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Original Research Article

Explanation of the historical dynamic analysis model of business trips with a focus on Safavid era caravanserais*

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Abstract

Problem statement: Caravanserais are among the most important types of historical architecture that have played a major role in trade. Among the main uses of Caravanserais, we can mention security about trips, temporary accommodation for passers-by, storage of goods for merchants, and taking care of their animals along their routes. Many researchers have paid attention to caravansaries structure, unless expanding cliodynamics in historical analysis, it wasn't possible to find proportions between physical features of caravansaries and social behaviors about caravansaries. So this research tries to answer the current question: how can the physical spaces of Caravanserais influence preferences of business trips?

Research objective: Therefore, the present article aims to propose a mathematical method that estimates business trip potentials relevant to caravansaries physical features.

Research method: This research is descriptive analysis method, using the library study and quantitative analysis. Also, in a case study, a quasi-experimental strategy was used with 3D simulations in 3D Max software and volumetric analysis in Rhino software. Within this context, an explanation of a formula, which has been tested in 16 case studies and 14 simulated trips.

Conclusion: The results of this research have led to the explanation that Isfahan city in the Safavid era was the main destination of business trips, and the Kerman city was the origin of trips that lead to Isfahan. On the other hand, by paying more attention to the Silk Roadways, it became clear that the trade ring flowed from today's Pakistan to Isfahan, and from this city to the northwest, northeast, and south of Iran.

Keywords: *Typology, Cliodynamics, Caravanserai, Business trips.*

Introduction

Architectural works cannot be studied without considering the influential factors affecting them (Johnson, 2005, 73). Examining the foundation based on which architectural genres have formed throughout history, can provide a

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more comprehensive perspective of architectural evolution, including those influenced by the condition of society and various commercial, religious, and political factors, and so on (Kavian & Gholami, 2016, 50). The current research introduces the concept of architectural typology in its evolutionary sense, took from the field of biology relating to history. The historical-evolutionary architectural typology is a common method used in many architectural studies, especially the Italian Moratoria approach to art history, which involves historical-evolutionary typology to reconstruct the historical chain of researches and basic patterns by relying on the knowledge and study of territories' historical roots of architecture. Despite the rich heritage and long history of architecture, this method has not been widely used in Iran due to the lack of a methodology focused on the history of architecture in line with this perspective (Memarian, 2014, 35).

Like other methods, Moratoria's historical-evolutionary typology is also criticized despite benefiting from history to describe type changes due to incomprehensive typology, lack of some influential indicators in the evolution of form, and typology methods derived from a simplistic approach to Cartesian ideas. This critical approach contrasts today's science with the past, as contemporary researchers tend to move from a reductionist and simplistic approach towards a more complex mindset (Morin, 2015, 10). This mindset combines the variables and simultaneously assesses them instead of separating them. In contrast, instead of using linear equations to describe scientific processes, thermodynamic dynamical equations obtain a comprehensive understanding of a subject by unifying and interweaving information instead of analyzing and separating them, focusing on uncertainty and a different understanding of organizational behavior (ibid., 114).

In the context of historical analysis, this is called "Cliodynamics", which was developed by Peter Turchin (2003) to construct a mathematical tool for historical measurements. In the realm of historical analysis, this method is called "Cliodynamics." Peter Turchin introduced it in 2003 to create a mathematical tool for historical measurements. The goal was to transform historical data into scientific patterns, combining the disciplines of long-term analytical historiography and mechanical knowledge (Turchin, 2003, 63). This term was scientifically recognized in his article in 2008 in the journal Nature (Turchin, 2008). Based on the ideas of Ibn Khaldun (A 14th-century Muslim historian) on recurrent historical patterns and the experiences of some previous researchers, such as Jack Goldstone (2003), Randall Collins (1999), John Komlos (2009), Sergey Nefedov (Turchin & Nefedov, 2009), and Andrey Korotayev (Korotayev & Malkov, 2012), Turchin proposed cliodynamics as an interdisciplinary subject and a tool for writing long-term historical patterns to investigate dynamic trends in long-term timeframes with many variables relying on historical data and suitable quantitative tools associated with computer science and mathematics and even predicting the future as recurrent historical patterns. Therefore, cliodynamics can be used to establish a link between historical-evolutionary architectural typology and its historical context. Just as typology strives to describe a pattern for historical changes in types of architecture and effective contexts, cliodynamics seeks to describe phenomena by exploring the simultaneous effect of several variables and explaining a dynamic pattern for changes in phenomena.

Caravanserais, constructed for reasons ranging from security, military, economic, to geographical reasons, stand as some of Iran's most invaluable cultural and civilizational heritage. With the development of trade between East and West during the Parthian era and the initial foundation of the Silk Road (Fazeli, 2011, 11), the need to build temporary residences on long routes and maintain the safety of caravans became more noticeable. These structures experienced many changes throughout history based on their location and purposes. The Safavid era is known as the golden era of caravanserai construction

in Iran due to the expansion of central governance and trade development. During this period, the number and size of caravanserais increased, playing a decisive role in drawing trade and transit routes. In addition to documenting the experiences of travelers, researchers such as MaximeSiroux (Daniel & Tajdar, 2022), Arthur Upham Pope (2020), Andre Godard (Tajdar et al., 2016), Robert Hillenbrand (2015), and Mohammad Karim Pirnia (Pirnia & Memarian, 2016) have analyzed various dimensions of this type of architecture in Iran. These studies have demonstrated that the functional, security and protection requirements, which had accelerated and reinforced caravan passageways, had influenced the caravanserais' body and function, including the geometric form of the plan, space placement, and the definition of the caravan passageway to location in trade routes with a focus on Iranian markets and caravanserais' structure, and had played a positive role in the prosperity of caravans, routes, and commercial development (Kohestani et al., 2017, 72). In this era, structures such as karbates, rabats, sabats, and the previous khans were part of the functional subsystem of caravanserais. The economic performance of caravanserais was considered more than other functions, and other factors, such as geography and climate, were regarded as influential in determining the location of the caravanserais (Farshchi & Haji Zamani, 2019, 4).

Based on primary location and physical features, caravanserais are divided into two types: urban and suburban. Thus, analyzing physical differences between urban and suburban caravanserais can greatly contribute to forming the current research roadmap. As the Safavid era is considered a period of prosperity with numerous caravanserais, it provides a suitable timeframe for investigation. During the Safavid era, attention to the location and architecture of caravanserais increased due to conflicts with the Ottomans and Uzbeks, aiming to secure the routes (Tabasi & Naseri Azghandi, 2020, 318). In contrast to previous periods where the focus was on constructing caravanserais within cities, the comparison of urban and suburban types during the Safavid era is significant from a military and security studies perspective (Kohestani et al., 2017, 68). Undoubtedly, the importance of trade throughout Iran can be considered one of the issues influencing the establishment of caravanserais' form and space plan, which has led to the transformation and evolution of caravanserais over time (Ghobadian, 2013, 48).

Examining the physical characteristics of architectural elements of caravanserais in social behavior calculations in consecutive periods is necessary and inevitable. The architectural elements of caravanserais consist of passenger rooms and alcoves, which constitute their most important concept (Mirzaali & Razmi, 2016, 4), which significantly impacts the architectural structure. Therefore, examining the physical characteristics and functional dimensions of rooms and alcoves in the architectural typology of caravanserais is crucial. These elements are defined as one of the main layers of caravanserais. The importance of preserving and maintaining livestock led to the construction of stables, usually located behind the chambers, providing space for keeping livestock during the journey (Rahim Por, 2015, 32). On the other hand, the stables' spatial organization and architecture made sense due to the high priority of trade trips on routes such as the Silk Road and other trade routes (Shiani & Arabpour, 2015, 8; Bimakr & Bavandian, 2019, 9). Therefore, it is vital to examine the physical characteristics of the stables due to their relationship with climatic issues and socio-economic factors in caravanserais.

The courtyards of caravanserais were essential for economic functions, business development, revenue generation for the treasury, individuals, and charitable purposes. Other cultural and service functions such as storage services, hospitality, and religious ceremonies, aligned with political, security, military, and educational purposes, also benefited from the main house or the main courtyard of caravanserais (Basouli & Derakhsh, 2021, 9).

Fig. 1 shows the process of the emergence of the main elements of the caravansary, which emerged based on the provision of the main needs of the caravans.

The role of such layering is crucial in the current typology research. For contextual studies, considering the background and course of trade between the points of origin and destination in the period of commercial prosperity of the Safavid government will enable us to explain a dynamic mathematical model for the relationship between the body of caravanserais and relevant historical studies.

Research Background

The growth and access to big data have had a profound impact on social sciences and have had promised a new revolution in measuring, modeling, and simulating human behavior (Shabani, 2019, 4). An example of this can be seen in the presentation of the dynamic equation of changes in the Silk Road (Malkov, 2014) to assess JermyBently's hypothesis on the various variables governing the changes in the Silk Road, the advent and fall of great empires across Eurasia, and the changes in the transportation industry. In another study, population dynamics and the cycles of emergence and extinction of living organisms have been introduced as a function of a mathematical model resulting from biological changes. The results of these studies show that every social phenomenon is dynamic in nature, and its fluctuations can be institutionalized and established as a mathematical model, or at least the order of its fluctuations can be transformed into a general law (Turchin, 2003).

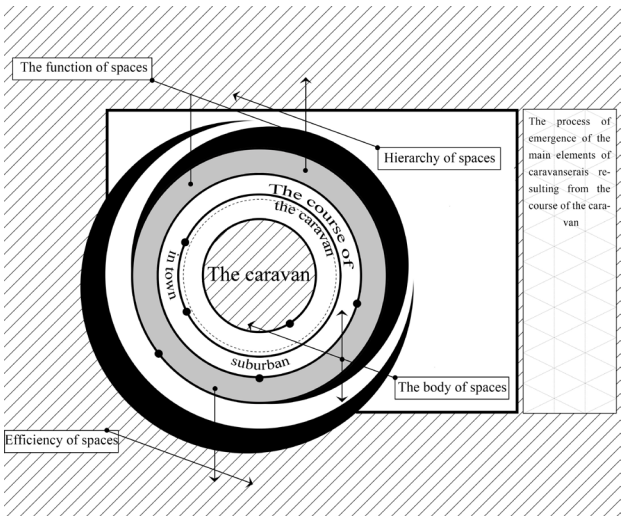

Fig. 1. The process of the emergence of the physical elements of caravanserais. Source: Authors.

Mashhadi and Aminpoor (2017) investigated the factors affecting the types of the typology from a social perspective on the historical monuments in Arak. They demonstrated that indicators do not affect types, and the subset of a specific type exhibited different behaviors in terms of architectural features. In the study conducted by Noghrehkar, Zarei Hajiabadi, Mohammad-Ganji and Danaeinia (2018), an attempt was made to model the cognition of the history of Iranian architecture, introducing the physical aspects of types as the result of social behaviors. Articles related to caravanserais, considering the reasons for their relational, economic, military, and geographical connections demonstrated that security is the most crucial characteristic for the prosperity of trade in the Safavid government. This reliance is rooted in a specific architectural style (Kohestani et al., 2017, 68). In this research, Pourmohammad (2013), has explored the response to social needs based on the structure of caravanserais, showing that the plan, volume, facade, and specific decorations of caravanserais result from social evolutions. Farshchi and Haji Zamani (2019), in their research titled "Investigation of Iranian Caravanserais and Associated Structures," analyzed the principles and construction of caravanserais and inns in Iran. They identify historical and cultural indicators influencing the communication system of caravanserais, shaping their development. Ultimately, they differentiate dominant patterns of caravanserais in various regional climates. Basouli and Derakhsh (2021) have explored the potential of history using a perspective approach. Despite the classification of different types of caravanserais in previous studies, the social dimensions' impact more than 100 years and the explanation of social patterns or a dedicated mathematical model for this architectural genre have not been addressed.

Theoretical Approach

Typology aims primarily at categorizing and classifying samples based on functional, structural, social, and environmental features (Hayati et al., 2020, 68). It serves as a framework for discovery and a deeper understanding of the studied context (Mirsajadi & Farkisch, 2017, 72), extracting components influencing the research's nature (Sadberenji, 2017, 5; Omidvari & Basouli, 2022). These studies, beyond uncovering relationships between micro-components and macro-components, reveal the connection between the past and future (Shahteimori et al., 2012, 43), addressing multidimensional historical and geographical issues (Noghrehkar et al., 2018, 19).

The architectural typology emphasizes the significance of types in the continuity of events related to evolution (Mashhadi & Aminpoor, 2017, 176). It reveals the foundations, components, theoretical basis, and basic patterns (Mohamadianmansoor & Faramarzi, 2011, 97). Extracting new meanings from the concepts of types indicates numerous contradictions in defining the nature and the material of a specific case (Mirsajadi & Farkisch, 2017, 75). This ability to interpret new social and evolutionary samples (Mashhadi & Aminpoor, 2017, 177) is influential in evolutionary architectural typology. In this approach, the physical, functional, and environmental aspects act as logical functions in the primary structure of architecture, while social, economic, and political factors serve as compulsory functions, demonstrating architects' utilization of typological concepts. Despite the influences of political, economic, and social components, architectural typology in space follows a rooted pattern (Memarian & Dehghani Tafti, 2018, 27).

Based on this theoretical approach, the conceptual model of the current research (Fig. 2) is built on examining the relationship between various components of an architectural typology, namely caravanserais, and their evolution over time. It explores their connection with the social and historical activities of commercial trips during the Safavid era. The study analyzes the proportion and position of architectural elements, using them as representations of commercial needs. By establishing relationships between these indicators and factors related to the environment, geography of travel, and commercial centers, a computational model is developed to depict a logical connection among them.

Methodology and Samples

The current research is descriptive-analytical which is using a modeling approach. The required data were collected through the selection of specific samples and library research.

- **Stage one: sample selection**

Considering the theoretical approach of evolutionary typology in architectural structures to identify influential social, economic, and cultural components, the selection of study samples is crucial from multiple perspectives. The first aspect involves choosing a time frame when trade flourished, focusing on the location and placement of caravanserais along trade routes that captured the attention of traders and travelers (Yusofnia, 2014, 142). The second aspect is about considering the climatic diversity along the route, which influences the architectural structure of caravanserais

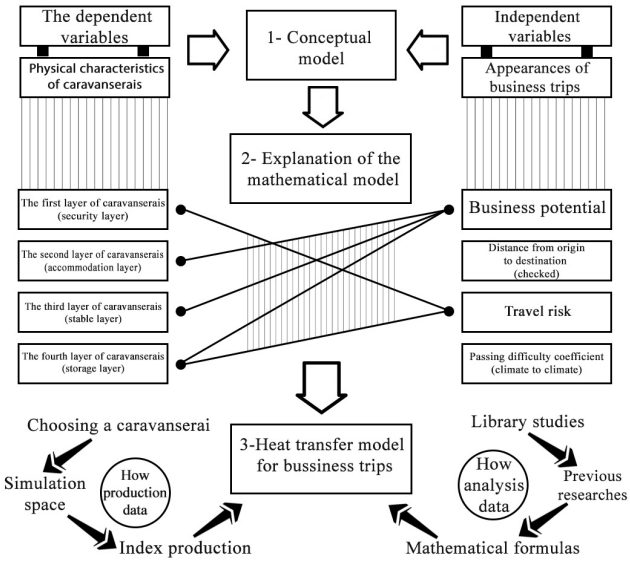

Fig.2. The conceptual model of the research. Source: Authors.

(Shahamipour, 2013, 634). Another aspect is the typology of structures with similar applications that enable an assessment of the examination of evolution (Noghrehkar et al., 2018, 74). The presence of these features in the samples, and the computational social science studies typically require at least two hundred years of investigation (Turchin, 2003, 64), can minimize potential errors.

To ensure reliability, a segment of the Silk Road and its surrounding routes, recognized as the most thriving trade route, has been selected for locating the chosen samples. Furthermore, attention has been given to trade and security variables as social and economic factors (Fig. 3).

Considering the significance of politics in establishing trade stability, choosing a period with prolonged political stability and commitment to trade development, such as the 235-year Safavid era and the lands under their rule from the 10th to the 13th century AH[1], is proper for examining this influential variable. (Fig. 4) depicts this study area and a segment of the Silk Road and its surrounding routes. Iran during the Safavid era drew the attention from domestic and foreign merchants due to its unique position on the Silk Road and limited development of commercial shipping in the Europe. This led to the construction of bridges, caravanserais, and various urban developments during the reign of Shah Abbas I (Yusofnia, 2014, 144). Among these, the uniform type of caravanserais from this period is worth exploring as it provides the opportunity for typological analysis.

Hence, the sixteen caravanserais belonging to this era were selected considering the written documents. Fig. 5 presents the names and architectural plan of these structures (Haji-Qasemi et al., 2004).

The precise matching of these caravanserais and the regional map aligned with Safavid borders indicates that the study area encompasses five climatic variations. Therefore, the selection of samples based on the theoretical approach of evolutionary typology in architecture and other variables is appropriate for a case study, having no ambiguity.

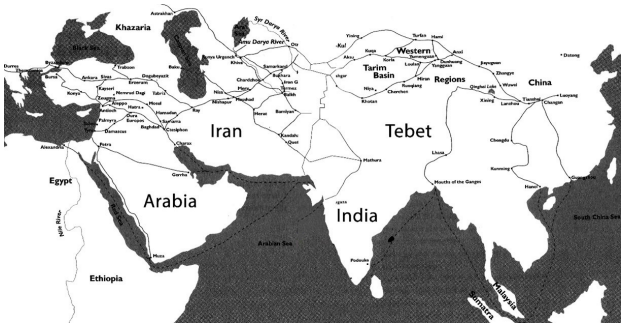

Fig. 3. Silk Road trade routes between the Asia and Europe. Source: Tucker, 2015, 43.

Fig. 4. The precise matching of the Silk Road route with the territorial map of Safavid era. Source: Authors baced on Sahab, 2004.

- **Stage two: generation of indicators**

Caravanserais are consisting of four distinct layers with different and complementary functions.

The first layer is security-related, including the external wall, entrance gate, guardhouse, and guard towers (in some caravanserais). This serves as a suitable indicator for calculating the travel risk on trade routes and dealing with threats from bandits, wild animals, and tribal wars. The volume of the first layer reflects the level of attention to these threats by local and national authorities.

The second layer comprises resting rooms for caravan travelers, directly correlating with economic prosperity, the density of trade travelers, and the volume of commercial goods. The indicator for the volume of this layer reflects the volume of passing caravans and the prosperity of the trade route within a specific time frame.

The third layer of caravanserais is the stables.

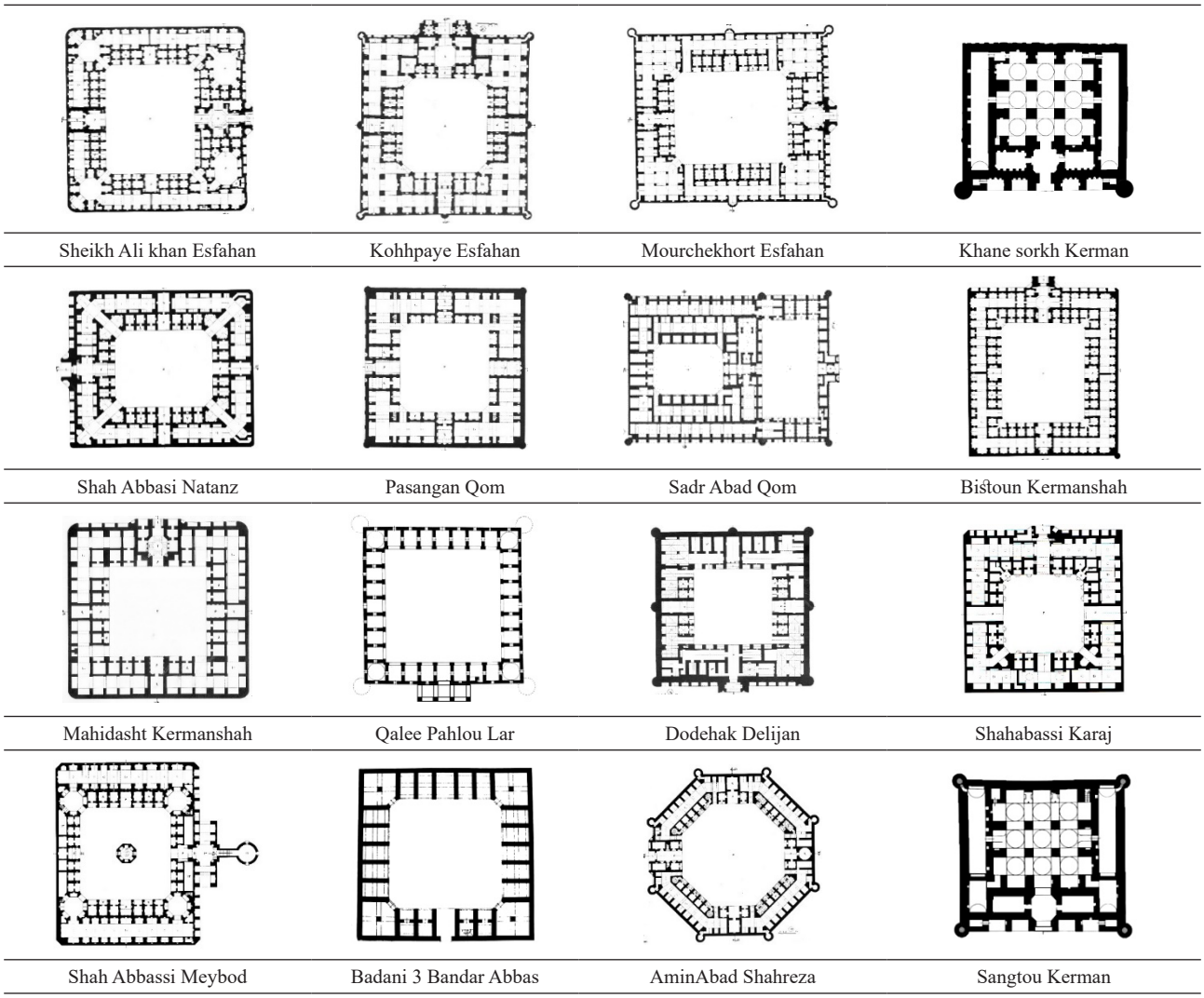

Fig. 5. The architectural plans of the case study caravanserais. Source: Haji-Qasemi et al., 2004.

The roadkeepers were rewarded for guarding the caravan's load based on the value of the animals carrying them (in descending order: camel, mule, horse, and donkey). The variety of livestock signifies the importance of traders and caravans, and the volume indicator of the third layer has a meaningful and direct correlation with the amount of taxation, travel duration, the difficulty of movement between origin and destination, and the geography of the route. The relationship of the volume indicator of the third layer with the climate, route, and the contrast between mild climatic conditions and flat terrain with mountainous geography is related to the speed of caravan movement. Since the profit of trade is directly proportional to the travel time between origin and destination, the volume of the third layer will have an inverse relationship with travel time.

The fourth layer of caravanserais belongs to the courtyard and chambers of the caravanserais. This layer is crucial for storing goods in direct sight of the caravan travelers during rest times and serving as a campsite for military forces. The volume of this layer is related to the density of exchange goods and the security sensitivity of the trade route.

In this research, to measure the mentioned indicators and obtain their ratio with the overall volume indicator, disregarding the thickness of the walls and considering the scale, 3D Max simulation software has been used, while Rhino software has been utilized for calculating the volume indicator, and the

graphic presentation of the data has been prepared using Photoshop (Fig. 6).

The analysis results of the relative volume indicators have been presented in Table 1.

Table 1 presents 64 resulting numbers for the four indicators in the sixteen case study caravanserais. The numbers have been rounded up.

- **Stage three: model design**

From a thermodynamic perspective, heat transfer is considered a process of transitioning from one equilibrium state to another, independent of time and based on speed. Heat transfer depends on the temperature difference between two points and the heat conduction rate. Therefore, in the present model, each caravan serves as heat energy in the process of transferring from the source to the destination with a potential difference in trade. T_1 represents the potential trade at the origin, T_2 represents the potential trade at the destination. x_1 and x_2 are the coordinates of the source and destination, and the travel risk is determined by the coefficient *k*. Assuming a flat surface, the value A is its area, and the coordinates x_1 (origin) and x_2 (destination) on the plane make the flow of goods between the two points calculable. However, considering the difference in height coordinates and its impact on the caravan's speed, travel risk, trade, and the need for caravan inns, the matching of the elevation

Fig. 6. Volume indicators of the four .main layers of case study caravanseraisSource: Authors.

Table 1. Volume indicator of the layers of case study caravanserais. Source: Authors.

Count	Caravansary	Layer 1. Volume index	Layer 2. Volume index	Layer 3. Volume index	Layer 4. Volume index
1	Aminabad	11	48	81	42
2	Bistoun	3	8	12	10
3	Khanesorkh	4	4.5	10	4.5
4	Pasangan	11	16	64	40
5	Dodehak	25	12	27	20
6	ShahAbbasi Karaj	2	6	12	6
7	Qale pahlou	16	3.5	26	3.5
8	ShahAbaasi meybod	10	16	26	18
9	ShahAbbasi Natanz	15	22	57	27
10	Sheikh ALikhan	14	13	40	22
11	Badani 3	3	16	18	30
12	Sadr Abad	6	13	17	14
13	Sangtou	7	3.5	3	3.5
14	Kouhpaye	22	19	26	53
15	Mahidasht	14	32	20	20
16	Mourche khort	16	42	16	28

difference is initially calculated using the following method. Assuming the height from sea level is z_1 at the origin point x_1, and z_2 at the destination point x_2, the actual approximate distance can be calculated using sine trigonometric function (Figs. 7 & 8).

Another important point for calculating the goods conduction flow is the changing climatic variety of the regions between the origin and the destination. The geographical conditions also impact the travel speed and risk level, and consequently the trade profit (Fig. 9).

Heat conduction, or the caravan's route in equilibrium climatic conditions, is quickly calculable and similar to heat conduction in a vacuum. However, it is not in line with the reality of intercity trips, especially the slow speed of caravans on the Silk Road. Therefore, considering climatic differences as a type of heat conduction coefficient is essential (Fig. 7).

To calculate the travel risk, the differences in the first layer (security) and the fourth layer (courtyard) of caravanserais are utilized, which have a direct correlation with travel risk. The positive and negative differences in the volume indicator of the first and fourth layers of caravanserais at the origin and destination indicate whether the travel risk from origin to destination is low or high. Therefore, the travel risk (k) can be calculated as follows (Equation 1):

Equation 1: $$k = Coefficient_k = C_{kl1} - C_{kl4} = \left(C_{kc(Destination)} + C_{kc(Origine)}\right) - \left(C_{kc(Destination)} + C_{kc(Origine)}\right)$$

In this equation, Ckl_1 and Ckl_4 indicate risks related to the first and fourth layers respectively, and they are resulted from the difference between the caravanserais of the origin and destination.

The second layer of caravanserais (residential space) and the third layer (the stables) simultaneously with the fourth layer (courtyard as a temporary store for goods) contribute as indicators of the prosperity of trade. The positive and negative differences in the volume indicator of the second layer of caravanserais

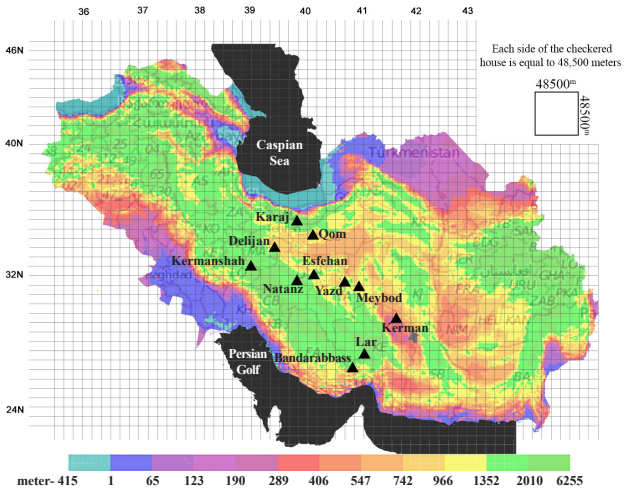

Fig. 7. The elevation map according to sea level, aligned to Iran's territorial map during Safavid era. Source: Sahab, 2004.

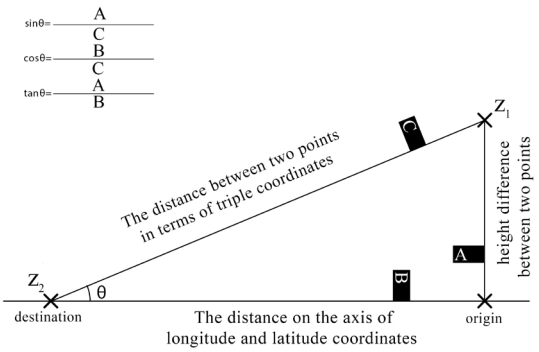

Fig. 8. Trigonometric calculation of the height difference. Source: Authors.

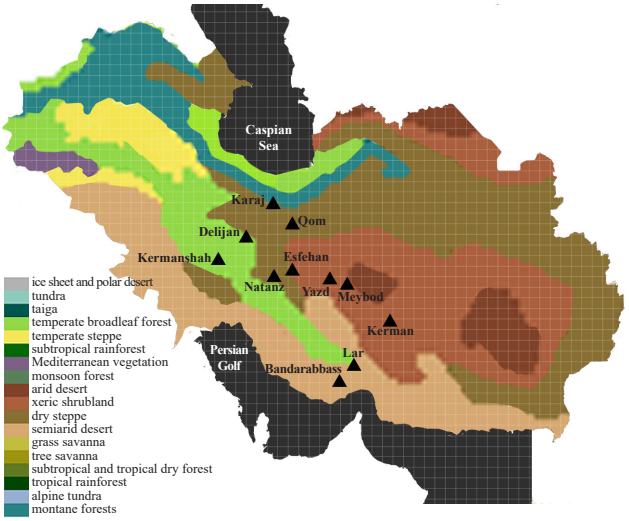

Fig. 9. The map of various climatic region types of Iran, matched with the territorial map of Safavid era. Source: Mohammadi, Mohammadkhani and Gholizade, 2017 & Sahab, 2004.

at the origin and destination indicate whether the trade potential at the destination is high or low compared to the origin. Therefore, to calculate the trade potential (delta T), the following relationship can be used (Equation 2):

$$\text{Equation 2: } \Delta T = f(T_2) - f(T_1) = \left(\sum_{Destination} [L_2 + L_3 + L_4]\right) - \left(\sum_{Origine} [L_2 + L_3 + L_4]\right)$$

In the above equation, *f(T1)* and *f(T2)* represent the sum of the volume indices of the second, third, and fourth layers of caravanserais at the origin and destination. ΔT is the difference between these two numbers, indicating the difference in trade potential between the origin and destination caravanserais.

In addition to these internal variables, the argument A is defined as the conditions of the transit route, representing climatic conditions and, as a constant scale (the same origin and destination climate equivalent to 0.1, adjacent climate change equivalent to 0.5, and multiple climate changes equivalent to 1). These three levels can serve as indicators of climatic diversity in the travel conductivity of caravans.

Finally, considering the defined caravan flow as the heat conduction flow between two points and incorporating the extracted indices, a formula similar to the heat conduction formula is presented as a dynamic historical analysis model for the current research.

- **Stage four: summarizing the findings**

To summarize the findings derived from the generated indicators, it is necessary to calculate the travel conductivity between the origin caravanserai and the destination caravanserai. For this purpose, fourteen hypothetical journeys have been simulated between the sixteen selected caravanserais. Fig. 10 illustrates the simulated journeys between the selected caravanserais with corresponding numbers.

In calculating the travel conductivity between the selected caravanserais, the indicators extracted from the second stage (production stage) are initially utilized. These indicators will be used to calculate the commercial potentials of the journey and the travel risk in the proposed model. Then, the refined distance, taking into account the elevation difference between the origin and destination cities, is calculated based on the surface vector distance and then using trigonometric relationships. Finally, considering whether the simulated journey undergoes a climate change during the trip or not, the corresponding coefficient is applied. This coefficient ranges between 0.1, 0.5, and 1. Table 2 includes the specifications of all the indicators extracted from the generated data. Table 3 also examines the convergence of research components.

Table 2 presents the indicators generated by each caravanserai and the simulated travels, quantity of travels (M), the four indicators of caravanserais (L),

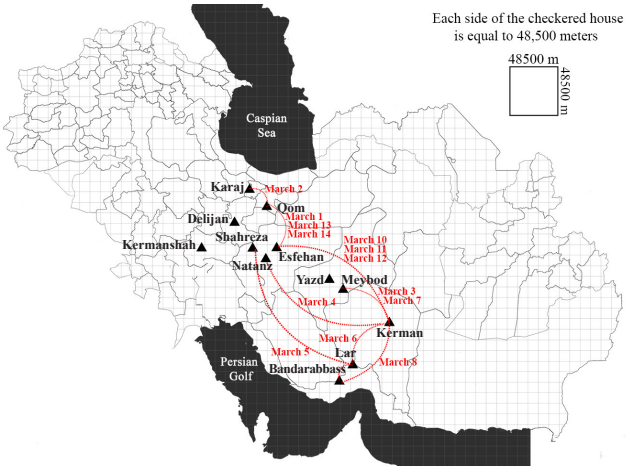

Fig. 10: Simulated travels on the studied range. Source: Sahab, 2004.

Table 2. Specifications of the simulated travels. Source: Authors.

Travel	Origin	Destination	Origin caravansaries layer index				Destination caravansaries layer index				Flat distance (Km)	Height difference (m)	Angle θ°	Actual distance (Km)	Hardness factor	Land type	
			L1	L2	L3	L4	L1	L2	L3	L4							
1	Sheikh Ali khan Esfahan	Pasangan Qom	14	13	40	22	11	19	64	40	300	-639	65	798	0.5	Dry steppe	Taiga
2	SadrAbad Qom	ShahAbbasi Karaj	6	13	17	14	2	6	12	7	165	376	65	470	0.1	Taiga	Taiga
3	Khane sorkh Kerman	ShahAbbassi Meybod	4	9	10	9.2	10	16	28	18	413	-690	59	1150	0.1	Dry desert	Dry desert
4	ShahAbbasi Natanz	Sangtou Kerman	15	22	57	17	7	7	3	7.2	694	108	8	120	0.1	Dry desert	Dry desert
5	Aminabad Shahreza	Qale pahlou Lar	11	48	81	42	16	7	26	7.2	846	-1816	65	2270	1	Dry steppe	Semi-arid desert
6	Qale pahlou Lar	Khanesorkh Kerman	16	35	26	35	4	9	10	9.2	489	1816	74	1853	0.5	Semi-arid desert	Dry desert
7	Shahabbasi Meybod	Sangtou Kerman	10	16	26	18	7	7	3	7.2	413	690	58	696	0.1	Dry desert	Dry desert
8	Badani se bandar Abbas	Khane sorkh Kerman	3	16	18	30	4	9	10	9.2	489	1747	74	1782	0.5	Semi-arid desert	Dry desert
9	Sangtou Kerman	Badani se Bandarabbass	7	7	3	7.2	3	16	8	30	552	-957	60	3190	0.5	Dry desert	Semi-arid desert
10	Sangtou Kerman	Sheikh Ali khan Esfahan	7	7	3	7.2	14	13	40	75	671	-189	15	290	1	Dry desert	Dry steppe
11	Koohpaye Esfahan	Khane sorkh Kerman	22	19	26	53	4	9	10	9.2	671	189	15	290	0.5	Dry steppe	Dry desert
12	Sangtou Kerman	Kouhpaye Esfahan	7	7	3	7.2	22	19	26	53	671	-189	15	290	0.5	Dry desert	Dry steppe
13	Mourchekhort Esfahan	Sadabad Qom	16	42	16	28	6	13	17	14	300	-639	66	31950	1	Dry steppe	Taiga
14	Mourchehkort Esfahan	Pasangan Qom	16	42	16	28	11	19	64	40	300	-639	66	31950	1	Dry steppe	Taiga

Table 3. The average and standard deviation of volume indicators of the studied layers. Source: Authors.

Numerical statistics	Layer 1 volume index	Layer 2 volume index	Layer 3 volume index	Layer 4 volume index
Average	11.1875	17.3438	28.4375	21.3438
Standard deviation	6.83	13.23	21.59	14.79
The minimum	2	3.5	3	3.5
The maximum	25	48	81	53

calculated trigonometric distances (ΔX), and the type of the lands.

Finally, the travel conductivity of simulated journeys ($Q_{(M)}$) is explained based on Equation 3 and presented in Table 4. In this equation, the travel conductivity is equal to the travel risk multiplied by the difficulty coefficient and further multiplied by the result of dividing the commercial potential by the actual distance between the origin and destination, where the relationship between caravan characteristics and travel is analyzed for historical dynamic analysis.

Equation 3:

$$Q_{March} = kA\frac{\Delta T}{\Delta x}$$

Table 4. Quantitative specifications of the simulated journeys. Source: Authors.

Travel (M)	Commercial potential (ΔT)	Actual distance (ΔX)	Hardness factor (A)	Travel risk (A)	Heat transfer (Q)
1	48	798	0.5	-3	0.0451
2	-19	470	0.1	-4	-0.444
3	43	1150	0.1	-6	0.729
4	-86	120	0.1	-8	-12.89
5	-138	2270	1	5	-3.674
6	-42	1835	0.5	-12	-0.283
7	-50	696	0.1	-3	-1.257
8	-45	4782	0.5	1	-0.309
9	44	3190	0.5	-4	0.155
10	63	290	1	7	11.43
11	-79	290	0.5	-18	-9.057
12	88	290	0.5	15	8.451
13	-42	31950	1	-10	-0.063
14	37	31950	1	-5	0.016

In calculating the travel conductivity of simulated journeys, the numbers have been computed as real numbers with three decimal places. The term $Q_{(M)}$ is an abbreviation for the level of goods transportation in the form of a commercial journey. Now, the obtained results from this equation need to be examined to determine its explanatory power for historical dynamic analysis.

Discussion and Analysis

Among the 16 caravanserais studied during the Safavid era, three caravanserais, KhaneSorkh of Kerman, QalehPahlou of Lar, and Sangtou of Kerman, shared common architectural features. This commonality lies in their location in the semi-arid desert and semi-arid steppe climates. All caravanserais had a plan with a central square or rectangular courtyard, and only Aminabad Caravanserai had an octagonal plan, indicating an additional qualitative emphasis on security and visibility. In Sangtou and KhaneSorkh of Kerman caravanserais, the second and fourth layers were identical, and compared to other studied caravanserais, they had a smaller scale.

Sadrabad Caravanserai of Qom also has a second layer, indicating a high volume of commercial travel. Ten of the studied samples (Sangtou, Aminabad, Shah Abbasi, Dodahak, QalehPahlou, Sadrabad, Pasangan, KhaneSorkh, Murchekhort, and Koohpayeh) have security towers within their first layer.

The first-layer volume indicator of caravanserais is consistent with a low standard deviation, with only Dodahak of Delijan and Koohpayeh of Isfahan caravanserais showing an increase, indicating points requiring security due to external factors.

The second-layer volume indicator implies the prosperity of trade and stable security. Aminabad, Mahidasht, and Murchekhort caravanserais have the highest indicator value, highlighting the commercial significance of the roads leading to them.

The third-layer indicator or the stable is a variable with significant fluctuations, demonstrating that, in addition to trade variables, factors such as climate also play a role. Aminabad and Pasangan of Qom caravanserais have the highest volume in this layer.

The fourth layer is simultaneously influenced by climate and trade, with the highest values observed in three caravanserais: Aminabad, Koohpayeh, and Pasangan.

Regarding the quantitative findings simulated by the model based on the priority of high-traffic routes, Table 5 illustrates the convergence between the model components. Commercial potential shows a significant negative relationship with trade distance, while it has a positive and meaningful relationship with the security layer and the size of the courtyard. Within the caravanserai layers, relationships between the structural aspects, demonstrating a positive and meaningful connection between the courtyard, residential space, and the stable layer. Convergence relationships indicate that the model has successfully established connections between internal and external variables.

The travel conductivity for simulated journeys falls within the range of -12 to +12. For instance, journeys originating from Caravanserai Shah Abbasi

Table 5. Convergence between the model components for simulated journeys. Source: Authors.

Components	Commercial potential (ΔT)	Actual distance (ΔX)	Hardness factor (A)	L1	L2	L3	L4
Commercial potential (ΔT)	1	-	-	-	-	-	-
Actual distance (ΔX)	-0.928**	1	-	-	-	-	-
Hardness factor (A)	0.031	0.471	1	-	-	-	-
L1	0.829*	-0.146	0.023	1	-	-	-
L2	0.543	0.142	0.188	0.346	1	-	-
L3	-0.086	0.157	0.329	0.324	0.709**	1	-
L4	0.829*	-0.186	0.023	0.533*	0.640*	0.790**	1

in Natanz to Caravanserai Sangtou in Kerman and from Caravanserai Koohpayeh in Isfahan to Caravanserai KhaneSorkh in Kerman exhibit high negative conductivity. Conversely, journeys from Caravanserai Sangtou in Kerman to Caravanserai Sheikh Ali Khan in Isfahan and from Caravanserai Sangtou in Kerman to Caravanserai Koohpayeh in Isfahan have the highest conductivity. This aligns with the historical routes of this period, indicating that the two identified routes were more significant during the Safavid era (Fig. 11). This analysis suggests that the current model can show the structure of caravanserais and their relationships with the commercial and environmental conditions of that period.

In addition to explaining the aforementioned equation, the results indicate that Isfahan served as a potential destination for commercial journeys in terms of goods type, commercial commodities, climatic conditions, and travel distances. On the other hand, Kerman was a suitable origin for commercial journeys with Isfahan as the destination. Simulated journeys toward southern cities and the Persian Gulf marginal lands suggest that central Iranian cities and those on the margin of the Persian Gulf were potential routes for traders. This was due to the development of the Maritime Silk Road in the Persian Gulf and the high seas south of Iran, which became prominent at the end of the Safavid era. These routes were built alongside older routes from the Kerman region during this period. Subsequent routes extended toward to the northwestern and northeastern cities of the studied area.

Investigating the volumes of the second and fourth layers (layers defining the commercial travel potential) of caravanserais in Isfahan and other cities, which served as commercial origins for Isfahan, reveals a high potential for commercial journeys in Isfahan and exhibit a very high conductivity, indicating the thriving trade in Isfahan during the Safavid era. Both domestic and international studies confirm this, as Isfahan experienced its most prosperous times during the Safavid era.

Conclusion

In pursuit of the research objective, aiming to present a model explaining the relationship between the structural framework and various components determining the prosperity and trends of trade, a dynamic equation derived from thermodynamic science regarding the thermal conduction rate has been proposed. This mathematical model has been examined by aligning the components determining travel difficulty and the criteria determining the architectural design of caravanserais with the simulation of a set of journeys between 16 selected caravanserais of the Safavid era. The evaluations conducted at various stages of the research have been performed with the following mathematical equation, considering the primary features of commercial journeys, including travel risk, origin and destination distances, climatic difficulties in journeys, the difference in elevation between

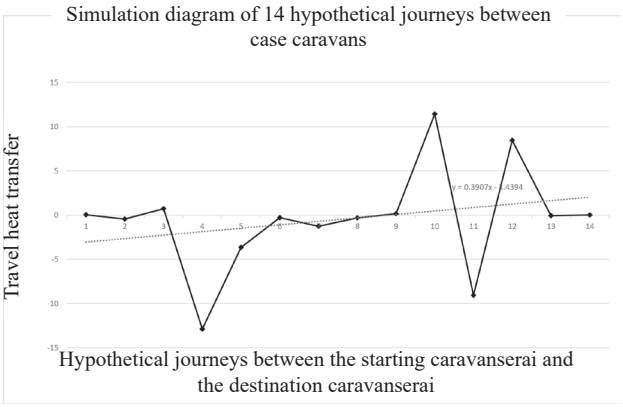

Fig. 11. The simulation diagram of 14 virtual journeys between caravanserais. Source: Authors.

the origin and destination of the journey, and the commercial potential between the origin and destination of the journey, in the context of a 4-layer categorization (Layer 1: Security Layer, Layer 2: Residential Layer, Layer 3: Stables, and Layer 4: Goods Storage) focusing on the characteristics of caravanserais. All data have been extracted for analysis using numerical indicators related to these 4 layers in caravanserais.

$$Q_M = kA\frac{\Delta T}{\Delta x}$$

The study method is similar to the research about the mathematical method of the Silk Road article (Malkov, 2014), whose designs its mathematical hypothesis about the cargo conduction equation along the Silk Road from East to West Asia, and then verifies its model confidence by analyzing the journeys of Marco Polo. Meanwhile, the current research focuses on the conduction rate of journeys within the geographical scope of the Safavid era. To validate the findings, it utilizes the physical characteristics of caravanserais. Throughout the research stages, conditions were imposed to enhance comprehensiveness, quality assessment, precision assessment, and validation, and these conditions were met.

Nevertheless, the impact of physical spaces in the application of studies in the field of computational-social sciences, particularly in the context of suburban caravanserais, requires the development of the current research. This development aims to generate more explanatory models and more executable solutions. Achieving this goal will be possible through the development of future research endeavors.

Endnotes

1. These lands include the AqQoyunlu state territory before their dissolution and collapse, approximate territory of the major Khanates in the early 10th century AH, the lands under influence of the Ardabil patriarch from the 980s AH, the Safavid conquests in the years 910, 916 and 1008 AH, the Safavid conquests in the year 964 AH in the western border, and the lands they conquered after 1059 AH.

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