and especially departments need to move, as their areas are required for production purposes. It comes to protests so that the suggested area cannot be used. Areas need to be reduced and new [redacted] (a specific building) concepts emerge. Furthermore, it became evident that also production areas are displaced by other production areas. IP6, for instance, said that not only departments are displaced to create new production areas, but also other production areas. IP5 stated that the area gets narrower and narrower. IP1 said that the transformability is limited where areas are limited and where through permanent transformations within buildings and facilities the development went towards UHPs so that one is only able to perform future transformations through exorbitant costs.

IP1 stated that a real-world factory that has reached BFPS-4 could be a bit leaner after a programme. Other interviewees made similar statements, e.g. IP4. IP7 said in the context of programmes that it is known that several overlaps will occur, but that this does not mean that these overlaps can be handled. IP4 said that overlaps and collisions occur in Greenfields and the more the Brownfield, the stronger they become. (The author has kept the translation of this sentence very close to the original statement.) The interviewees also described the development of the number of simultaneous projects and operations phases. IP2, for instance, said that in an older factory, even small areas can be a problem and lead to further problems (this statement was made in the context of a real-world case). Parallel projects lead to problems and substitution processes. IP8 stated that the number of projects and investment requirements increase over time. One must always accept compromises, outsource processes, rearrange objects and rebuild structures. It is always the same. IP6 stated that the required time increases through interdependencies. The more products and functions, which can compete, a factory involves, the larger the factory size and the more transformation requirements occur. IP6 added that increasingly fixed conditions and restrictions within buildings occur. This was validated by IP3, who further stated that there are always higher requirements towards buildings and new technological developments, e.g. [redacted] (a specific technology) technology-related ones. Furthermore, the larger and the older a factory becomes, the more maintenance is required. IP8 talked about a BFPS-4-factory and stated that there are permanent transformations. 'You just need to drive through this factory – it is a disaster' ("Katastrophe").

IP4 said that demolitions of intact structures occur repeatedly, while IP2 stated that demolitions often occur in car plants. IP5 talked about objects which could be used if the requirements would remain the same, but cannot be used due to transformations. According to IP5, this often happens. IP8 stated that demolitions are normal within Brownfield projects. IP6 argued that demolitions of intact structures occur more often in factories in which the area is completely occupied through buildings etc. IP3 said that demolitions happen where the capacity limit is reached – it is a 'never-ending story'. IP7 stated that buildings, parts of buildings and other structures are often demolished. This interviewee used the words 'really often' in this regard, and added that this takes place in construction projects in the case of change in use and when new additional objects must be implemented. Furthermore, building structures are very often demolished, as they inhibit transformations. They must be replaced in other positions. If one wants to perform a transformation within obstructed factories, demolitions are required. All interviewees provided sufficient information which confirms that displacements occur the more often, the higher the reached BFPS (the dilutive effect between BFPS-3 and BFPS-4 must be considered). Displacements and moves/relocations of

FOs/FSs are very often accompanied by demolitions, reconstructions and/or new constructions.

IP4 argued that the more projects are performed in a factory, the more difficult it becomes to take decisions at the right time and to define their impacts. The complexity increases extremely and often leads to second-best solutions. IP2 stated that the complexity of a factory generally increases when it grows. IP2 further stated that it is often not possible to handle project complexities as required. This is in line with IP4, who said that the complexity in several factories is not manageable. This statement was made against the backdrop of several BFPS-4- and some BFPS-3-factories. Further statements of IP4, such as the following one, are also relevant in this regard: These different (product) derivates must be coordinated which is extremely difficult. This is a statement which was made in the context of factory and project complexities. It emerged from the interviews that cases exist in which the mentioned coordination is not possible. Another statement of IP4 was the following one: How large can the area be at all, so that it can still be managed due to dimensions?/. As there are interactions and mutual impacts, or the multi-storey car park which is [redacted] minutes (more than 25 minutes but less than 40 minutes) away from the plant. There is a maximum factory size that should not be exceeded, otherwise, the factory is not controllable anymore. (The author has kept the translations of this and the two previous sentences very close to the original statements.) IP2 said: What we always do is to build in parallel to the planning and there appear always changes which lead to huge efforts or cannot be implemented at all, but otherwise (i.e. if we do it in a different way) we cannot keep required project durations such as the 36 months for a Greenfield. IP8 stated that one experiences during a project that other dimensions and functions (than the planned ones) must be extended. It emerged from the interviews that it is the normal case within Brownfield projects that at some point in time requirements emerge which cannot be considered upfront. IP7 stated that changes occur always. Product definitions impact on facilities and when changes occur this leads to domino effects. IP5 talked about a BFPS-4-factory and said that the management and coordination of transformations in this factory are extremely difficult. IP7 argued that delays of single projects are not foreseeable. IP4 and IP8 made similar statements. It emerged from the interviews that there are projects and programmes which are difficult or impossible to manage. It also emerged from the interviews that 'as is'-statuses of factories are often so complex that these cannot be defined as required in order to appropriately perform transformations. Undocumented (keyword: digital factory) process owner/user changes are only one aspect that underpins this fact. That 'to be'-factory statuses normally cannot be anticipated has been sufficiently discussed.

Appendix 6.3.1_01 TAS-Requirement Profile (1 of 2)

IP1 and IP3 argued that the modularity would generally lead to an increase of the transformability of factories. IP8 said that the development of intelligent modules is required. A statement of IP3 made evident that modules which are not physically bound with the area are advantageous. IP5 stated that when buildings are extended, roads and s&d infrastructures must be shifted, while topographical differences must be aligned. Areas around buildings should therefore be movable, the same as buildings. IP5 added that roads are anyway changed during a factory lifecycle. Furthermore, transformable areas within buildings are required. IP2 announced that the (technical) infrastructure should be located where one will not construct a building later, but this is hardly possible. This interviewee further argued that the problem is that infrastructure requirements change over time, and consequently infrastructure dimensions and positions. IP7 stated that it would be advantageous if free areas in the middle of the factory could be generated. IP7 further stated that it would be sensible if factory objects and structures that are larger than containers were movable, especially as different departments and sections change. (IP7 made further statements in this regard.) This emerged from all interviews, the same as the fact that other objects and structures must be relocated and that it would be advantageous if fixed points (e.g. s&d plants) were movable/relocatable and reintegrateable. IP7, for instance, further stated that it would be great if production elements could be plugged to one another as required, e.g. a whole building or parts of it, or if this building could be segmented in order to unplug and re-plug areas. This interviewee also stated that factory solutions should be sophisticated, and unproblematically pluggable and unpluggable. Particularly subsections 6.1.10, 6.2.4, 6.2.6 and 6.3.6 involve further relevant information in these regards.

Appendix 6.3.1_02 TAS-Requirement Profile (2 of 2)

IP5 said that roof structures are complicated and comprise steel structures, conveyor technologies and s&d infrastructures, e.g. data networks, air ducts, pressurised air etc. These are either directly assembled to the roof structure or to a separated steel construction that is mounted to the floor (IP3 talked about intermediate structures in this context). Heavier engines require a heavier steel construction. This leads to intertwined structures within buildings and roofs. According to this interviewee, steelworks lead in most cases to transformations of media routes. IP5 further stated that s&d lines and pipes within buildings are not only in the area or below the floor. Energy and media are also provided via (process) media lines/routes (superstructures; "Medientrassen"), as it is simpler. Thus, there is not always a need to dig up floors. This is, according to IP5, anyhow too expensive and too laborious. Nevertheless, it emerged from all interviews that it is difficult to transform s&d infrastructures (consider also the following statements of IP5). IP1, for instance, said that it is difficult to transform s&d infrastructures. This interviewee argued that this is because of their rigidity. IP2 said that infrastructures are under and beside roads. It would be good if it were possible to retrofit or implement additional s&d infrastructures. It emerged from the interviews that this is hardly possible without demolitions and work effort. IP7 stated that it would be very good if the technical infrastructure was modularly adaptable, while IP6 argued that a modular and flexible infrastructure is required and not a fixed one. IP1 stated that it would be advantageous if new and changed characteristics and functions could be integrated more easily. IP6 (also) stated that not only the transformability of superstructure networks, but also of substructure networks is required. This statement was validated by IP8. Furthermore, IP6 talked about a second installation layer, and argued that normed and scalable plug-systems are required. IP5 stated that it would be good if the infrastructure was more easily transformable, as the requirements change; this means that it would be good if it would not be necessary to first neutralise inhibitors in order to transform infrastructures. IP5 also said that optimal positions of objects change and with these objects also the infrastructure. The infrastructure must be simpler transformable, as requirements change. It is currently complex and laborious to construct and transform infrastructures. IP7 said that inclusion of additional pipes must be enabled, because this is required to transform supply infrastructures. IP8 argued that it would be beneficial if structures could be flexibly integrated into the substructure. This interviewee also stated that she/he cannot imagine how this can look. This shows that TASs are not considered in factory planning practice. Statements of IP4 show that flexibility and transformability of sub- and superstructures are required. This interviewee talked about movable production cells and claimed that these objects can be shifted, but that these objects also require s&d infrastructure connections and appropriate floor load capacities. The supply of production cells with energy and media is often provided over the roof structure, which is not as ideal as if it would be possible to go through a transformable ground. If I go over the roof, I must first get to the roof. I hit directly diverse roof structures. There are often collisions with structures that are already integrated there, e.g. with the conveyor technology. To go over the roof leads to interfering contours for cranes, conveyors and different kinds of supplies. IP4 further stated that the strongest collisions occur between conveyor technology and ventilation systems. Regardless of whether intermediate structures or roof structures are used, both lead to inhibitors, either on and off the floor or off the roof. The same applies to s&d infrastructures above the floor/ground. Second installation layers must be accessible but should preferably not negatively impact possible floor loads. This emerged from the interviews. IP2 stated that one can excavate and relocate almost everything, but it cannot be planned because one never knows what will happen. IP2 also stated: If I have empty conduits, pipes or canals, I can of course ("natürlich") include something, but I must have them in the right positions with the right characteristics. It emerged from the interviews that areas and substructures (e.g. technical infrastructures) are constructed and shortly afterwards are areas, roads and/or other structures opened to include s&d

infrastructures and/or other FOs/FSs. IP6 stated that a pipe system is required that can be transformed more easily. This, for instance, is required if one must include fibre optic cables. This interviewee further stated that the possibility must be given to flexibly standardise areas. The infrastructure must be standardisable and modularly standardisable so that one can always provide transformability as required. IP3 said that it would make sense to use standards for a defined timeframe (e.g. ten years), to improve technologies within this timeframe, and to implement afterwards new standards.

TASs support this idea and enable flexible, customisable or rather transformable standardisation, which means that standards can be changed and exchanged. Thus, standards can be implemented into TASs and retrieved by FOs/FSs which are combined with these systems. Afterwards, standards can be comprehensively changed if required, while it is anyhow possible to change single structures of TAS-elements as required. This transformable standardisation leads to better utilisation and reusability of TASs and FOs/FSs. Furthermore, it has advantages with regard to pre-producibility, as changes have not an as worse impact as in the case of today's factories. This means that changes can be better handled. Again, structures of TAS-elements can be changed/transformed and/or exchanged, while this additional transformability potential is not necessarily required and can be optionally implemented. TASs are thus standardised technical products which either less or more involve the potential to transform belonging structures; the higher this potential, the higher the degree to which the abovementioned transformable standardisation can be utilised. Both standardisability and transformability/ customisability are not separated but combined in one system which unlocks the possibility to comprehensively implement 'transformable standardisations'. This allows transforming factories and other industrial and non-industrial structures to new standards.

Nevertheless, this additional transformability is not necessarily required due to the various MASs. MASs enable TASs (with their specific characteristics) and also objects and structures that are integrated in or located/positioned on top of TASs to be moved/relocated and/or exchanged without any or fewer (re)construction works, which is a big advantage compared to today's factories. In addition, transformability is considerably increased. S&d infrastructure elements, for instance, are accessible and can be simply disassembled, which is not possible if these elements are under the soil (substitution processes must be considered if the supply must go on; the same applies to other issues). Thus, even RFOs/RFSs experience advantages, as their transformability is enabled despite the fact that their basic characteristic is rigid.

Further requirements emerged from the data: IP6 argued that it would make sense to integrate escape routes within substructures. According to IP6, substructures are also usable for underground car parks and material supplies. IP2 also emphasised the accessibility of areas and substructures for employees and that diverse transports (e.g. of employees and parts) to a factory and away from it can happen in the underground. It also emerged from the data that it is often advantageous to integrate conveyor systems and other systems/technologies into areas/ substructures – but in the case of today's factories, this is only advantageous for a limited timeframe.

Different basic factory planning principles (Schenk, Wirth and Müller, 2014, p. 293) emphasise holistic planning which involves all flows and focuses on efficient and green processes, whereas long-term economic efficiency requires a transformable factory. In addition to these principles, a 'production depths and integration principle' can be defined based on the interview data. This underscores the need to integrate as many (at least tier-1) suppliers into an OEM-location as possible, while aspects such as given product structures, available production possibilities, and the number and locations of customers of suppliers (e.g. OEMs) must be considered in this context. Future developments could simplify the implementation of such production networks (see subsections 6.3.6 and 7.3.3).

Appendix 6.3.1_03 Terrestrial TAS Design Options and TAS Hybrids

TerTFCs can be transformable within separated factory sections (only), across these sections, and furthermore beyond these sections. To enable such a holistic transformability, TAS-substructures must be comprehensively implemented based on the maximum requirements towards spatial substructure dimensions and load-bearing capacities, e.g. of a press shop. This is more expensive and requires more work and time, but enables changes of uses of sections. Consequently, TAS-substructures, which provide the bases for TAS-elements, can be designed as cross-sectional (options 1 and 3 in figure 90) (and/)or specifically for each section (options 2 and 4 in figure 90) (see also '(a)' in figure 10 which depicts the substructure of the area system Hydrofield for further clarification).

Height differences between substructures of sections (and other FOs/FSs which are discussed in the second last paragraph of this appendix in order to avoid a further complexity increase) lead to disadvantages when Hydrofield or Railfield are used (these disadvantages are not critical in the case of maritime TASs, as the latter can be levelled through tank-systems etc.). These differences make the connection between sections difficult as it is recognisable by considering the two upper and the lowest side views in figure 90. For reasons of simplification, not all factory sections are depicted.

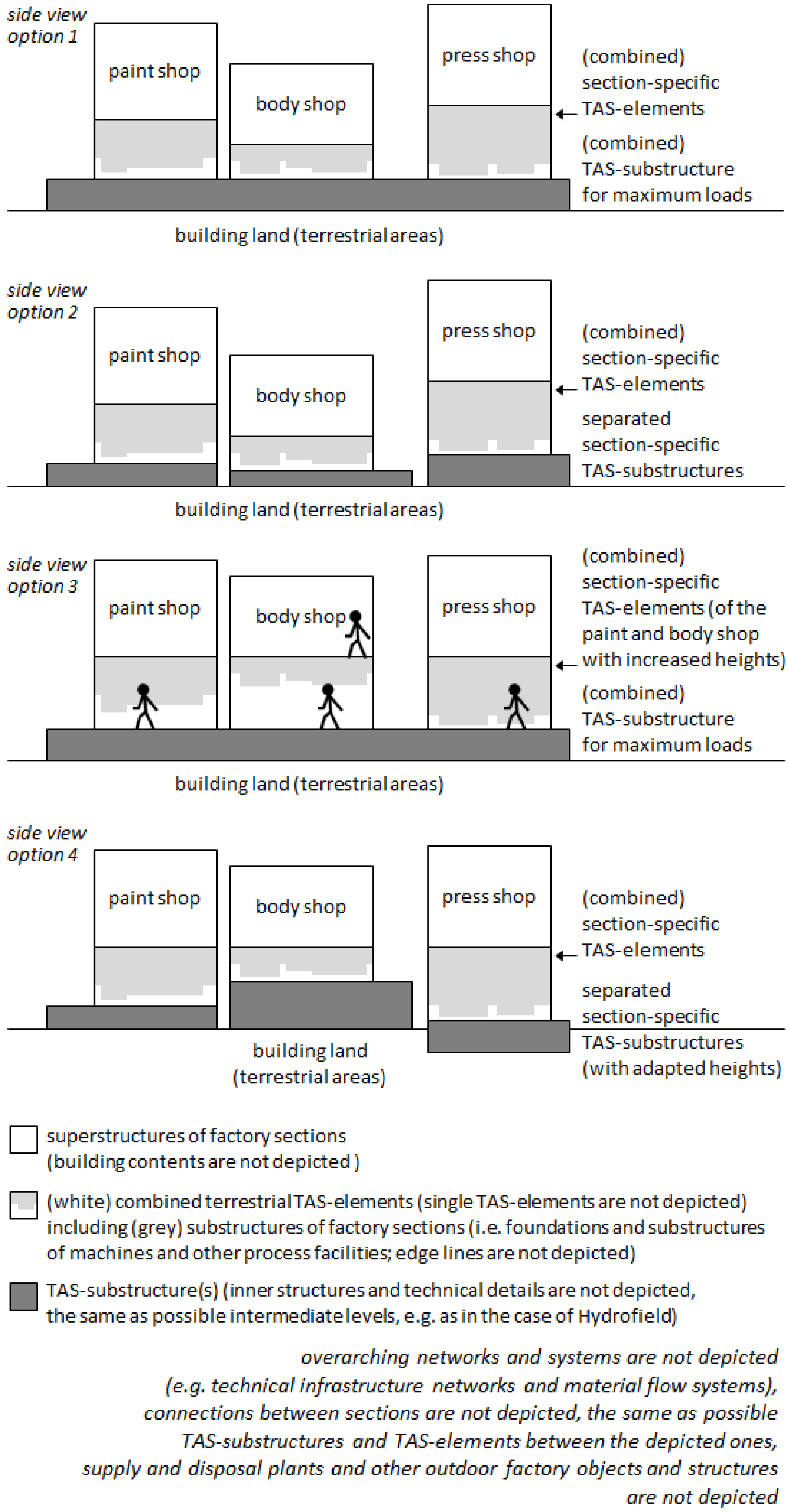


Figure 90: Height aspects of terTFCs and how they can be solved

The two lower side views depict how this problem can be solved, while option 3 can provide the best transformability of all these 4 options, as both the TAS-substructure and the TAS-elements enable the greatest transformability. Option 4 leads to problems with regard to TAS-substructures and TAS-elements between the depicted ones, the same as option 2, while option 1 faces the problem with TAS-elements between the depicted ones but not the problem with the TAS-substructure. Furthermore, TAS-elements can be high enough to enable people passing through the sections.

Besides bottom-plates (as in the case of Hydrofield) or rails (as in the case of Railfield) (etc.), an additional option for terrestrial TAS-substructures is conceivable: 'TAS-substructure-frameworks' which can, in combination with TAS-elements, be designated as 'Framefield'. Figure 91 depicts a terTFC that is based on separated Framefields for each section.

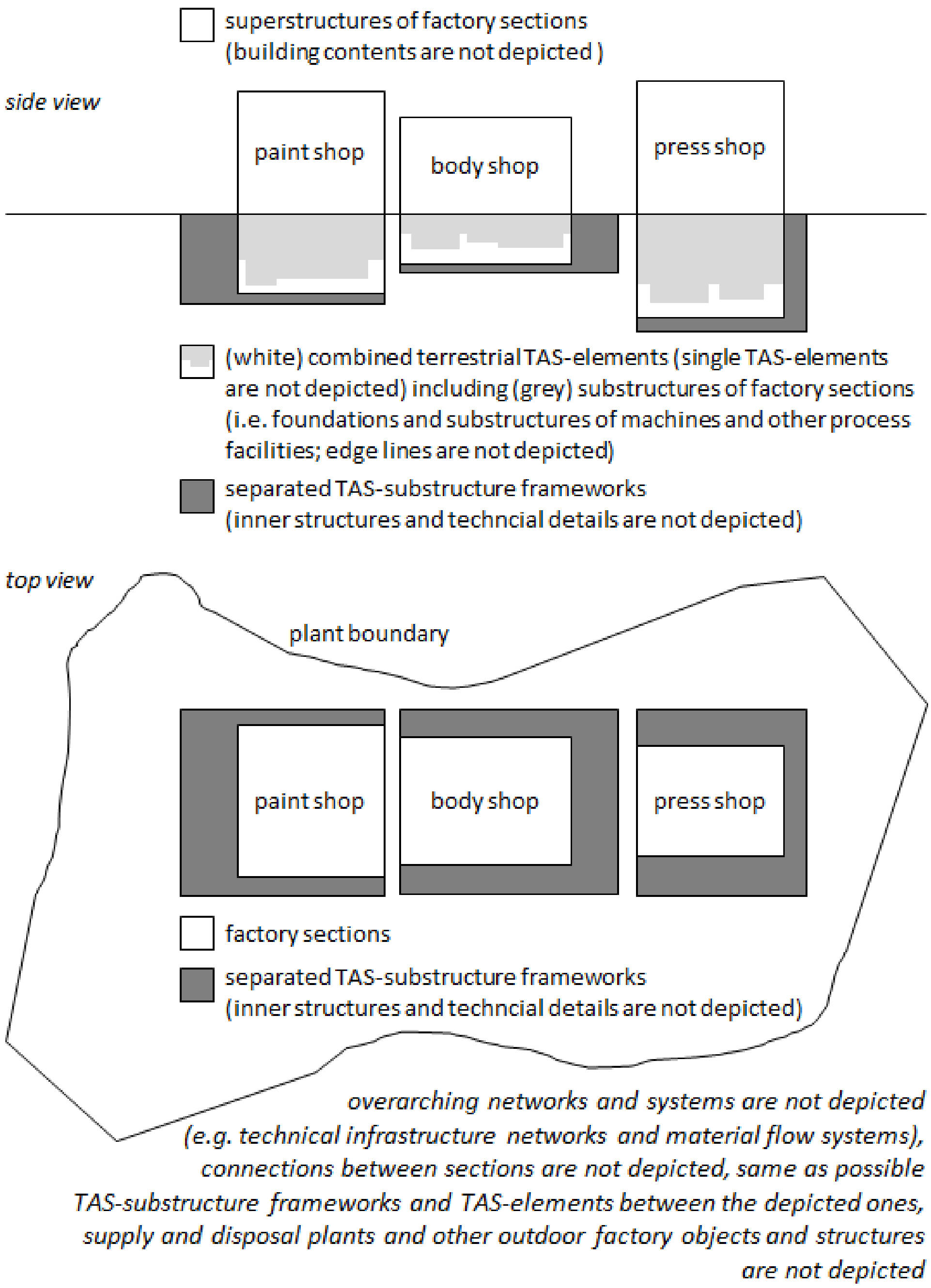


Figure 91: TFC with separated Framefields

A separation of Framefields (figure 91) requires less works and time (for the Framefield works), and leads to lower investments and lower transformability compared to a combined Framefield in which TAS-elements of different sections can be relocated as desired (figure 92).

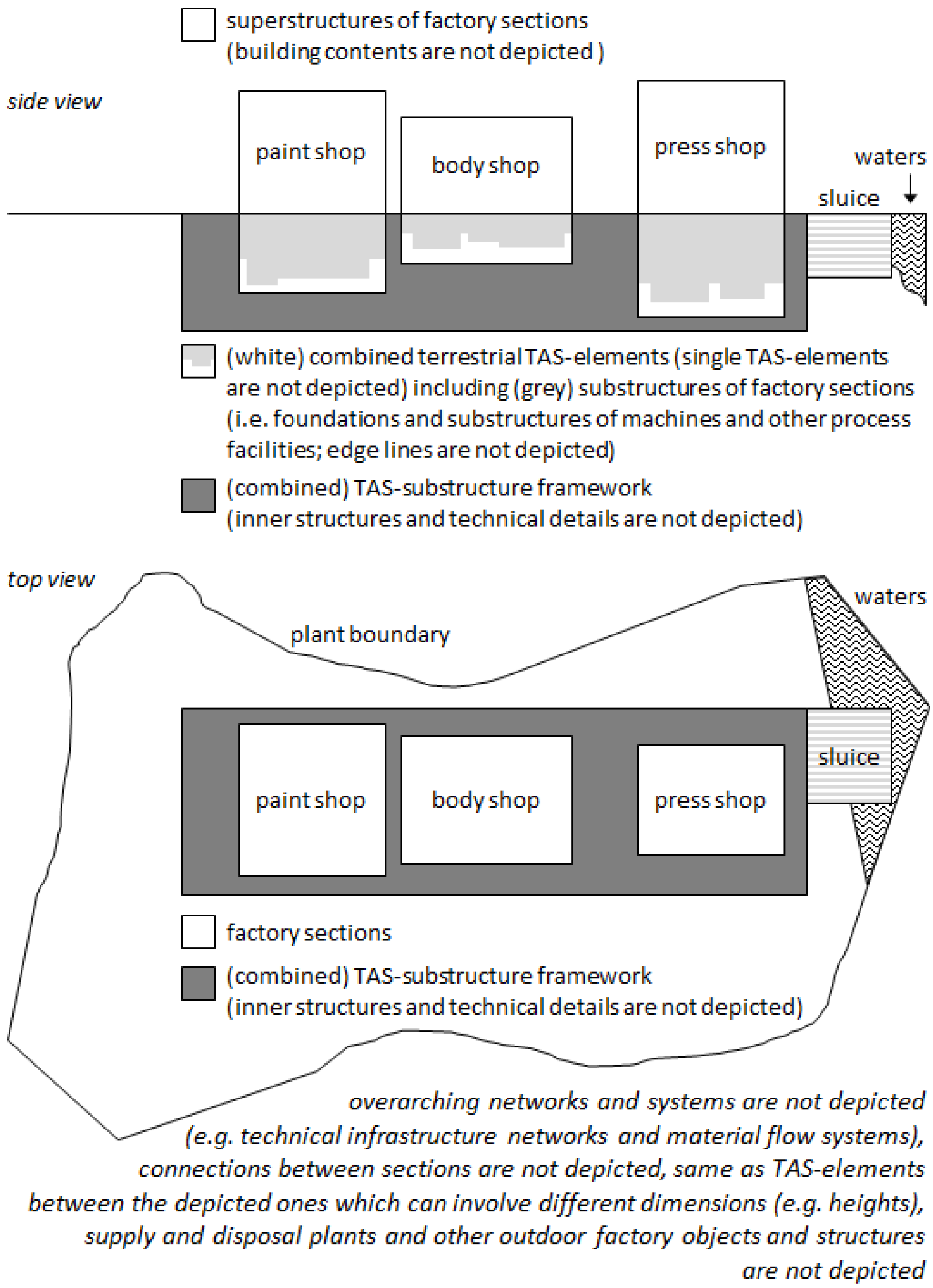


Figure 92: TFC with a combined Framefield

In addition, a connection to a body of water can be considered in order to enable a hybrid terrestrial and maritime system, which means that a hybrid can be the outcome of combinations of different terrestrial and maritime TASs and/or TFCs (and even area systems). This connection would require a sluice with a transfer system (e.g. with a lifting-function or the like) in which functional and environmental aspects must be appropriately considered – especially when TAS-hybrid-/TFC-hybrid-elements are shifted from terrestrial parts to waters and vice versa. Such TAS-hybrid-/TFC-hybrid-elements can comprise different layers of the known systems, while these layers can be exchanged during a transfer if required, e.g. base layers with tank-systems. Such a sluice can involve larger proportions than the depicted one; the same applies to the TAS-substructure framework. TAS-elements can furthermore have the same height (as in option 3 above), what is not depicted. The optional hybrid leads to a dilutive effect between terrestrial and maritime systems. It is furthermore possible to construct a terTFC beside waters (terTFC_bw) which enables the transportation and integration of objects and structures which exceed container dimensions (e.g. pre-produced and pre-tested objects and structures), with or without belonging TAS-elements (while it makes normally more sense with TAS-elements), into this terTFC (without having a hybrid-solution but conceivably another type of sluice). A connection to waters via large rails is thinkable while the brought objects and structures can be transported to the interface between waters and a terTFC via ships, other floating structures and/or maritime TASs. A sluice can also be used to shift FOs/FSs (with or without belonging TAS-elements) to their (quasi-)final location in the TAS-substructure. (Large rail system networks from a factory or shipyard which produces TAS-elements are thinkable, but rather not economic and sensible, as large rails over long distances would be required.)

For clarification, a Framefield is depicted again in figure 93.

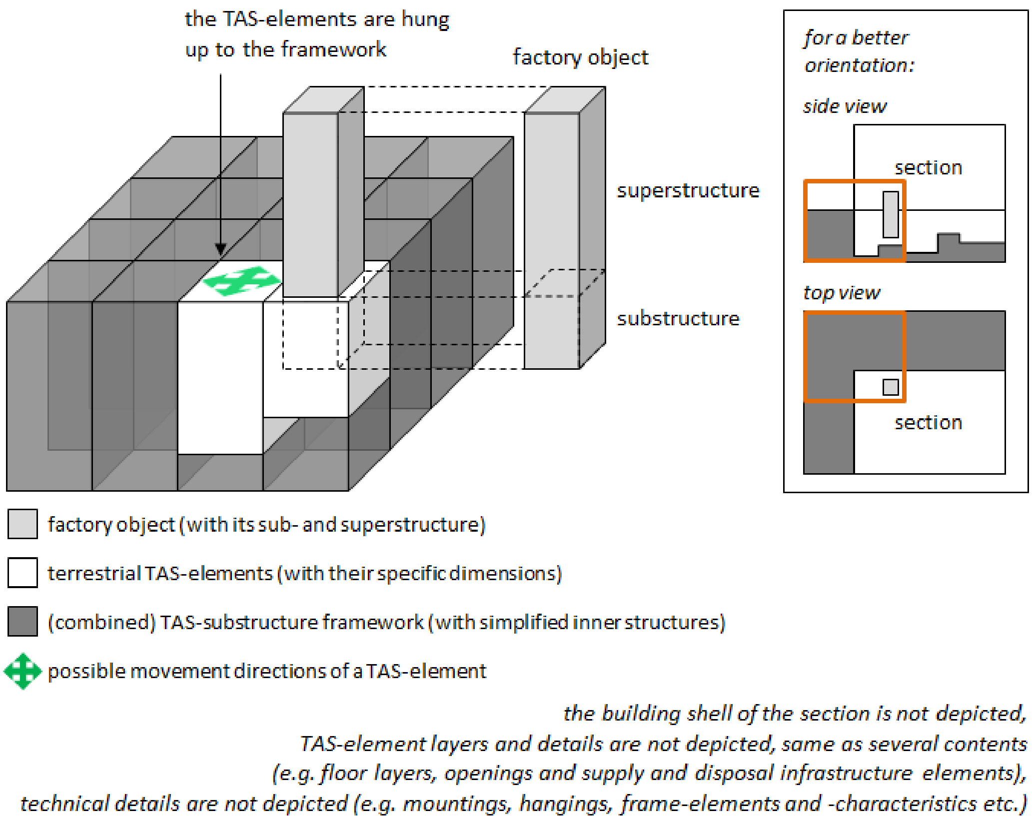


Figure 93: Framefield with different TAS-elements

To hang TAS-elements upon the TAS-substructure framework (figures 91, 92 and 93) can lead to problems such as that single framework structures must be removed or retracted (e.g. automatically) to enable movements of TAS-/TFC-elements. It is also difficult to accommodate TAS-elements with different dimensions. Moreover, MASs are restricted. Weights are a further problem.

Besides the option to hang TAS-elements upon the TAS-substructure framework, another option exists: all TAS-elements are placed on a TAS-substructure as in the case of Hydrofield and Railfield, and are additionally fortified by means of a framework(s) (figure 94), at least with framework-structures at the outer borders of the TAS-substructure. TAS-elements in this option have (approximately) the height of the framework(s). Further options and combinations are conceivable. Furthermore, all terrestrial TASs can be constructed above ground level which requires fewer excavation works and can avoid problems with groundwater and dewatering. This, of course, leads to other problems such as that connections to the external technical infrastructure can lead to difficulties.

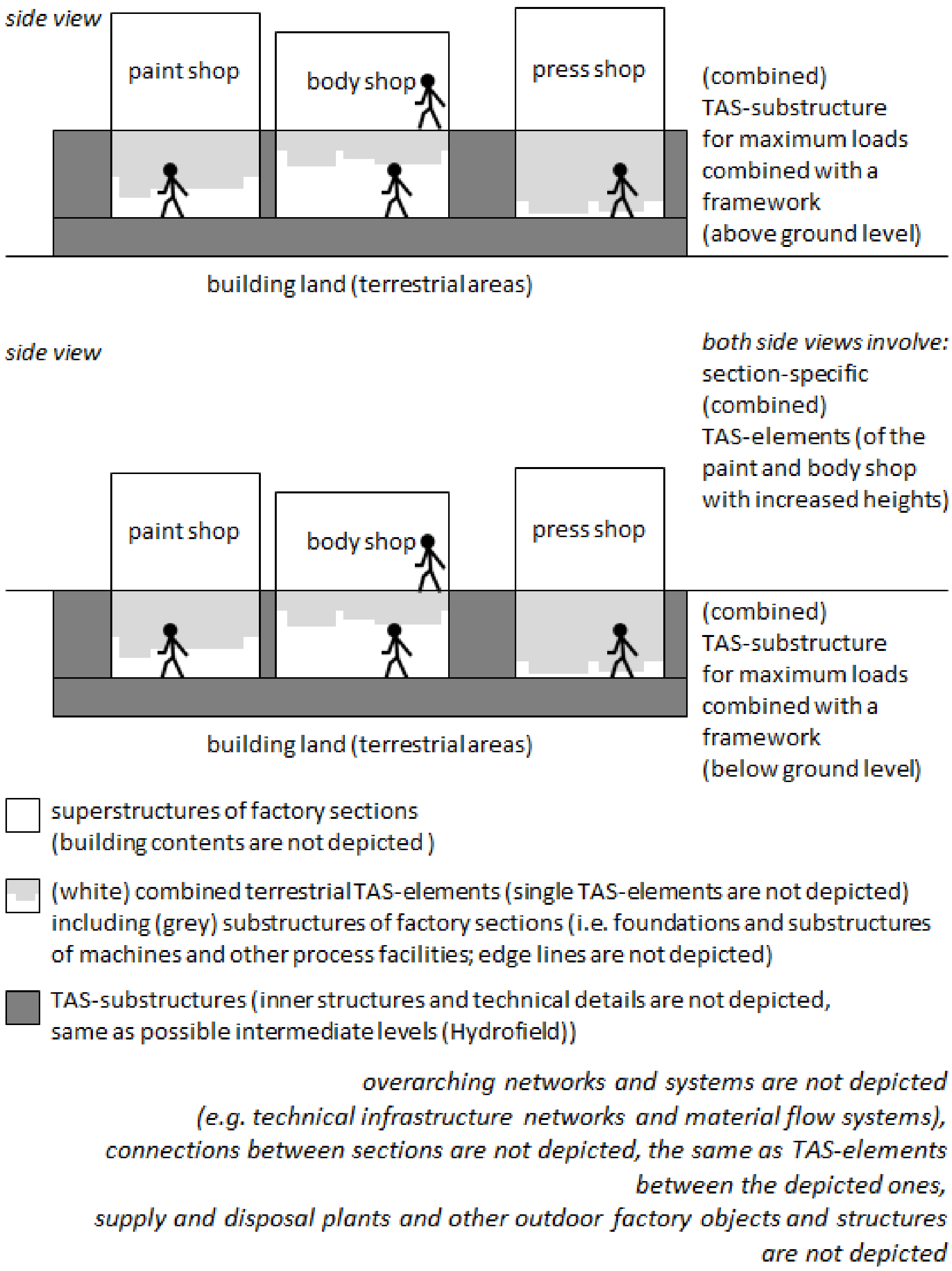


Figure 94: Combined terrestrial TAS-substructure

All combined solutions (of the different TAS design options) have in common that either (a) TAS-substructures (also frameworks) can involve required maximum dimensions and load-bearing capacities only and that the TAS-elements are specifically designed for each section (and smaller structure levels if required), or that (b) the TAS-elements also involve maximum dimensions and load-bearing capacities, which increases their universal usability, e.g. for changes of uses without moves. Finer subdivisions of TAS-elements within sections are possible, e.g. a TAS-element that serves as a walkway might involve and require smaller dimensions etc. than one that is provided as a basis for a machine. It should be considered that maxima lead in general to more work and required resources, longer timeframes and higher initial investments, but also to better transformability which leads to an increased number of possible factory configurations with the implemented or given system.

To use a combined TAS-substructure that bears maximum loads and involves maximum dimensions in combination with specifically designed TAS-elements per section can be advisable for a body shop, an assembly shop (other sections such as workshops, tool and machine shops for parts and tool manufacturing and for the production of gearboxes and engines etc.) and possibly for a paint shop. Such a combination can lead to a reasonable trade-off between costs and transformability, despite the fact that such an oversizing leads to higher initial investments etc. It is probable that it could make sense to keep a press shop (and possibly a paint shop) separated with its own TAS-substructure and combine the other sections only. It is also conceivable that it could make sense to construct sections such as a press shop (and a paint shop) the traditional way (at least against the backdrop of currently implemented solutions). In doing so, this section should be located at a corner of the concerned factory/site. It must be considered that such an option destroys at least partly the basic idea of TFCs and that higher logistics and further costs are required. Other FOs/FSs (e.g. departments and s&d plants) with their TAS-elements also require a TAS-substructure(s). This also speaks for combined solutions in which the requirements of these FOs/FSs etc. should also (to) be covered.

Maximum TAS-substructures indeed increase transformability. The better the transformability, the more configurations are possible with a system. Nevertheless, it must be considered that combined/unified or in other words, cross-sectional TAS-substructures are oversized for the other sections but the one which requires the(se) maximum/highest loads and/or dimensions, which leads also to disadvantages such as the already mentioned ones and larger space requirements. Which combination of TASs (e.g. a Railfield combined with a framework(s) or a Hydrofield combined with a framework(s) or a framework(s) in combinations with both Railfield and Hydrofield) is advisable depends on the specific case in hand. The abovementioned disadvantages of frameworks must be considered for such combinations. Thus, one needs to think twice about the question if framework-structures are sufficient at the outer borders of the TAS-substructure or if these should also be integrated within the system, e.g. to fortify the system. The use of combined terrestrial TAS-substructures – with framework-structures at the outer borders – for terTFCs and terTFCs beside waters (terTFCs_bw) is in any case recommended and defined as a prerequisite for the following subsections, sections and chapter 7. To avoid a further complexity increase of this thesis, neither the designations Framefield nor TAS-substructure framework will be used. Simply TAS-substructure(s) will be used further. Centres of gravity, moments of inertia, relations between forces, dimensions and masses, and many further aspects must be considered for the further development of TASs/TFCs. In particular, relations between forces, dimensions and masses may limit the capabilities of terTFCs. It must also be considered that larger rails (e.g. for larger TAS-elements) can lead to restrictions for smaller TAS-elements, even though substructures of TAS-elements (i.e. their bottom), advantageous rail designs (e.g. a rail design which is usable for smaller and larger TAS-elements), telescopic rails (e.g. of which parts are liftable), otherwise transformable/changeable rails and/or a change of rails can be supportive. Such restrictions are reasons why a separation e.g. of a press shop from other sections can make sense.

TASs and TFCs require further analyses and development. Not only initial investments have to be taken into account, but above all the advantages that these systems can bring (especially the maritime systems which do not require TAS-substructures). The following subsections, sections and chapter 7 involve further relevant information in this regard.

Appendix 6.3.2 Universality and Further Aspects

Changing (effective) arrangements and links of heterogeneous FOs/FSs are required to maintain efficient processes. TFCs enable a 'heterogeneity-transformability-combination'. Thus, an effective arrangement and linking of heterogeneous FOs/FSs can be enabled throughout the BFPSs. Universality is not necessarily required, even if it is rather possible and better applicable through TASs/TFCs. TASs directly enable universality (e.g. through area content integrations and inner transformations of e.g. s&d infrastructure elements) and also involve a quasi-sleeping transformability/ customisability, which can lead to further universality through transformations/ customisations of TAS-element-structures. If these transformations are fully automated and do not require a planning of human beings, one can speak about flexibility. Contrary to statements of other authors, universality does not necessarily lead to oversizing. Universality can but must not necessarily require additional areas/spaces and impact negatively on the efficiency. One machine with a tool changer/turret can be (less efficient or) more efficient than two of which each has no turret and only one tool. Furthermore, the machine with the turret can require fewer areas/spaces. Technological/technical and other changes can determine what is efficient and thus impact on required areas, e.g. area sizes and characteristics. One machine with a footprint of e.g. 50 m x 50 m (2,500 m²), which, for instance, is based on a new technology, can be more efficient than 40 machines with a footprint of 15 m x 15 m each (in sum 9,000 m²) (and vice versa). Furthermore, a large and linked machine system (i.e. a production plant) can require more areas/spaces and be less efficient than several machines which require fewer areas (and vice versa). Numerous further cases are possible. Thus, the universality and/or efficiency of FOs/FSs (co-)determine factory dimensions and other factory characteristics, as the dimensions, the (effective) arrangement and the linking of (several/all) FOs/FSs determine the required area size(s)/space(s), area shape(s) and area and substructure characteristics, and thus the efficiency of a factory (and required future transformations). (This also shows that efficiency and effectiveness cannot always be clearly delimited.) Efficiency can thus determine area requirements and other requirements, and can impact on future transformations (and on the required transformability). Universality can determine efficiency, area requirements and other requirements, and can impact on future transformations (and on the required transformability). Given objects and structures determine the given degree of universality. The inherent transformability of given objects and structures determines the additionally achievable universality through structural/ physical transformations (of the elements/structures which an object or structure consists of). This means that the given transformability can determine the future universality. The given transformability impacts in any case on future transformations.

Transformation requirements occur over time and have an impact on factories. What is defined as 'being efficient' (e.g. what an efficient machine is) changes over time. The required efficiency, universality and transformability also change over time, and must be newly defined. Effective arrangements and links of FOs/FSs change through different developments which occur over time. This leads to the abovementioned transformation requirements. The best case from a transformability perspective would be to meet any transformation requirement as well as possible (consider that one does not know what will be required, where, and when). Besides the data in the main body of text, the information in this appendix shows that a maximum transformability of factories without a decrease in efficiency must be aimed for. It is necessary to increase transformability, and this is possible with TASs/TFCs, e.g. due to the MASs.

Appendix 6.3.6 Further Data for the Development of Concepts

The interviewees were asked about their desires in the context of factories. IP3 stated that areas should not be contaminated. Furthermore, areas should be levelled and have a sufficient floor load where one can directly start the construction. IP4 argued that the area should be levelled and large without a river, mountain or tree. IP6 said that substructures should be transformable due to continuous changes. IP6 also stated that a modular and scalable infrastructure would be desirable. This interviewee added that the infrastructure should be modular and flexible, and not fixed. IP6 further stated that there are wind power plants in the [redacted] (compass direction) of [redacted] (a country) and that there are no power lines to the [redacted] (compass direction) of [redacted] (a country) where we have meanwhile, from an economic power perspective, the strongest states. This limits further growth. IP6 also talked about a growing number of product variants, and that this changes the production of an automobile plant in a certain area more and in others less. IP6 said that it is not foreseeable and not pre-plannable what will be required and where. Therefore, as further argued by IP6, a modular and flexible infrastructure is required and not a fixed one. Buildings must be standardised and interchangeable. It would be best if I could make a real area exchange, but on land – on the fixed floor – this is hardly possible. IP1 said that buildings, facilities, and infrastructures must be more transformable. Furthermore, simpler changes of use and a more flexible use of buildings are desirable. IP5 stated that it would be desirable to always have areas in the required amount, or to have a new factory. IP8 also talked about free areas as a desire, while IP6 said that extension areas for the future should also be available in the inner of a factory, as the inner factory structure is also changing. Similar statements were made by IP1 and IP7 (see the next but one paragraph).

IP6 stated that infrastructures should not only be scalable, but also movable, particularly large-scale infrastructures. IP1 made a similar statement. IP2 said that it would be desirable if several buildings could be moved and that it would be good if buildings were movable. IP6 talked about the wish to have interchangeable buildings. A shift of s&d plants is on the wishlist of IP5. IP3 said that it would be desirable that a factory always has an optimal location close to the market, and close to a motorway, railway, harbour, and airport. What the interviewees said about transformation requirements and fixed points must also be considered.

'Are there cases where it would be sensible if factory objects/structures that are larger than containers would be movable?' IP8 answered that it would be advantageous if an entire body shop could be moved. IP8 also stated that today, there is no absolute flexibility and transformability. IP7's answer led in the same direction. IP8 raised also the question how this can be enabled, to move a body shop of [redacted]00,000 m², and that this must be answered. IP7 stated that mobile areas, which can be flexibly combined, would lead to advantages.* IP8 argued that the paint shop and the body shop are fixed and that they cannot be moved. This interviewee was also asked if it would make sense if the entire general structure, ergo the layout, were mobile, relocatable and interchangeable. IP8 said yes, of course, like a “Lego”-puzzle. This would, of course, be great. IP2 said that a lot of objects are larger than containers and added that almost everything is larger than containers. This interviewee argued that if one wants to move a building, she/he also needs to move the contents of this building. IP2 expressed that this is not possible today. IP2 also said that one can extend a building. Substitution processes are required, and a dust protection/cover. Then, a building can be extended. IP2 described domino effects in this regard. IP3 said that it would be very sensible if objects that are larger than containers were movable. IP3 further stated that the mobility of factory objects is very important, but limited today. IP5 stated that it would be sensible if buildings and building contents were movable. IP6 said that the mobility of machines is important, and that it would be sensible if entire buildings were movable. This interviewee also said that such objects and structures penetrate areas. *IP7 further stated that it would be sensible if factory objects and structures that are larger than containers were movable, especially as different departments and sections change. Consequently, it would be nice if we could generate free areas in the middle (of the factory). IP7 said in this context that it would therefore be sensible to move entire buildings. IP4 stated: What is required on a small scale with production cells is also required on a large scale which means (as further stated by IP4) that it is required to move buildings and to reconfigure buildings as required. A reconfiguration or change of areas enables one to free areas, to remove inhibitors that can be moved somewhere else, and to bring afterwards the free areas together to win again a larger free area – this would be a nice to have. IP4 reinforced her/his statements as she/he also said that a shifting of areas is desirable. IP5 added that power and wastewater treatment plants should be movable. Furthermore, it would be advantageous and sensible to move objects to be able to implement other ones instead. Moreover, IP5 said in the context of a factory extension that decisions were taken and objects constructed which one would like to change afterwards, but that this is not possible. IP1 said that it would, of course, be sensible if factory objects that are larger than containers were movable, because then a completely new dimension of transformability would be achieved. Buildings could be moved. This is required as building displacements take place (IP1 made this statement in the context of a real-world case). IP1 also said that a flexible substructure would be required. This interviewee also stated that one could shift a building to the periphery and instead, put more important ones in the middle. This would be sensible from a production flow(s), control process and management process perspective, the same as from a production networking perspective. This is because the single buildings could be (re)arranged as required.

The interviewees made further relevant statements: IP1, for instance, stated that the area, the ground needs to be flexible and movable to enable area-transformability. This interviewee also stated that this would be advantageous, as one could then move and relocate single elements where they make more sense and where they are more reasonable from an economic perspective. IP1 added that (thus) shorter planning and implementation times could be achieved. This interviewee emphasised the limited transformability of the body shop. 'Static' was the word which was finally added by this interviewee. The statements of IP1 are in line with IP5, who stated that body shop units could be brought together and more easily exchanged if the area would be transformable. IP4 said that transformation durations would decrease and objects could be optimally moved if the area would be transformable. This interviewee explained that these durations would decrease, as dismantlements, demolitions and multiple moves could be avoided. IP8 said that the production structure would be independent of the production system if areas were transformable. Independently of what I want to produce, it is producible. This would be an evolutionary step compared to the current status, as today we intervene in the entire system to make a change. If areas were transformable, I would only impact parts of the system. The statement of IP7 goes in the same direction. IP7 argued that fewer transformations would be required if the area was transformable. I would only transform single elements and not the whole system or large parts of the system as today. IP2 talked about conveyor systems and argued that if a line is extended, drive and tensioning stations could be shifted if the area was transformable. To do this, it would be necessary to shift area elements back and forth, like a piece of a puzzle.

Author's Position

This research reveals the impacts of terrestrial areas and transformable area systems (TASs) on the transformability of factories and factory planning processes (FPPs). New basics with regard to today's factories and TAS-based factory concepts (TFCs) have been developed; area systems and TASs are now considered, which has not previously been the case. In addition, this work provides a picture of dynamic factory planning. Increased transformability is required in order to enable different factory requirements at relevant points in time. This can be achieved using TFCs, and in the light of long and sustainable factory lifecycles it should be especially aimed for.

TFCs are the correct approach, as today's factories face unavoidable problems. Based on the contents of this work, theories can be improved to some extent, but the fundamental problem of today's factories cannot be solved if factories are built in the traditional way upon terrestrial areas. Real-world factories can merely survive today, as all of them face the same limitations: rigid areas and substructures. This could be changed using TASs.

Areas (and substructures) must be transformable. This is relevant for factories as well as other structures, e.g. cities. **It is senseless to statically build on terrestrial areas objects and structures that follow a certain dynamic** and which must be transformed, even if it were known what will be required in future.

With TASs, the Fourth Industrial Revolution and more can be achieved. TASs can unlock numerous doors to sustainable value creation. The advantages of TASs are important not only for factories, but also for other industrial and non-industrial structures/purposes and their combinations.

This work provides relevant data for better cognition, understanding, and application, and further development of theoretical and practical solutions. The thesis results provide the groundwork and data basis for future research in this field.

It is not the case that factory planners do not find a solution, but the way to this solution does not have much to do with planning or with the initially aimed at solution – this solution is a compromise if it is achievable at all, and projects are often delayed and overrun their budget. Longer planning and timeline extensions are possible, but these increase the risk of change and of new transformation requirements.

Today, it is hardly possible for companies to think and act in a long-term manner against the backdrop of self-centredness, (short-term) profit orientation, consumer wishes, competitive pressure and the adjustments of our economic system and monetary policy which penetrate large parts of the world (please consider diverse investment possibilities and interest effects).

The characteristics and settings of the human-globe system will primarily decide whether TASs and TFCs (independently of their advantages) will be viewed only as a visionary idea or more than that, and will decide if and how these concepts will be used. The human-globe system involves substantial faults which must be eliminated. One of these faults is the fact that extensive sustainable solutions can hardly be implemented in competitive environments.

On the one hand, TASs increase sustainability. On the other hand, they cannot currently be implemented by OEMs due to increased initial investments that are required. This illustrates one dilemma of the human-globe system. Thus, a change in thinking and ultimately changes of parts of this system are required. A wider viewpoint on this is essential for future research.

Environmental conditions lead to a global pressure, but 'sustainable manufacturing' and other approaches are caught in an outdated human-globe system in which genuine long-term thinking is disabled. Even though we know that we are destroying our environment, global separation and consumerism are promoted and pursued – and there is hardly any escape from environmental destruction without global consensus and unity. It does not suffice to put pressure on enterprises to become sustainable. The egotism of regions, states, countries and world powers must be eliminated; otherwise, there can be no real change and no total benefit. As this is not the focus of this work, only a few words on this are given. Nevertheless, this topic requires serious consideration and is the most important aspect for future research, as it is clear that the human-globe system requires substantial change.

The human-globe system is currently dominated by short-term thinking, self-centredness, profit-orientation, environmental destruction and other actions that work against our own species, and should be characterised instead by long-term thinking, sustainability and value addition for our species. We act against our own life and survival (consider the long-term consequences of our actions, which are partly unknown).

Escape from this system is most likely accompanied by personal disadvantage.

Given the current situation, environmental destruction will progress even further.

Our species is highly endangered.

Environmental conditions will force us to change our thinking and ways of acting. Rather than dealing with symptoms, causes must be identified and eliminated, and we must work on them **together**. We must **identify and eliminate the roots of the problems**, which are in the human-globe system; otherwise, these man-made problems will destroy mankind.

Large parts of the human-globe system require a rethink.

The Fourth Industrial Revolution can be achieved, but we must make a **Global Evolutionary Step** without short-term thinking, self-centredness and greed for profit, and without a global separation that leads to wars, environmental destruction etc. A change of the human-globe system for the better of flora, fauna, and mankind requires global consensus and unity. Thinking in terms of profit and ill-considered growth is outdated, and is not an appropriate fit for the current era and for the challenges that are faced by mankind.

We should not only write and talk about change, but should also perform change.

The author is not against the human-globe system, but is against its mistakes and some of the related symptoms, **which go beyond all conceivable limits of reason and logic**; the author is deeply committed to the survival of our species.

The main aim of a species is life and survival, and further development. As a species, we have never failed more than in the last 105 years – there is no global consensus and unity. There is only one world, but currently we are driving into a dead end, as our species can hardly adapt itself to the forthcoming conditions as fast as it should and as fast as most probably will be required in the future.

This research has led to the identification of several system faults, and the research can help to improve these faults, at least to some extent. Technology can help, but we cannot breathe, eat and drink crude oil, plastic and metal.

TASs and TFCs must not be misused in a way that supports, advances and boosts consumerism and our throwaway society. With the use of TASs, this misuse is possible and negative developments can be accelerated – even though factories might be more sustainable and green. We must at least to some extent return to our roots, and use TASs for good.

With our accomplishments we can enable a good life for everyone, so we should stop acting like cavemen with weapons of mass destruction, who live in a system in which questionable non-value adding actions which act against our own species are rewarded. The human-globe system requires a holistic change, but this is possibly only a dream when one observes the totality of what is currently happening in the world. There is not more that can be said if, despite all the achievements of our civilisation, we are still faced with the primitive actions and stupidity of mankind.

"A time will come in which intelligent people will remain silent, idiots will speak and people who live their lives based on the expense and work of others will become rich ... If people knew how little intelligence is ruling the world, they would die of fear."

Ivo Andrić