Digital Applications in Archaeology and Cultural Heritage 30 (2023) e00277

Contents lists available at ScienceDirect

Digital Applications in Archaeology and Cultural Heritage

journal homepage: www.elsevier.com/locate/daach

Morphological analysis of historical landscapes based on cultural DNA approach

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ARTICLE INFO

Keywords:
Historic Persian garden
Cultural DNA (CD)
Pattern language
Visual computing
Space syntax
Unmanned aerial vehicles (UAVs)

ABSTRACT

Recent trends in landscape architecture investigate new approaches, methods, and technologies to understand, monitor, manage, continuity, and sustainably develop heritage landscapes. Cultural DNA (CD) represents designs' transferable geometric, behavioural and functional properties. The morphological structure of Persian historical gardens possesses discoverable hidden patterns, computable through the CD's mathematical and computational models. This study aims to investigate and discover effective parameters in the spatial structure of historical Persian gardens using Space Syntax. Six Persian Gardens were surveyed, and spatial structures were analysed using DepthMap10 software. The results show that these spaces follow meaningful mathematical patterns and rules that can be formulated in the context of generative processes and generalized for the evolutionary continuity of gardens. However, further research is proposed to develop more advanced computational methods, such as artificial intelligence (AI) algorithms and AI-based decision support tools, to help to generate design scenarios and to transmit culture through the design process.

1. Introduction

1.1. Transferring tacit knowledge of heritage landscapes: a goal and several approaches

It is a significant issue to understand the fundamental nature-society interactions in historical landscapes, why and how these interactions have changed over time, and how they may be affected in the future. Examining the past in determining future paths in cultural heritage studies, as one of the main elements of sustainable development, does not only mean the preservation of the physical remains of the past but also the significant issue of a life lived within the transition between the past and the future (Auclair and Fairclough, 2015). This issue goes beyond preserving the remaining features or protecting the landscape; indeed, this process shapes the future character of the landscape. To survive, the historical landscape must be used, altered, redesigned, improved, and managed to manage change and create new landscapes (Fairclough, 2019). The landscape of the historical Persian Gardens includes the deep connection between man and nature over time. Exploring knowledge of these landscapes' evolutionary design approaches, change management, and sustainable development led to a two-way investigation of design and planning theories and the relationship between man and nature. In a non-linear-adaptive process, historical landscapes obtain semantic-physical identities and evolve following the culture, environmental conditions, and time while transferring implicit knowledge (Min and Lee, 2019).

Knowing the cyclical process of converting implicit knowledge into explicit and vice versa is a holistic and non-linear viewpoint of history and historical places and knowing the structural components of these places. The reflection of landscape changes in non-linear historical developments in the form of a cross of the past, present, and perception of the future to improve our understanding of today's identity of a historical landscape and how they continue, has been proposed in the recent research trends of landscape architecture (Brink et al., 2016; Kolen and Renes, 2015; Rezaei Ghale and Pirbabaei, 2020). Future changes in the design and development of the heritage landscape should be considered concerning what happened in the past and the physical effects that will remain in future actions. There is a need to study this

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https://doi.org/10.1016/j.daach.2023.e00277
Received 8 November 2022; Received in revised form 27 May 2023; Accepted 31 May 2023
Available online 15 June 2023

issue from different viewpoints regarding the heritage landscape, especially in historical Persian gardens.

In the past, several approaches have been used in conserving and developing heritage landscapes. The landscape biography approach, as a strategy in heritage management (Roymans et al., 2009), landscape design, and spatial planning, with an analytical, exploratory, and phenomenological approach, analyses landscape changes in the history of a place, especially in the future, awareness of long-term landscape changes, and regional heritage (Brink et al., 2016; Kolen and Renes, 2015). In the landscape archaeology approach (Żemła-Siesicka, 2022), the manufactured landscape is perceived as a sequence of transformations that have been experienced and processed in the past and are constantly changing.

Researchers in this field used the landscape archaeological approach to understand landscapes as reflections of past societies (David and Thomas, 2008), documenting landscapes and using quantitative methods for predictive modeling of landscape changes (Verhagen, 2012). As a result, by expanding the history of landscapes over time and continuing to process their spatial structural units, the past is always present in today's landscape, and they non-linearly shape the process of landscape formation today. Another approach is the ecological wisdom, which considers cultural heritages and indigenous architectures as individual artefacts or collective knowledge that have been achieved over time through transformations and internalization (Min and Lee, 2019), and it can be revealed and used in today's landscape design. This collective knowledge is evidence-based, time-honored, and expresses the ecological wisdom of the space.

Nowadays, regenerative design researchers (Mang and Reed, 2012) believe that the dissemination of knowledge and learning from past experiences, the effective use of existing knowledge, and the creation of new information at different scales can help to strengthen the co-evolution of humans and natural ecosystems (Roös, 2021). While nature adapts to survive, built environments, including historical landscapes, must be consciously transformed based on the collective knowledge embedded in the spatial layers of their constituents. Native and traditional cultures in flourishing civilizations have developed a method to incorporate environmental awareness into their Cultural DNA and pass this knowledge on to the next generation while observing their ecological boundaries (Hopkins, 2009). The research trends mentioned above share a common approach to managing heritage in the present, preserving and continuing the values of existing landscapes in future scenarios, and transforming historical landscapes from vulnerable landscapes to living and flexible social landscapes. Recently, the "Cultural DNA (CD)" approach is a method that combines several strategies and solutions to provide a holistic approach to achieving this common goal.

1.2. Transferring knowledge in the context of CD: definitions and background research

CD, as a comprehensive digital approach, seeks to make knowledge for transferring cultural concepts and their evolutionary continuity using different tools. CD researchers seek to discover ecological wisdom in existing designs, reversing the degeneration process and co-evolution of cultural-ecological systems by focusing on shape grammar, analysing patterns, and introducing CD discovery tools in the fields of morphology (IBD, 2015). They attempted to study cultural phenomena using well-known scientific and rule-based methodologies in cultural phenomena (Lee, 2016, 2020). These efforts resulted in the computational design of behavioural patterns and a socio-cultural analogy to DNA and architectural components (Lee, 2016). Artificial languages made by humans, such as musical and written ideas, carry cultural information that evolves by receiving and transmitting this information by humans, and culture also evolves (Distin, 2010). These languages comprise elements and basic structural units that create an integrated system. Different heritage landscapes that express cultural information in human habitats (Chan et al., 2016) are composed of units or elements as an artificial language (Sari et al., 2020). The concept of DNA in "cultural DNA" can correspond to these units or structural elements (Min and Lee, 2017). The dynamics of relationships between these structural units in heritage landscapes over time have led to spatial-cultural transformations, architectural styles, and pattern languages. These landscapes, which result from human interventions in nature based on ecological wisdom, have been developed over the years through trial and error and experience and feedback.

The computational approach of the CD tries to understand the overall units or components of these architectures, discover the existing cultures and knowledge in the forms, and predict the functional pattern of the structures and how they will continue in the future. Indeed, CD means both a tool for representing culture and a mechanism for transmitting culture from one generation to another (human design), where culture in its broadest sense includes a spectrum from implicit social knowledge to explicit technical knowledge (Gero, 2018). Based on the Onion model, CD researchers analyse culture into four interrelated layers: Objects, Behaviours, Rite/Ritual, and Value. This model's cultural layers and elements carry genetic information and express CDs (Min and Lee, 2017). The CD of an artefact, such as an architectural product, is defined as a combination of environment, owner, master/designer, and craftsman and the interaction between these parameters (Hopkins, 2009). Thus, design as a product of this combination includes value systems consisting of a heterogeneous set of cultural components and layers in its structure, and these value systems form the basis of culture (Gero, 2018). The design seems to be the most evident place to find cultural layers and DNAs because it is a design that a user mostly experiences. The study of CD in designs assumes that the CD locates in the transferable representations of the designs; that is, the representations express the CD (Gero, 2018). These representations include geometry (shape grammar), topology, increasing properties of matter, and behavioural and functional characteristics (grammar of space), creating CD together. In representations, implicit knowledge in the space is discovered and turned into explicit knowledge. Over time, using explicit knowledge in the process design of evolutionary development of heritage landscapes will turn into tacit knowledge again. In this way, in the cyclical process of converting tacit knowledge into explicit and vice versa, CD creates an identity landscape that reflects the past and looks to the future (Gu et al., 2017). The CD uses different approaches and tools to understand the implicit knowledge in space, including Space Syntax methodology tools, systems code, artificial intelligence algorithms, deep neural networks, and machine learning approaches. This computational approach generally focuses on the arrangement of spaces and facilities and patterns of movement through spatial configuration rather than morphology (Atakara and Allahmoradi, 2021; Oliveira et al., 2018; Xiao, 2017).

Topological criteria are highly correlated with the logic and social activities of space (Xia et al., 2019); human activities and public organizations at different scales are also affected by Shapes and relations are topological relations of space (Li et al., 2023). This two-way communication, which forms an essential part of the tacit-objective knowledge of space and the CD of space, can be addressed and analysed in the framework of Space Syntax approach modelings. Extracted the rules in the spatial structure of Traditional Chinese Private Gardens using graph theory, Mathematical Measurement, and Parametric Design and presented new patterns with parametric tools. Such methods have been applied in Malay Houses (Seo, 2017), Mongolian Gardens (Economou and Grasl, 2017), and Frank Lloyd Wright's Prairie houses (Gero, 2018). Specifically, structural units are extracted from existing species then new species are predicted based on transferred DNA that has been made. Also, the book "A New Perspective of Cultural DNA" (Lee, 2020) explains the fundamental theories and methodology underlying CD research with a computational approach.

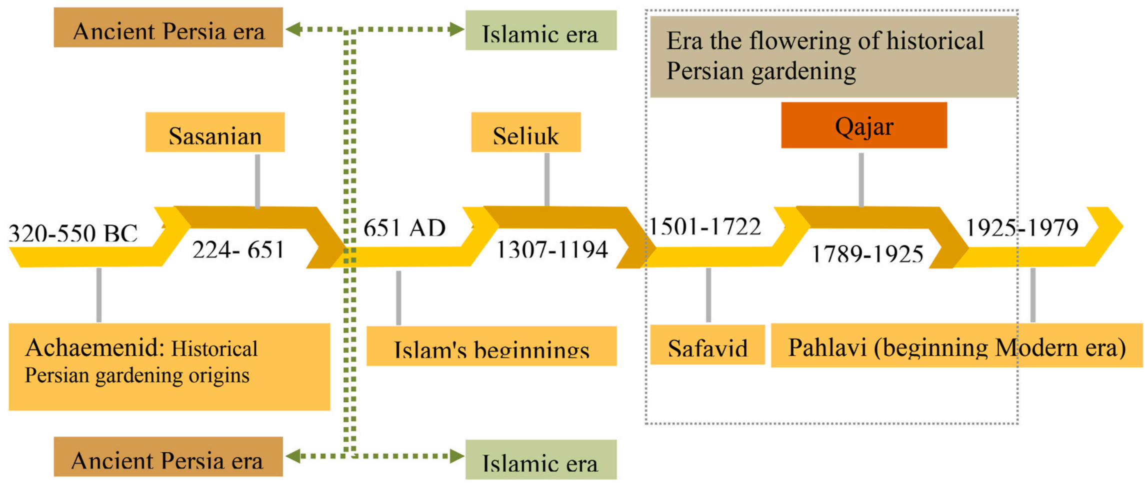


Fig. 1. Iran's most important gardening period.

2. Studying CD in the historic Persian Garden

The Persian Garden is a unique, multi-layered network consisting of living systems within a geographical area, which is a product of the complex interaction of time, ecology, and culture and is a clear example of regenerative flows (Habibi, 2021). The Achaemenid period originated gardening and the formation of spatial structure principles in historical Persian Gardens. These heritage landscapes' structural-spatial and philosophical evolution continued during the Sassanid period. From the beginning of Islam in Iran to the Safavid period, gardening did not cease but descended its prosperity. Iranian gardening literature refers to this period as the silent era. As the last link in the development of historical Persian cities, gardening has always been influenced by important factors such as economy, religion, politics, and cultural developments; therefore flourished again during the Safavid period, based on the previous principles. We are witnessing the peak of evolution and transformation in the gardens' spatial structure in the Qajar period. As a result, these heritage landscapes have been developed over centuries based on collective ecological wisdom until the Qajar period in Iran (Fig. 1), but this flow has stopped in modernization.

In this research, we seek to know the tacit knowledge in space and the possibility of transferring and generalizing it to the contemporary and future eras. Due to its evolutionary process and development during different historical periods, the interwoven structured layers and systems in the design of the Persian Gardens are an accumulation of information and CDs. This type of heritage landscape has maintained its presence among Iranians over time due to its connection with beliefs (Value), the inherent characteristics of Iranians (Rite/Ritual), and the ability to adapt to environmental conditions as an archetype until the contemporary period (Rostami et al., 2016). The pattern of the Persian Gardens in different parts of Iran, regardless of the climate, has common qualitative and physical characteristics (objects) that have manifested above all in the spatial configuration system of this type of architecture. "Concepts," "Values," "Semantics," and "Beliefs" in these landscapes have achieved physical manifestations over time by passing through multiple cultural layers (Mohammadi and Valibeig, 2018). The mentioned components create a cryptographic system using signs over time. In other words, the physical forms (tangible CD) of the code system in the Iranian landscape, which are related to or form the semantic quality of the landscape (intangible CD), are affected by different layers of culture over time (CD) and in the form of Physical elements appear. The form in product architecture is a complex set of layers and generators. Semantic, as one of the main generative factors of design, can be considered a link that keeps all considerations and layers coordinated and coherent; Similar to the role of DNA, semantics act as the hidden molecule that carries the instructions that design needs to emerge and evolve (Eilouti, 2018).

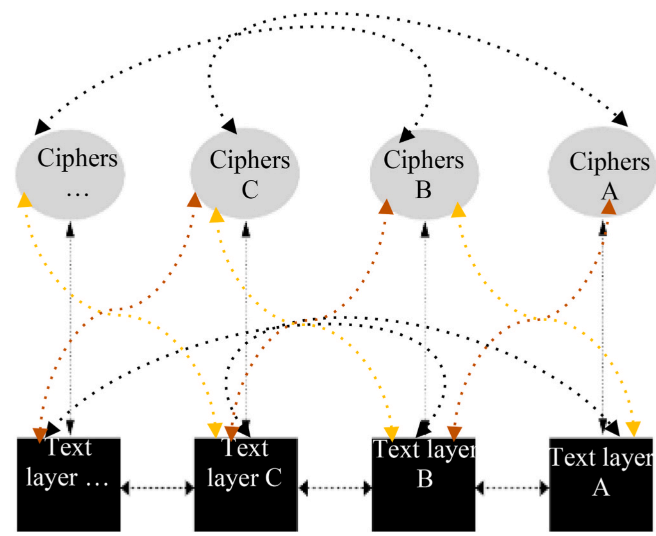


Fig. 2. Conceptual model of interweaving textual layers forming the CD of heritage landscapes based on the layered semiotics approach.

Architecture has always had a sacred meaning to all traditional civilisations through millennia, which means man has tried to provide for himself a manifestation of the heavens. Using Sacred Geometry, Persians measured the proportions of heaven and reflected them in the dimensions of gardens and buildings on the earth; indeed, Architecture was a symbolic language by which Archetypal Ideas could be expressed in patterns which were conceivable by human understanding (Hejazi, 2005). Therefore, the conceptualization of the Persian Garden's symbolism in the theoretical context of layered semiotics is made possible by the identity of the symbolism that constitutes layers of its CD Conceptual model.

New studies of semiotics (Hébert, 2019) linking meaning pay attention to cyphers. Based on these investigations, cyphers create a framework where the signs gain meaning; indeed, cyphers turn signs into meaningful systems. This research emphasizes how to put cyphers together, the concepts of cyphers, the method of transferring meaning, and the context in which the meaning of each cypher is determined (Deely, 2005). In the layered semiotics approach, the text is not the result of companionship between cyphers but between layers (Sojodi, 2008).

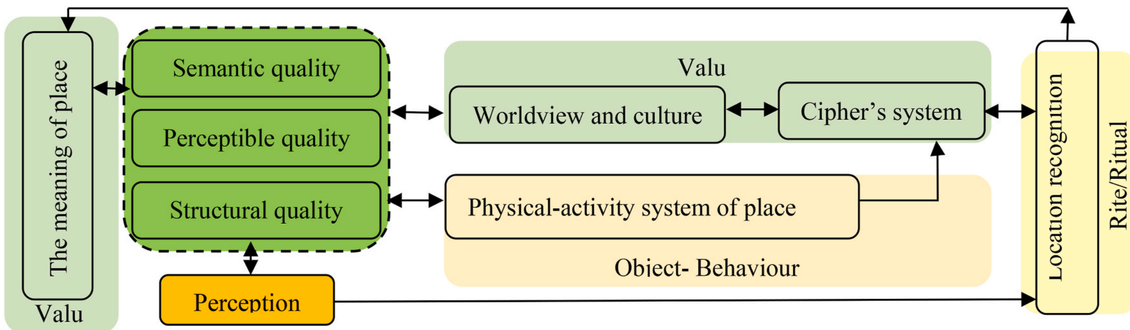


Fig. 3. The conceptual model of the continuity of the meaning of place based on the CD layers-layered semiotics.

Each has been objectively realized based on the choice of those cyphers in the communicative act (Fig. 2) and creates a system. Therefore, every place as a text contains unique communication layers; the action of these layers together gives a special meaning to the place. Norberg-Schulz believes that the relationship between meaning and place necessarily emerges in a specific place, and this emergence determines the character of the place. Whether these characters are in natural or artificial places, they are defined by physical processes and are

Fig. 4. Persian Gardens analysed in this study, (a): Shazdeh Garden- Mahan, (b): Fin Garden – Kashan, (c): Delgosha Garden – Shiraz, (d): Dolat-Abad Garden – Yazd, (e): Chehlseton Garden – Isfahan, (f): Eram Garden – Shiraz. These images were taken by the first author using the Phantom 4 Pro 2 drone.

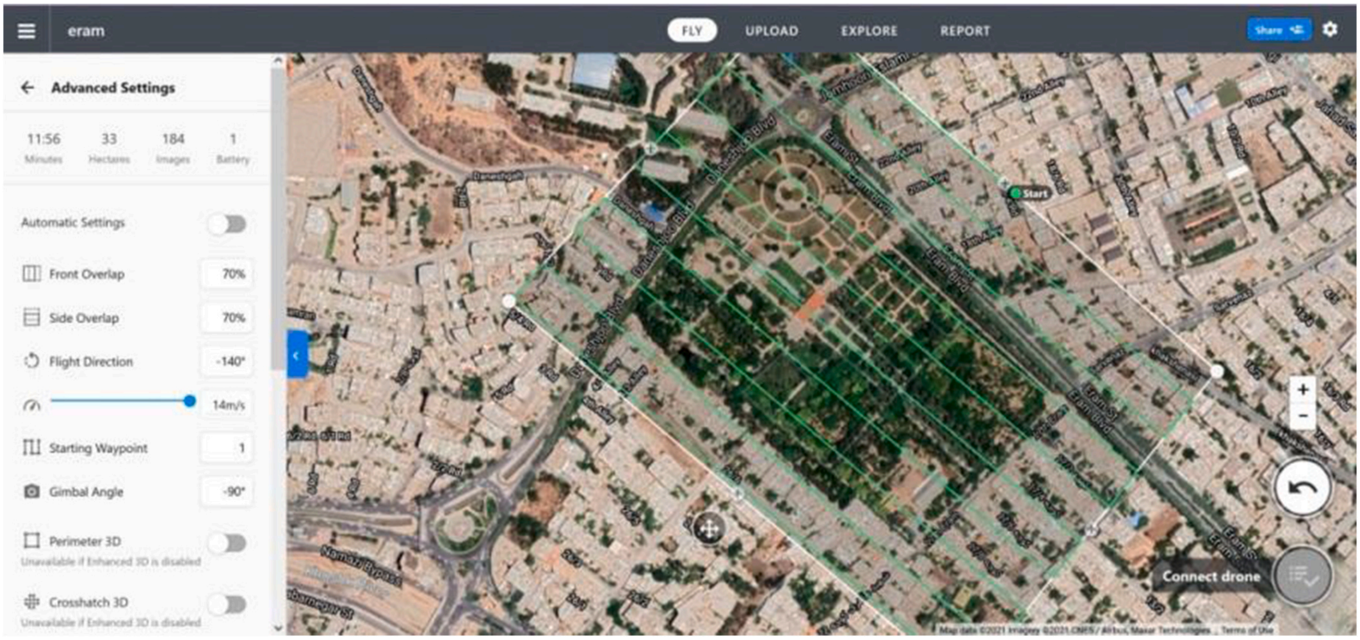


Fig. 5. UAV flight trajectory at the height of 120 m, taking an Orthophoto, Eram Garden.

expressed using qualitative concepts such as structural composition, direction, texture, colour, etc. He states that "the personality of the environment is the spirit of the place" (Norberg-Schulz, 2000). The investigated layer in layered semiotics is the layers that carry CDs in human environments and symbolic heritage landscapes.

The landscape of the Persian Garden as a text and a specific place has physical qualities and quantities, each of which can be considered a layer. These layers include signs and cryptographic systems and interact with others to create new cryptographic systems. In addition, these layers can include the soil, water, and plant layers and create structural, tangible, and meaningful qualities to enhance the meaning of the place and, as a result, the spirit of the place. Based on the layered semiotics approach, the relationship and correspondence between quantity and quality in the form of a cypher's system lead to the specific meaning of the place and, as a result, the formation of identity, sense of place, and semantics of place. It also leads to an important correspondence between quantity and quality resulting from beliefs and worldviews expressed in behaviour and form under the influence of culture. Therefore, a place's meaning continuity occurs when its quality recognizes connecting its nature. As a result, the three important indicators of "perceptible quality of place," "semantic quality of place," and "structural quality of place" are the three critical indicators of the continuity of the meaning of the scenery of the place and its historical continuity, which obtain from the companionship of the communication activities of CD layers (Fig. 3).

3. Research aims

The difference in the weight of the parameters constructing the CD layers makes the communication power of these layers different in different types of a landscape; therefore, heritage-historical landscapes need specific analytical models. The historical Persian gardens are a special kind of heritage landscape known with regular geometric structures worldwide, whose CD layers have evolved over centuries and created a symbolic landscape. These landscapes seem to have hidden patterns following specific computing systems, and their implicit knowledge is discoverable, generalizable, and transferable to the next generations. This research aims to analyse the morphology of examples of historical Persian gardens using computational tools to identify hidden patterns in space. We perform these analyses based on a conceptual model derived from the CD approach and layered semiotics. This model is useable in examining heritage works with similar thoughts and structures.

4. Material and methods

4.1. Research area

As mentioned above, the beginning of gardening in Iran dates back to the Achaemenid period, but the height of its construction is related to the Safavid (1501-1722) and Qajar periods (1789-1925) (Etezadi, 2014). There are various types of Persian Gardens (see (Abbas et al., 2016; Langgut et al., 2013; Wilber, 1994), and in this study, we looked at examples of palace gardens (Fig. 4) of these two historical periods. We selected these six gardens from two historical periods because historical Persian Gardens' theoretical and design principles and meaning reached their pick of evolution in Safavid gardens and continued in the Qajar with creative structural developments.

4.2. Methods

4.2.1. Data collection using drone and data processing

To achieve the research aims, we needed detailed maps of the gardens. Thus, data was gathered using an Unmanned Aerial Vehicle (UAV), a Phantom 4 pro v2 drone with an internal camera that had a 1-inch, 20-megapixel CMOS sensor, an 8-mm FOV 84-degree lens, and Shamim's RTK-GPS system (a GNSS network created by the Organization of Registration of Real Estate and Documents of Iran), which was used to survey ground control points with a maximum position error of 1 cm. The process was broken down into the following three steps:

1. Long-range flight to provide the map and qualitative information from the immediate area:

i.e., in the long-range flight for mapping, the flight height of 120 m, overlapping images of 70%, camera angle of 90°, and a surveying accuracy of 2–5 cm are, which can provide reliable two-dimensional information (Fig. 5).

2- Short-range flight for 3D modelling background: Flying in a regular and perpendicular grid with a pre-designed mesh makes it possible to obtain suitable images for building a 3D model. This flight includes the following three stages:

2-1- Flying in the context of a Perpendicular checkerboard grid at the

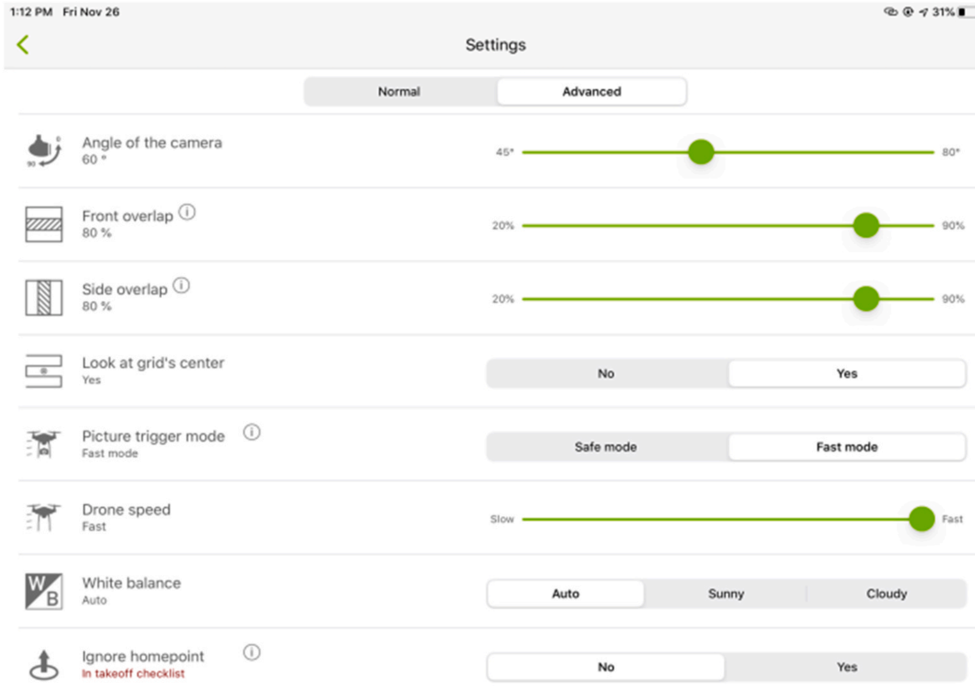


Fig. 6. details of the UAV flight at the height of 60–80 m without focusing on the central point, Eram Garden.

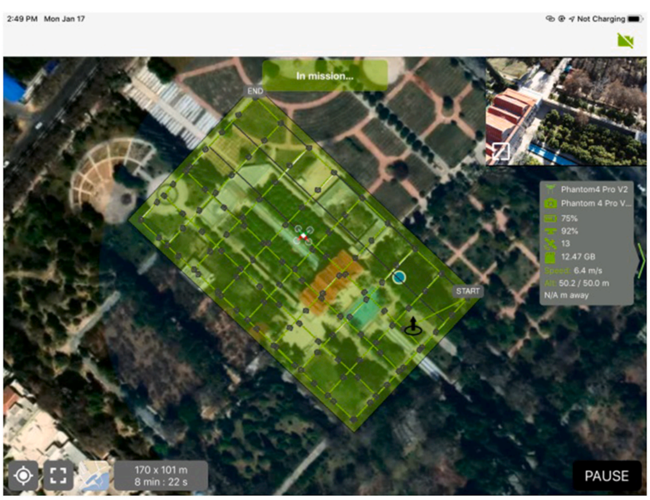


Fig. 7. 3D flight in an array, focusing the cameras towards the central point, Eram Garden.

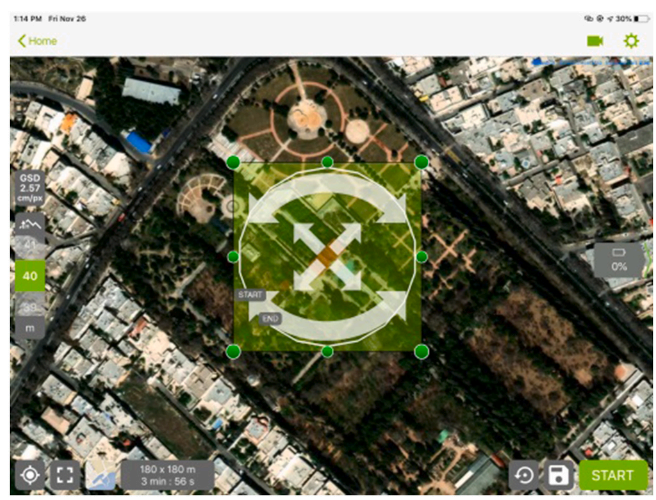


Fig. 8. Circular flights in the centre of Eram Garden.

height of 80 to −60 m (according to the height of trees and surrounding buildings), an overlap of 80%, camera angle of 90° without focusing the UAV on the central point (the points selected in different parts of the garden and flighting around them) (Fig. 6).

2-2- Flying in a perpendicular checkerboard grid, at the height of 50–70 m (according to the height of the tree crowns), the overlap of 80%, camera angle of 60°, and focus of the UAV on the central point (Fig. 7). The purpose of this flight is to survey structures and elements at a height lower than the trees' crown.

2-3- UAV flying in a circle according to the area of the garden at the lowest possible height of the tree's crown and surrounding architectural structures with an overlap of 75% and a camera angle of 60°. This method used circular flights in the corners and the centre of the garden (Figs. 8 and 9) (at two different heights) for data collection.

3- 3D linear and circular flight on the sides of the garden: The use of Hammer software in the 3D surveying method of gardens has provided the possibility of flying linearly at three different heights to know the walls and the skyline. This method increases the accuracy of data collection to obtain the vital elements and their arrangement in the historical Persian Gardens to build 3D models. The bird's flight was done by focusing on the walls and considering the trees' height and the garden wall at two heights of 15 and 25 m with a camera angle of 50° and a height of 40 m with a camera angle of 75°. In this method, the image overlap is 75% (Figs. 10–13).

In a multi-step process, the processing of images captured from UAV as raw data was done using Agisoft Metashape 1.8.4, a powerful photogrammetry software. In the first step, the images were imported into the software; Then, in an automatic process, the images were aligned. The matching process and overlapping images are done based on key points, and its output is a 3D space point cloud (Fig. 14a) with relative location and without scale. The images captured by the UAV and

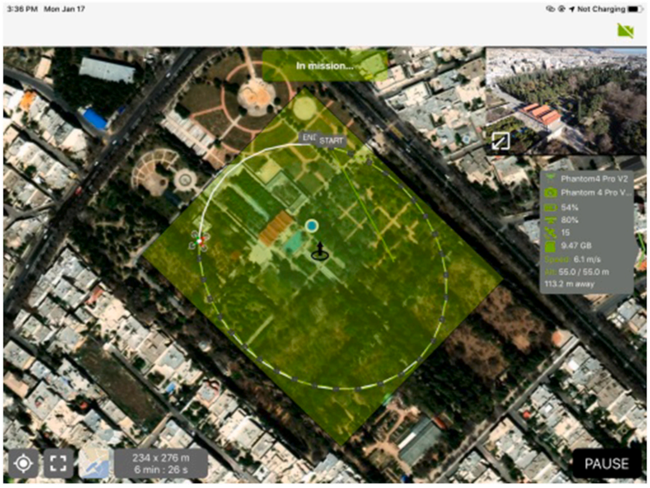


Fig. 9. Circular flights in the centre of Eram Garden with focus on central point (palace).

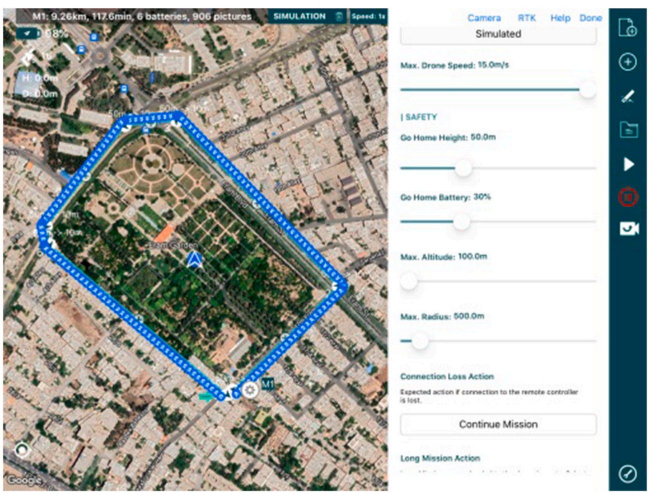


Fig. 10. 3D linear flight on the sides of the Eram Garden in heights of 15 m.

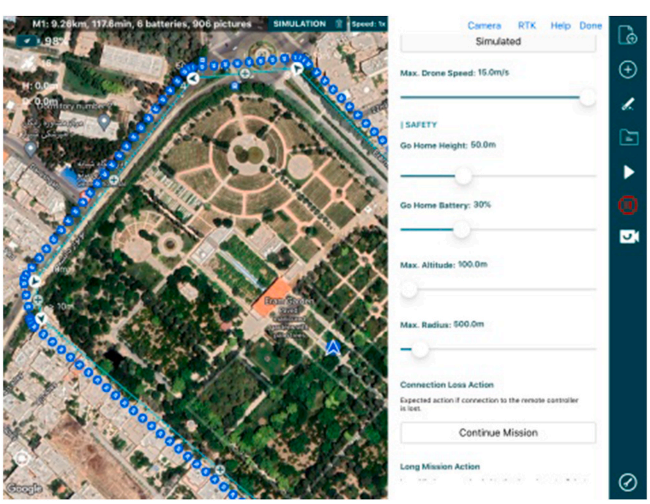


Fig. 11. 3D linear flight on the sides of the Eram Garden in heights of 25 m with a camera angle of 50°..

Fig. 12. 3D circular flight on the sides of the Eram Garden in height of 40 m with a camera angle of 75°..

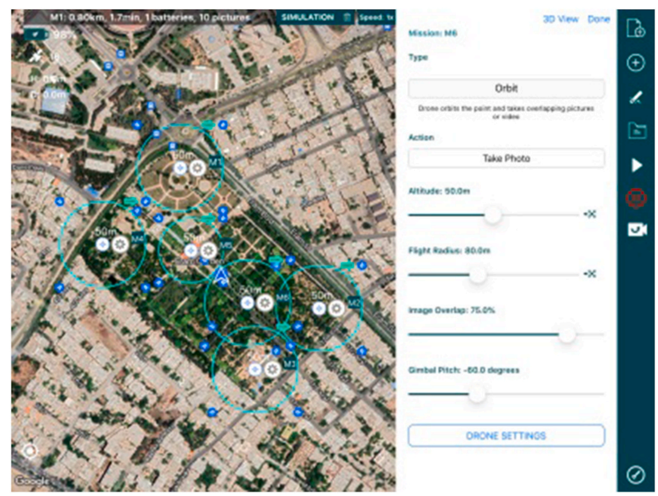


Fig. 13. 3D circular flight on the sides of the Eram Garden in height of 40, flight details.

ground control points (GCPs) are in separate coordinate systems. The UAV records GPS data for each photo in a coordinate system. For each historical Persian Garden, we measured at least 3 GCPs with GPS-RTK (Global Positioning System-Real-Time Kinematic) to create an accurate and correct 3D model from them. During the processing after creating the dense point cloud (Fig. 14b), for rectifying the entire model, correctly geolocating, and higher relative accuracy, the known coordinates of these GCPs (Tal and Altschuld, 2021) were added to the dataset. In the next step, after the construction of a 3D dense point cloud, Digital Elevation Model (DEM) (Fig. 14c) and Orthophoto (Fig. 14d) have been produced. These steps were done for 6 Persian Gardens, and then a detailed plan for each garden was drawn based on Orthophoto and DEM.

4.2.2. Data analysis using Space Syntax

In line with the continuity of identities and the transmission of culture, the CD approach uses different computational design approaches and tools to quantify built environments; Space Syntax and shape grammar have systematized this approach (Seo, 2017). Many types of research conducted in the context of computational design use Space Syntax or shape grammars for morphological analysis and CD decoding in archaeological artefacts (Mamoli, 2021) and architecture (Eilouti and

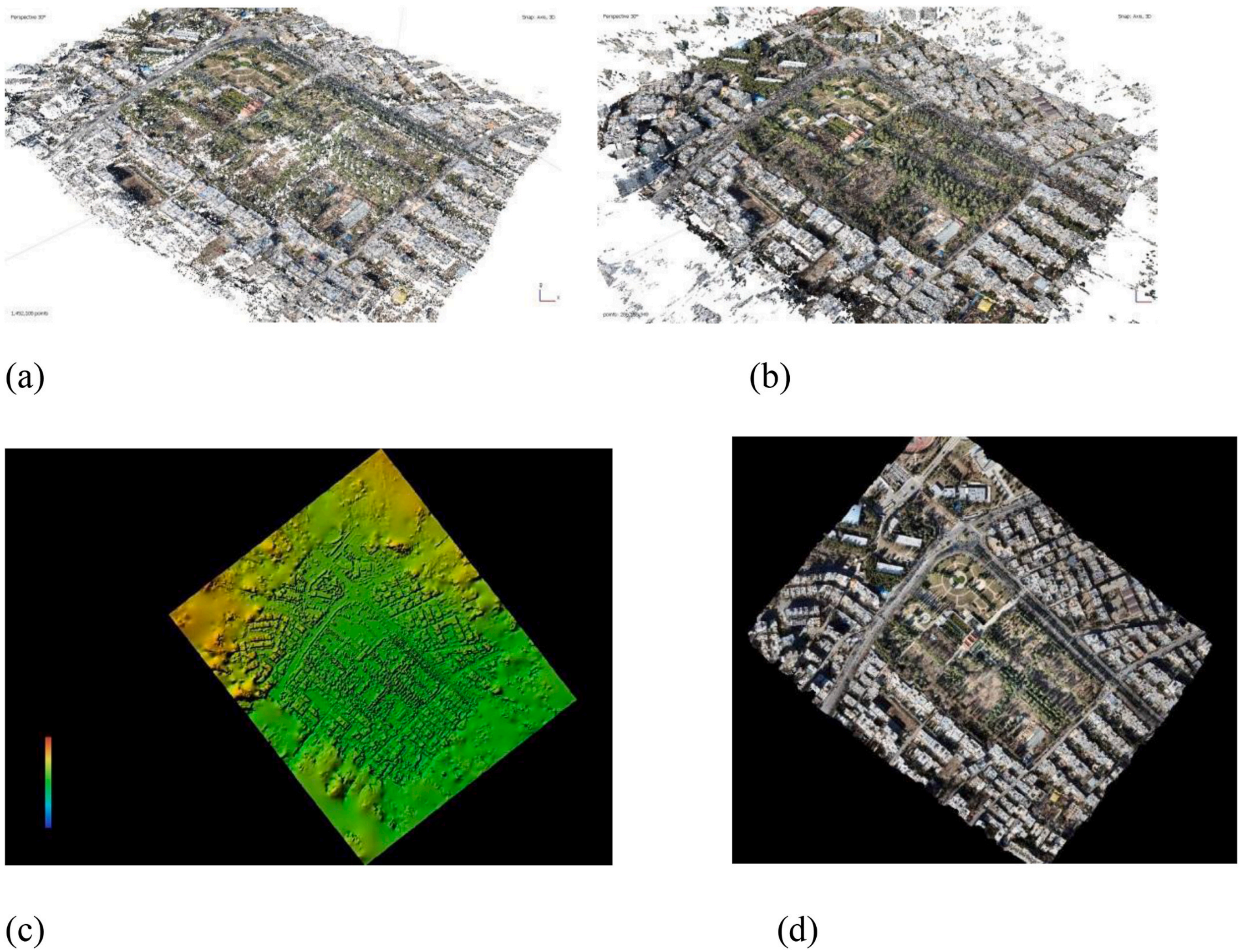


Fig. 14. 3D sparse cloud (a), dense cloud (b), Digital Elevation Model (DEM) (c), Orthophoto (d) based on data processing of Eram Garden as a case study.

Hamamieh Al Shaar, 2012). The Space Syntax defined by (Hillier and Hanson, 1984) deals with the knowledge of spatial configuration and spatial pattern with a logical organization and provides the possibility of its analysis.

Indeed, Space Syntax, describes the topological relations of spatial units in a spatial configuration. In this research, the open-source Space Syntax software Depthmap 10 (https://www.spacesyntax.net/software/) is used to find the hidden patterns in the physical space of six Persian Gardens. The space's explorative indications in this tool can analyse CD layers to a large extent. In this research, we have expressed the physical-behavioural characteristics of space using some of the Space Syntax's basic units of analysis (Penchev, 2017), such as "depth (topological distance)," "Isovist," "connectivity," "integration," and types of accesses. One of the essential capabilities of the Space Syntax theory for design analysis is the perception of the spatial configuration by translating their properties into Visibility Graph Analysis (VGA) or topological diagrams and then analysing them mathematically (Min and Lee, 2017).

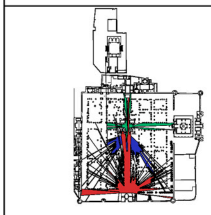
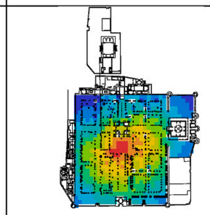
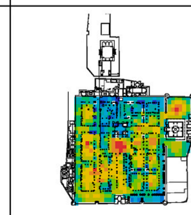
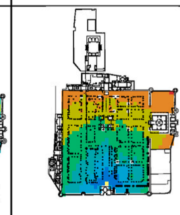
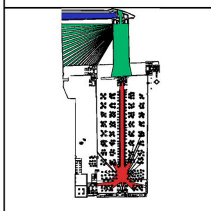
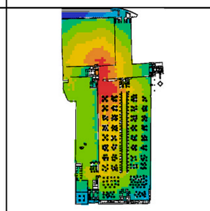
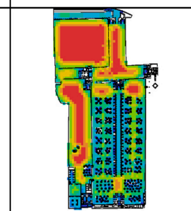
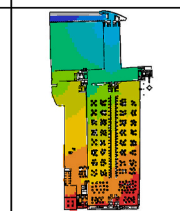
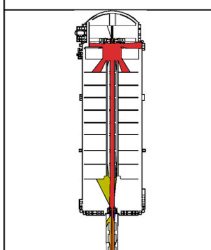
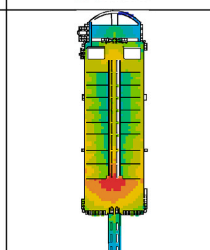
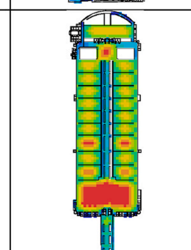
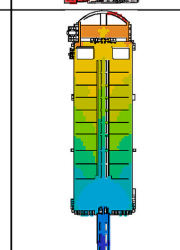
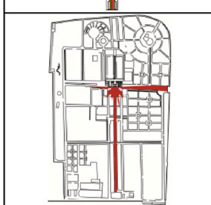
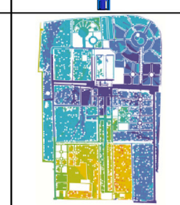
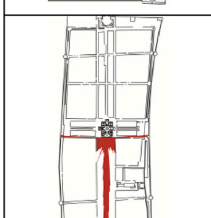
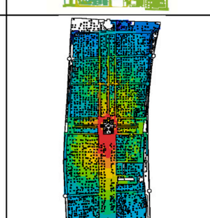
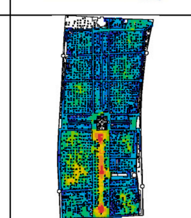
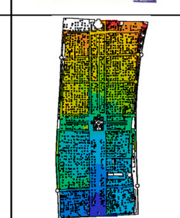
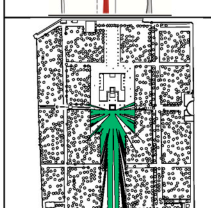
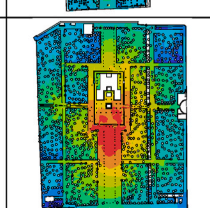
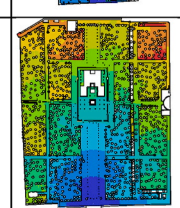
In the Space Syntax theory, connectivity is a feature of proximity and permeability states that refers to the possibility of direct access between two spaces. These defined spaces and their connections have been described generally as "maps," but mathematically, they are graphs that can be analysed. Therefore, in a map, the step depth representing the distance of the connection from the input node can be determined mathematically. Visual integration (the most important measure used in syntactic analysis), as the essential concept of Space Syntax, can be defined as follows: The average number of spaces from which one can reach other spaces; the average number of changes in direction from which one can reach all the spaces of a design. Therefore, visual integration in the Space Syntax has a relational concept, not a distance or metric; as a result, the concept of depth is more than the distance used. In Space Syntax, the concept of step depth describes the distance of spaces from each other. Moreover, the relative depth for each node indicates the degree of isolation of the spaces. In the first step, we drew a grid for each garden, where the dimensions of each cell were equal to the dimensions of the palace's central part.

The demonstration of meaningful proportions between the structure of the palace, as the main element shaping the structure of the Persian Garden, and other parts strengthened the hypothesis of meaningful relationships in the whole garden. In the second step, for a more detailed examination, after drawing the gardens' plans in AutoCAD, we entered them into the Depthmap 10 software to convert them into topological diagrams (Table 1). In the third step, the analysis of the Isovist in the gardens includes three stages:

- the first stage of the entrance
- the second stage after the main building
- the third stage of the view from the palace to the space in front.

According to (Pilechiha et al., 2020), Isovist is the field of view available from a particular vantage point, generally taken at eye height

Table 1
Topological diagrams or VGA graphs of the Persian Garden based on Space Syntax's units of analysis.

Isovist	Integration	Connectivity	Depth	Samples
				Fin Garden
				Dolat-Abad Garden
				Shazdeh Garden
				Eram Garden
				Delgosha Garden
				Chehelseton Garden

and parallel to ground level and facilitates the opportunity for seeing and being seen (as an influential factor in the legibility of the space structure) from a particular position.

The Space Syntax components examine to reveal the spatial geometry's hidden relations, and we present the numerical relations hidden in the visual structures. All these steps have been done by studying the plans of the Persian Gardens-palace and emphasizing a few existing samples that can be checked as a test. Therefore, the conclusion based on this must be repeated and developed in case of success.

5. Results and discussion

Manufactured landscapes, including Historic Persian Gardens, are artefacts whose form has evolved in a non-linear adaptive cyclical process continuously and inevitably over time through the co-evolution among humans and natural systems as well as local knowledge transfer. This process formation of heritage landscapes, as a generative process, creates pattern languages that can be described as a combination of geometric configurations that follow a specific grammatical structure, like natural language, and create explicit-implicit patterns, proportions, and rules in the structure of the spaces. Comprehensive utilisation of proportions in Persian architecture, such as in the design of plans,

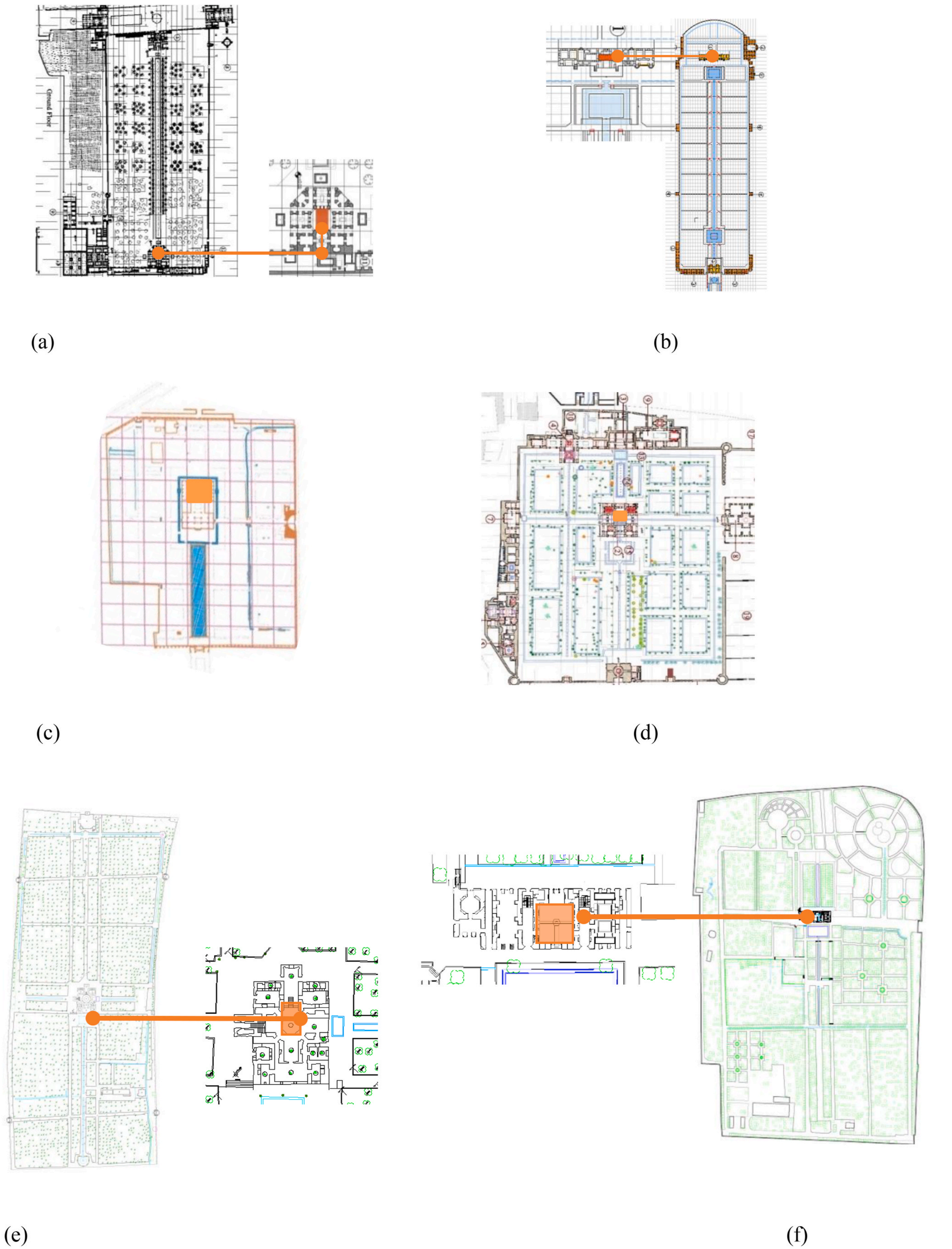


Fig. 15. The base module as palace's central part in case studies, (a): Dolat-Abad Garden (Qajar), 6*9, (b): Shazdeh Garden 9*4, (c): Chehelseton Garden (Safavid) 5*5, (d): Fin Garden (Safavid) 7.5*7.5, (e): Delgosha Garden (Qajar) 4*9, (f): Eram Garden (Qajar)8*9.

Table 2
Space Syntax data, Fin Garden (Safavid period).

Space Syntax's units of analysis	Max	Average	Min
Connectivity	48	28.3	1
Visual integration	1.06	80.	44.
Visual step depth	20.88	12.01	9.21
Step depth	34	20.87	0
Intelligibility		$R^2 = .08$	
Isovist	1714	9948	4117
	Step1	Step2	Step3

Table 3
Space Syntax data, Shazdeh Garden (Qajar period).

Space Syntax's units of analysis	Max	Average	Min
Connectivity	48	27.25	1
Visual integration	99.	78.	74.
Visual step depth	18.19	11.49	9.1
Step depth	29	15.3	0
Intelligibility		$R^2 = .21$	
Isovist	3404	5003	5863
	Step1	Step2	Step3

Table 4
Space Syntax data, Dolat-Abad Garden (Qajar period).

Space Syntax's units of analysis	Max	Average	Min
Connectivity	91	27.30	1
Visual integration	4.2	.95	.61
Visual step depth	27	12.7	0
Step depth	9.2	2.71	0
Intelligibility		$R^2 = .13$	
Isovist	2610	4657.57	4934
	Step1	Step2	Step3

Table 5
Space Syntax data, Eram Garden (Qajar period).

Space Syntax's units of analysis	Max	Average	Min
Connectivity	1142	317.85	1
Visual integration	2.18	1.49	.88
Visual step depth	21	10.06	0
Step depth	9.36	2.70	0
Intelligibility		$R^2 = .29$	
Isovist	46593	46402.5	41126
	Step1	Step2	Step3

elevations, geometric and architectural patterns, and mechanical and structural features, can be proved through the discovery of the underlying rules of generative processes and geometrical analysis of Persian historical buildings (Hejazi, 2005). The palace is the primary and influential element in the design of a Persian Garden. To understand the meaningful relationship between the design of the palace and the landscape around it and to achieve the basic modules in garden design, the palaces were studied more carefully (Fig. 15).

For the analysis of the "base module," draw a grid for each sample of gardens, and we have considered the grids' size according to the palace's central part. The palace's geometry is based on the nine-part geometry in which the central part is the primary and essential part; according to the examined samples, the central part is considered the "base module" for other parts. This central part or module was square in the Safavid period and became rectangular in the Qajar period. Due to these changes, the axes and divisions in front of the palace also increased, creating a broader landscape in the Qajar period than in the Safavid period.

For a more detailed study of physical changes, the components of Space Syntax, such as connectivity, step depth, integration for structural quality and Isovist, and visual step depth, legibility, and permeability for perceptible qualities, have been investigated (Table 1).

Table 6
Space Syntax data, Delgosha Garden (Qajar period).

Space Syntax's units of analysis	Max	Average	Min
Connectivity	39	20.73	1
Visual integration	2.48	1.65	97.
Visual step depth	8.12	5.37	3.78
Step depth	10	5.04	0
Intelligibility		$R^2 = .16$	
Isovist	1891	840	1302
	Step1	Step2	Step3

Table 7
Space Syntax data, Chehelseton Garden (Safavid period).

Space Syntax's units of analysis	Max	Average	Min
Connectivity	1084	248.80	1
Visual integration	1.4	1.05	.56
Visual step depth	41	16.17	0
Step depth	20.31	5.31	0
Intelligibility		$R^2 = .068$	
Isovist	1561	950	1256
	Step1	step 2	step3

We have presented and analysed the calculations related to Space Syntax's units of analysis of historical Persian Gardens in Tables 2–7. For example, in the figures in Table 1, red indicates the highest integration value, and blue indicates the lowest integration value. In other words, red has the lowest depth, and blue has the highest depth of integration.

Spaces located at a lower relative depth have a greater spatial connection, and their control and permeability have been difficult. Intelligibility is a Pearson correlation between visual integration and connectivity to all nodes. Legibility, as one of the most important qualitative features of space, can be defined as the ability to organize the environment using coherent and imaginative patterns to facilitate spatial understanding; Intelligibility is the degree of our vision from the spaces of a complex, which is a qualified indication of the range of spatial perception and legibility (Askarizad and He, 2022). Indeed intelligibility contributes to improved legibility (Long and Baran, 2012).

Based on extracted data, the average connectivity between spaces in the gardens from the Safavid period to the Qajar period is numerically in the range of 20–28m. The visual integration space is 1.65-8, visual step depth 5.37-12.01, step depth 5.04-20.87, and intelligibility 21-09. Also, the average visual integration space in Qajar gardens compared to the visual integration space in Safavid period gardens is almost ½, which means visual integration space has decreased in Qajar period gardens. Therefore, with the increase in visual integration and the decrease in connectivity, the intelligibility legibility of spaces has often decreased (Figs. 16–20).

In the red parts, with the highest integration value, the most activity happens because the most direction changes to use other garden spaces happen in these areas. Indeed, spaces with lower depth are more legible and permeable; and need less control. In the Persian Gardens, the entrance gate, public spaces, and the main axis locate at places with high integration, and the palace is in more depth, i.e., in the blue area. Also, in the Persian Garden, like other traditional Iranian spaces, although the level of control over the entry of westerners increases by creating a spatial hierarchy and private spaces placed at more depths, it has a flexible space. The relationship between residents and aliens reduces in high-integration spaces, forming isolated spaces. In designing new gardens for public use, considering these points is necessary.

Regarding the connectivity of spaces, the gardens of the Qajar period have a similar connectivity situation, and this syntactic component in them is at a higher level than in the garden of the Safavid period. Based on the findings, the Qajar gardens (Tables 3–6) have higher spatial connectivity than the Safavid garden (Table 2, Table 7). On the other hand, intelligibility is the outcome of integration and connectivity parameters. Because of the lower visual depth, it appears that the longer

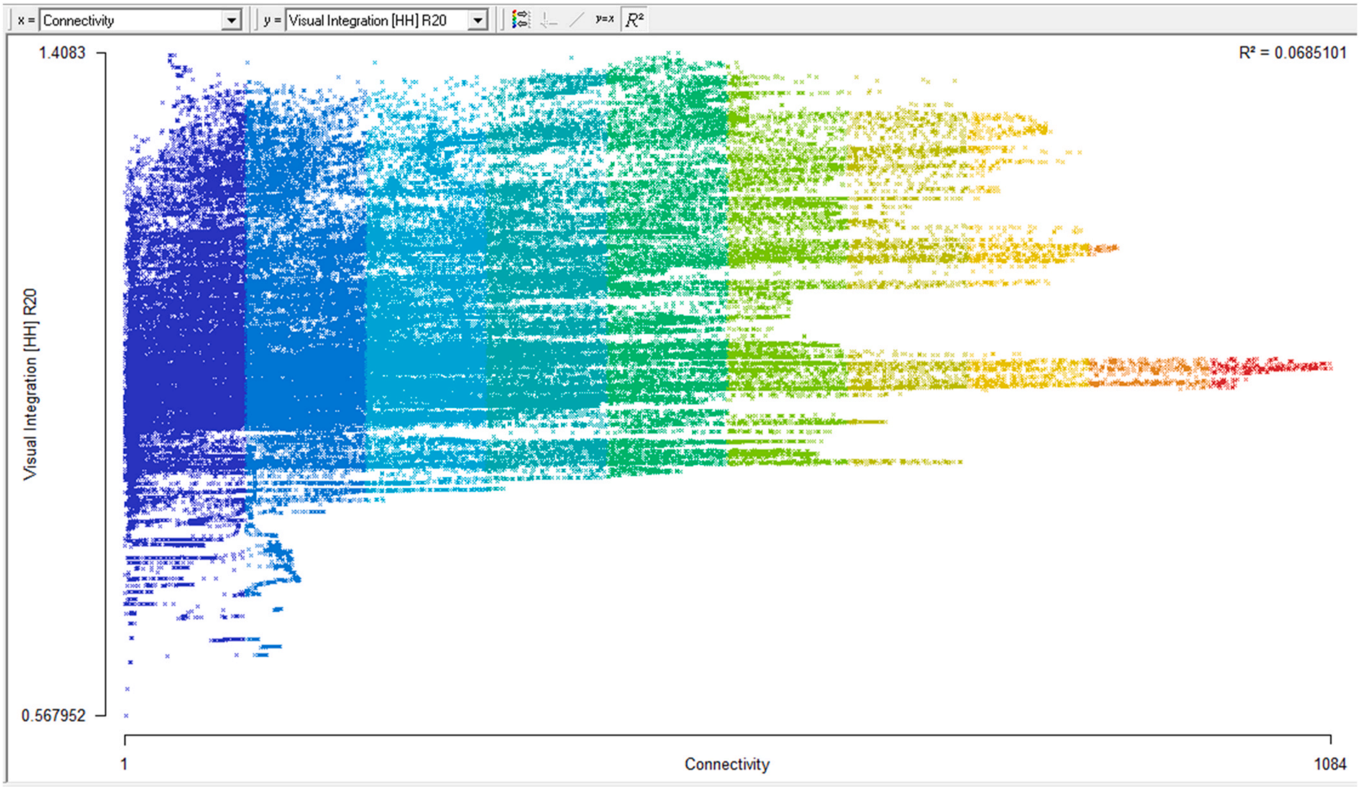


Fig. 16. Spatial intelligibility values (R^2) of Eram Garden.

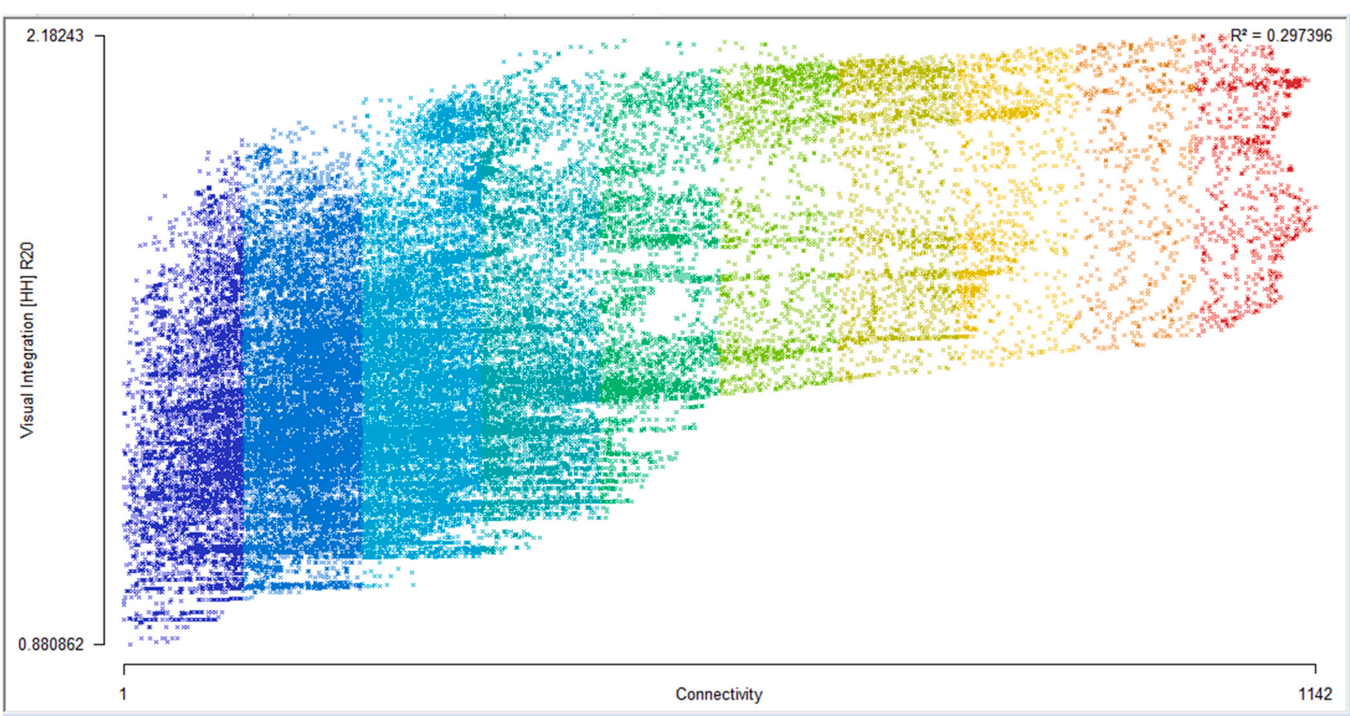


Fig. 17. Spatial intelligibility values (R^2) of Chehelseton Garden.

the main axis of the gardens is, the greater the degree of space connection; as a result, the space has more legibility; for example, the Shazdeh Garden (Fig. 19) has the highest legibility of the other Qajar gardens (Figs. 16, 18, Fig. 20). Although Dolat-Abad Garden (Table 4) is in the same situation as Shazdeh Garden (Table 3), in terms of spatial connectivity and integration, its intelligibility (Fig. 19) has decreased due to the more visual step depth. Also, Fin Garden's average visual step depth is 1.3 compared to Shazdeh Garden and Dolat-Abad Garden, which is related to the connectivity of spaces in the gardens. The data analysis above shows that legibility in the gardens has decreased with a

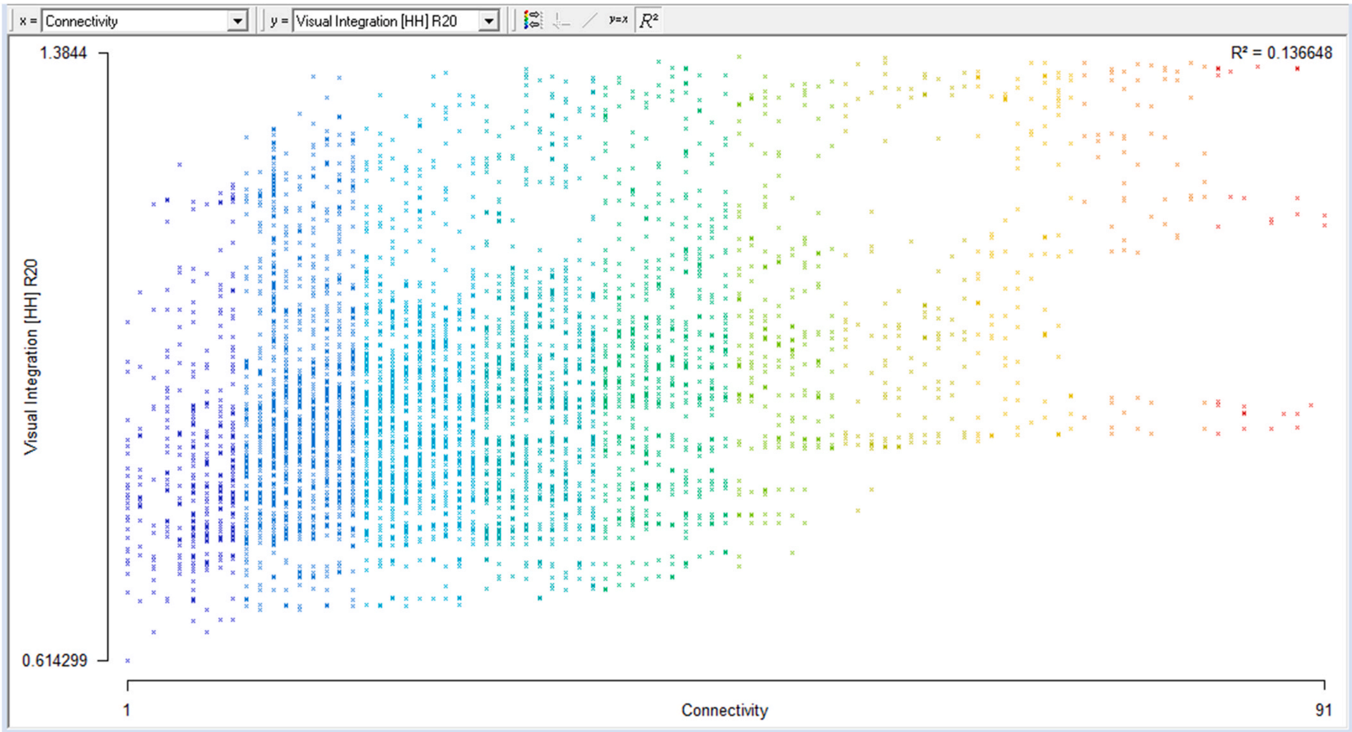


Fig. 18. Spatial intelligibility values (R^2) of Delgosha Garden.

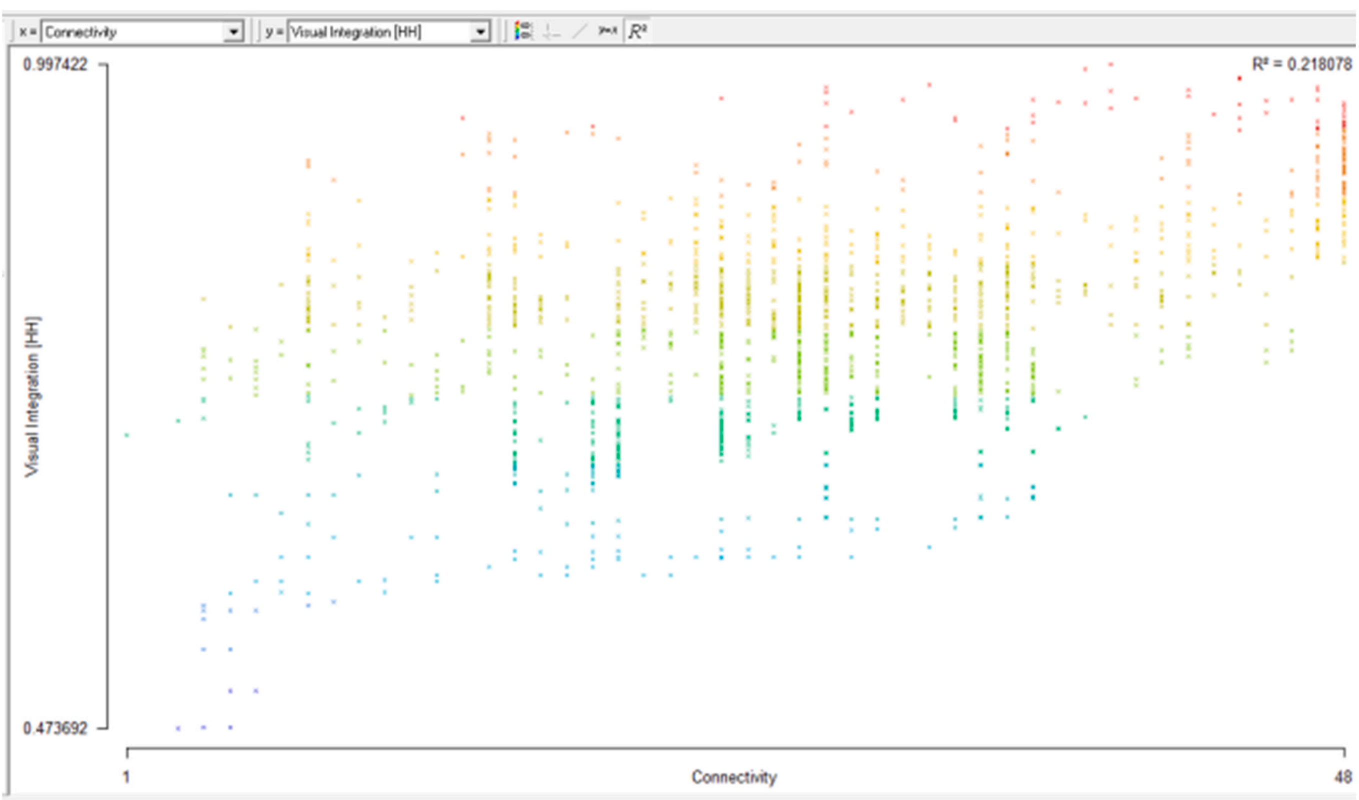


Fig. 19. Spatial intelligibility values (R^2) of Shazdeh Garden.

decrease in space intelligibility. Also, legibility in the Qajar gardens has increased compared to the Safavid gardens. According to (Dalton and Bafan, 2003), Isovist is the field of view available from a particular vantage point, generally taken at eye height and parallel to ground level and facilitates the opportunity for seeing and being seen (as an influential factor in the legibility of the space structure) from a particular position. According to the definition of Isovist in the 4.2.2 section, Isovist analyses can be the best syntactical analyses for investigating the

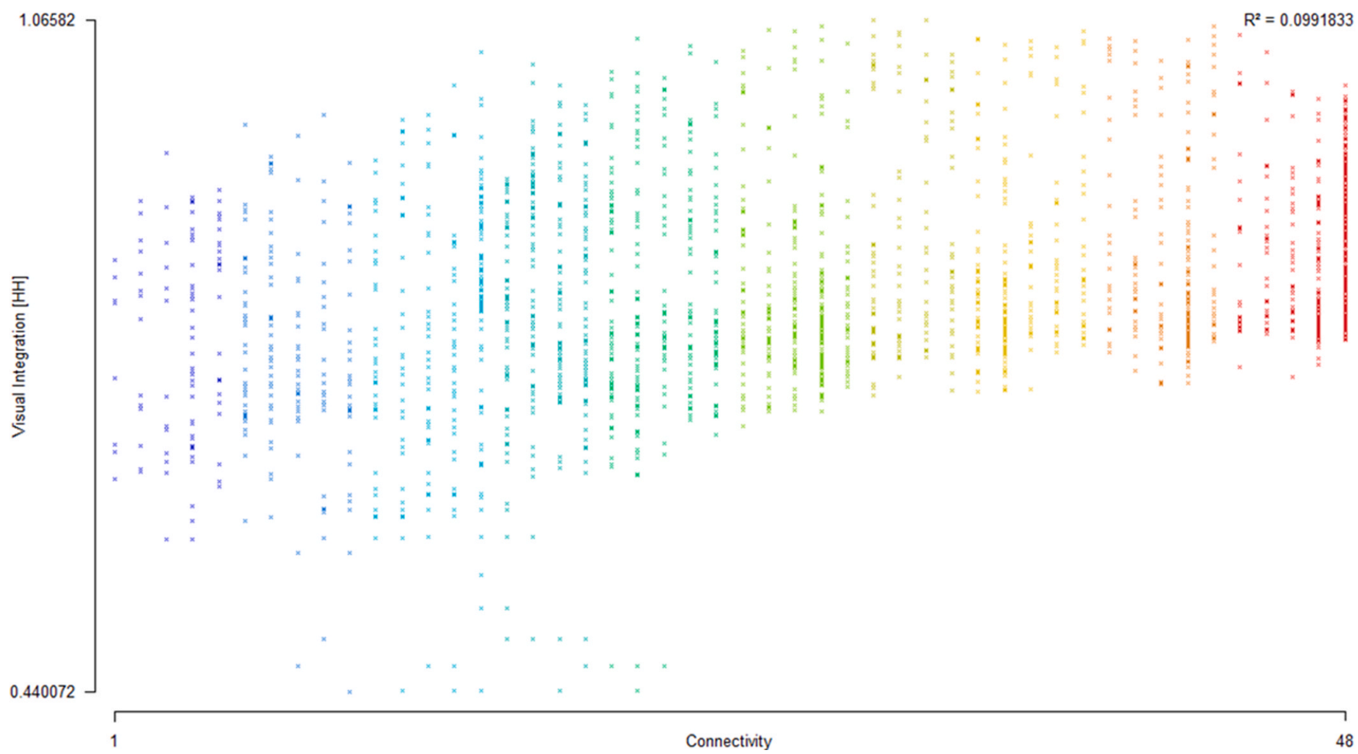


Fig. 20. Spatial intelligibility values (R^2) of Dolat-Abad Garden.

Table 8
Analysis of the isovist in the Persian gardens.

Samples	Min Radial	Max Radial	Compactness	Occlusivity	Drift Angle
Fin Garden	.22	253.184	.032	756.038	286.44
Shazdeh Garden	2.238	424.213	.034	812.15	359.553
Dolat-Abad Garden	5.453	231.753	.0065	2825.54	182.725
Eram Garden	3.29127	199.104	.68	262.947	178.221
Delgosha Garden	1.11	159.33	.39	610.99	268.42
Chehelseton Garden	1.52	147.56	.0039	3231.14	270.76

legibility (Askarizad and He, 2022) and intelligibility of space. According to the findings, the field of view from the palace to the space in front of Qajar gardens such as Dolat-Abad Garden and Shazdeh Garden has increased significantly compared to Safavid gardens such as Fin. Also, Fin Garden's ratio of Isovist value to Shazdeh and Dolat-Abad gardens was 1.5. We have presented the numerical values of the field of view related to the studied gardens and their components in (Table 8).

Based on data analysis, the Shazdeh Garden, among the Qajar gardens, has the largest field of view and the highest space intelligibility value; consequently, it also has the highest legibility. The basis of historical Persian Garden design philosophy emphasizes that the garden is a place to think about creation and signs of the existence of God in nature. Therefore, in this heritage place, the space is designed so that the user gradually discovers the whole space and perceives and imagines it. The low value of intelligibility and legibility in the cases studied also shows this issue.

As explained in Section 2, the Persian Garden structures evolved through history based on specific philosophies and worldviews. The goal of the garden designer, before and after Islam, has been to translate the mental concepts expressed about the promised paradise and visualize it on earth in the form of a spatial garden structure. Despite changes in religion and worldviews, the overall structure of the garden has been preserved. However, in this transition process, some elements' concepts have changed, and new unique signs, symbolic identities, and rules have been created. The syntactical analysis has aided us in achieving a new interpretation of the formative qualities of CD layers in the Persian Garden structure (Fig. 3). Data interpretation and analysis show that this heritage landscape followed specific mathematical rules like other Iranian pattern-oriented architectures. In this research, we achieved some of the hidden and meaningful rules in the gardens of the Safavid and Qajar periods.

6. Conclusion

This research has examined new approaches, methods, and technologies proposed in recent studies to understand, monitor, manage, and sustain historical landscapes; then has expanded the CD approach as a mechanism for culture transmission and the co-evolution of socio-cultural systems and natural systems in heritage landscapes and historical gardens as a particular species. This comprehensive digital approach includes various tools, solutions, and approaches to identifying and transferring cultural components in artefacts. This study has used the Space Syntax theory and the Depthmap software. Also, The Persian Gardens' Space Syntax analysis has studied tangible, structural, and semantic qualities. The applied computational approach represents one of the first attempts to analyse examples of historical Persian Gardens using mathematical measurements and computational tools to identify and describe the hidden patterns in these spaces. According to analysis data, the semantic quality, including visual depth, spatial communication, space perception, and legibility, increased somewhat in the Qajar period. This increase in environmental quality in the gardens is partly the result of the change in the structural quality, the body, and the syntax of spaces in the Iranian landscape environment; the Space Syntax data also confirm this issue. The cryptosystems of the Persian Gardens in the examined samples of the Safavid-Qajar period have evolved continuously with changes caused by the change and dynamics in the relationship between components in the structure of the Persian Garden.

The landscape of the Qajar period, having components from the Safavid period (past) and new components (present), has found an intermediate identity (transition between past and future life), and the semantic continuity of the Iranian landscape is perceivable in it. This continuity of meaning results from the transfer of DNA over time, in the perspective of the Persian Garden, which has created particular patterns of languages. It seems that the rule-based design and development process can help us achieve sustainable adaptive development in historic landscapes. Results show meaningful relationships in the space of gardens that can be updated through computational tools and used to design new examples of Persian Gardens or new landscapes with the CD of traditional gardens. However, reaching these goals and creating rule-based generative methods requires the examination of more examples.

On the other hand, although Space Syntax is suitable methodology for analysing the structure and rules of space, it cannot comprehensively analyse the layers of the CD of space because it is topological. Achieving holistic models that provide new scenarios of cultural-heritage landscapes in management, protection, development, and evolution requires other analytical and productive tools. Decision support tools based on artificial intelligence algorithms, machine learning, and image processing techniques are significant potential in this field. As ongoing research, the authors study this tool to generate new scenarios of world classical gardens, including historical Persian Gardens.

Author statement

Parichehr Goodarzi: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision.

Mojtaba Ansari: Conceptualization, Project administration, Writing - Review & Editing, Methodology.

Mohammadjavad Mahdavinejad: Writing - Review & Editing, Supervision.

Alessio Russo: Writing - Review & Editing, Methodology, Supervision.

Mahdi Haghighatbin: Supervision, Writing - Review & Editing.

Farzad Pour Rahimian: Writing - Review & Editing.

Declaration of competing interest

None.

Acknowledgements

The development of the solution presented in this paper was part of the first author's PhD study at the Department of Architecture, Faculty of Art & Architecture, Tarbiat Modares University, Tehran, Iran.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.daach.2023.e00277.

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