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Digital preservation of heritage urban facades: An integrated approach using historic building information modeling and shape grammar analysis

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ABSTRACT

Traditional heritage architecture is renowned for its unique characteristics, which are shaped by local climatic, social, and construction requirements, as well as specific architectural styles that contribute to a sense of identity and place. Preserving the aesthetic and cognitive values inherent in traditional styles poses a significant challenge compared to other tangible assets. However, the digitization of built heritage offers a proactive approach to conservation. In this regard, the management of heritage building information through Building Information Modeling (BIM) plays a crucial role in preventive conservation. The utilization of multi-dimensional digital information models, known as Historic Building Information Modeling (HBIM), is one such approach. This study aims to explore the application of HBIM in representing built heritage, focusing specifically on the research gap pertaining to the need for an effective and integrated methodology for modeling information related to heritage urban facades. The objective is to generate parametric models within the framework of HBIM information management, thereby contributing to preventive preservation mechanisms. The methodology employed in this study consists of two main parts. Firstly, information is derived by analyzing the structural characteristics of heritage facades using Shape Grammar. Secondly, the acquired information is utilized to develop a comprehensive library of HBIM for heritage architectural elements. The results of this study demonstrate the proposed methodology's effectiveness in determining heritage urban facades' morphological, mathematical, relational, and Euclidean characteristics.

1. Introduction

Historic buildings hold significant value and play a prominent role in attaining cultural eminence, establishing local identity, and facilitating urban development processes within heritage urban areas (Abdullah and Wahda, 2015). The built heritage category encompasses all structures with exceptional architectural or historical significance, meeting conservation standards and earning classification as World Heritage Sites (Shin et al., 2020). These heritage establishments possess diverse emotional, cultural, and utilitarian values (Sakshi et al., 2022).

Digital preservation in the context of Heritage Building Information Modeling (HBIM) is a key aspect in the conservation and management of architectural heritage. Digital models, also known as digital twins, allow for the documentation and recording of investigation results, enabling the detection and analysis of deformation and materials deterioration (Yanming et al., 2023). Integrating multi-source data and adapting scan-to-BIM processes are crucial in creating enriched models that meet the requirements of replicability and interoperability (Cecilia, 2023).

HBIM, or historic building information modeling, is a method used for the monitoring, maintenance, restoration, and virtual exhibitions of historical buildings (Olga, 2023). The reconstruction of HBIM from raw data such as point clouds and images is challenging, especially in terms of parametrical and semantic modeling (Lütfiye and Neslişah, 2023a). Recent studies have explored the use of architectonic grammar to facilitate this reconstruction process. The manual modeling of cultural heritage with architectonic grammar has been investigated, and a roadmap consisting of four levels of automation has been proposed: calibration, selection, combination, and generation. (Maha et al., 2023). These levels' quality improvement and cost analysis have shown that calibration and selection are currently the most suitable options for

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real-world applications.

Shape grammar has been proposed as a design approach for libraries of European Classical architectural elements (Maurice et al., 2021). This design is based on the development of library objects using architectural rules to construct parametric representations of architectural elements (Daniele et al., 2023). The generation of 3D objects for virtual reconstruction requires the application of computer algorithms and rules based on manuscripts. The use of graphicly constructed and coded parametric libraries in formal and open-source platforms is considered (Umberto, 2023).

Many studies have focused on preserving architectural heritage information, with some specifically applying concepts from Historic Building Information Modeling (HBIM) to urban heritage. Murphy, for instance, utilized survey data and pattern books to create preservation documents and model heritage elements from a specific time period (Murphy, 2012). Dore introduced procedural modeling tools that enable generating more precise and automated models from point clouds (Dore, 2017). Lütfiye discusses the integration of Building Information Modeling (BIM) technology into historical and cultural heritage structures, resulting in Historic Building Information Modeling (H-BIM) (Lütfiye and Neslişah, 2023b). Aida discusses the application of the HBIM process in the conservation and management of architectural heritage, specifically focusing on integrating thematic information in a HBIM model (Aida et al., 2023). María discusses using HBIM to manage and document conservation projects for historic buildings, specifically focusing on the analysis of building facades (María et al., 2023). Chiara proposes a methodological approach to incorporating 2D building archaeology analysis into the HBIM environment (Chiara, 2023). Elisa presents a methodology to derive 4D building models using machine learning techniques and historical maps (Elisa et al., 2021). Eleonora proposes a method for classifying 3D heritage models by segmenting their textures using supervised machine learning methods (Eleonora et al., 2018).

Previous research has primarily concentrated on modeling individual buildings, lacking a comprehensive methodology for extracting urban heritage information encompassing mathematical, relational, and morphological aspects. Therefore, this study proposes an integrated methodology for analyzing the architectural composition of urban heritage facades and subsequently modeling them within the framework of Historic Building Information Modeling (HBIM). This approach serves as a foundation for implementing preventive conservation measures.

2. Conservation

Architectural conservation pertains to the strategies implemented to mitigate or minimize the degradation or alteration of significant structures, thereby prolonging their lifespan while safeguarding their cultural and societal worth through minimal interventions (Feilden, 2003). As per the employed methodologies, conservation can be categorized into Preventive and Remedial Conservation (Emad, 2014):

Preventive preservation is a holistic and proactive approach aimed at safeguarding historical structures. It relies on the systematic monitoring of records and the diagnosis of specific cases to identify the causes of deterioration. By employing direct or indirect interventions, preventive conservation aims to prevent or minimize the future impact of these causes. This approach goes beyond considering only the building materials; it also encompasses the surrounding environment and the management of risks, materials, and external forces. To achieve this, a comprehensive understanding of the systems and factors influencing the building is necessary, aiming to extend the building's functional lifespan at a minimal cost (ICOM-CC, 2008). The management of preventive conservation encompasses various aspects, and one of the most important aspects is Information Management, this domain encompasses the exchange and representation of information as outlined in the references (PNCP, 2012; Emad, 2014), so, within this study, the utilization of HBIM in preventive conservation will be based on the scope of Information Management.

2.1. BIM and HBIM

The definition of Building Information Modeling (BIM) technology varies depending on its application in various domains such as design, manufacturing, construction, maintenance, and demolition. BIM is the digital representation of an object's physical and functional characteristics stored in a shared knowledge resource. It serves as a reliable foundation for decision-making throughout the entire life cycle of a building, from its initial concept to its eventual demolition (Marco, 2022). On the other hand, the term "Historic/Heritage Building Information Modeling/Management" (HBIM) refers explicitly to the utilization of BIM technology in the context of historic and heritage buildings. This term was coined to distinguish BIM applications in the realm of built heritage, which presents unique challenges due to the diverse range of component types and associated information. The concept of HBIM was first introduced at the Politecnico di Milano Applied Technological University in Milan, Italy (Murphy, 2012).

While BIM technology primarily focuses on managing information for new buildings and facilities, which have pre-configured object libraries, HBIM necessitates the creation of libraries containing objects and historical features. These libraries must be developed based on the building's specific heritage and urban characteristics. Consequently, the methodology employed in HBIM systems differs from that of BIM systems. HBIM aims to generate conservation documents and representation models, whereas BIM is primarily concerned with creating representation models alone. Furthermore, HBIM systems generate models that adhere to a particular architectural style within specific timeframes, in contrast to BIM models, which are more general in terms of architectural details and timeframes (Murphy, 2012).

HBIM models encompass various information types represented through components and elements (María et al., 2023). Firstly, geometric information pertains to the data used to construct 3D models. Secondly, semantic information describes the properties and characteristics of the components. Lastly, topological information elucidates the relationships between different components. Moreover, due to their high interoperability, HBIM models exhibit notable compatibility and coordination with various applications. Consequently, HBIM can seamlessly share information models with other technologies. Its ability to adopt multiple formats, such as geographic information systems (GIS), virtual reality, artificial intelligence applications, and descriptive programming languages makes this possible. The BIM informational models serve as a comprehensive database for other technologies to effectively manage, analyze, and interpret item information (Ramona et al., 2017).

2.2. HBIM libraries

The introduction of digital libraries containing heritage elements by Murphy (2012) was a landmark, but challenges arise in urban heritage due to diverse architectural styles and the complexity of heritage elements. Parametric libraries offer a solution, using architectural documentation and digital scanning to create three-dimensional models. Marko et al. (2020) highlight the key feature of these libraries, enabling information exchange and promoting interoperability within Historic Building Information Modeling (HBIM) platforms. HBIM libraries serve as constructive databases for building objects throughout their lifecycle, streamlining analyses and adapting to changing needs (Daniela et al., 2014). They encompass a wealth of information on built heritage, facilitating accurate depictions of changes and the creation of urban conservation documents (Quattrini and Eleonora, 2015). These libraries enhance information management, connecting with other data sources through BIM platform interoperability, improving structural studies, time and cost calculations, and managing conservation efforts.

However, a notable obstacle is a lack of applications effectively

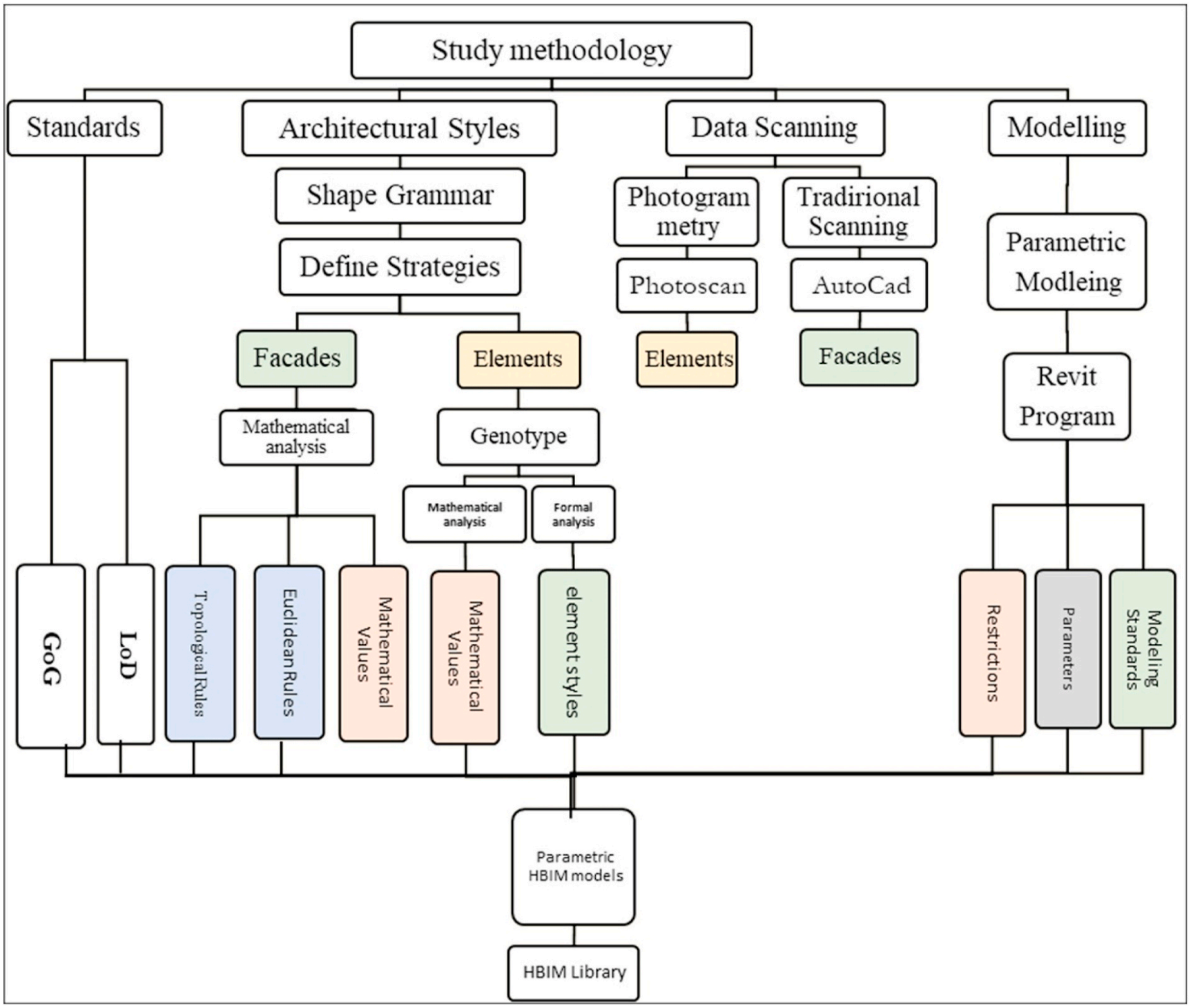


Fig. 1. Research methodology (source, the researcher).

utilizing these libraries for parametrically modeling elements in historic buildings with irregular surfaces. Most BIM libraries focus on pre-designed elements, and manual modeling is time-consuming. Importantly, HBIM libraries represent specific historical cases and do not cover all architectural styles in historic buildings.

2.2.1. Research aim

The primary objective of this study is to establish an applied work platform that utilizes HBIM to represent urban heritage information. A work methodology based on information analysis and modeling will also be presented. The sub-objectives include.

- Producing a digital architectural archive to manage the design and maintenance of historic buildings.
- Creating digital documentation for the traditional case study building (Mosul Old and City MOC-HBIM) for reconstruction and urban conservation operations.

2.2.2. Research problem

Despite the widespread adoption of building information modeling (BIM) in preventive conservation, there is a need for an integrated and effective methodology that can accurately represent the characteristics of heritage buildings. This methodology aims to create parametric information models, specifically an HBIM (Heritage Building Information Modeling) library, to facilitate information management of urban facades as a preventive preservation mechanism.

2.2.3. Objectives

The primary objective of this study is to establish an applied work platform that utilizes HBIM to represent urban heritage information. A work methodology based on information analysis and modeling will also be presented. The sub-objectives include.

- Producing a digital architectural archive to manage the design and maintenance of historic buildings.
- Creating digital documentation for the traditional case study building (Mosul Old and City MOC-HBIM) for reconstruction and urban conservation operations.

2.3. Materials and methods

The study employs the following methodology to develop a parametric library of urban heritage facades, as shown in Fig. 1.

2.4. Study concepts

This study will rely on concepts in the practical component that have been proposed in the methodology, encompassing the following.

2.4.1. Shape grammar

Stiny and Gips introduced a production approach in 1972 that generates shapes based on specific rules. This approach can generate designs in the same language or derive a new language (Stiny and Mitchell,

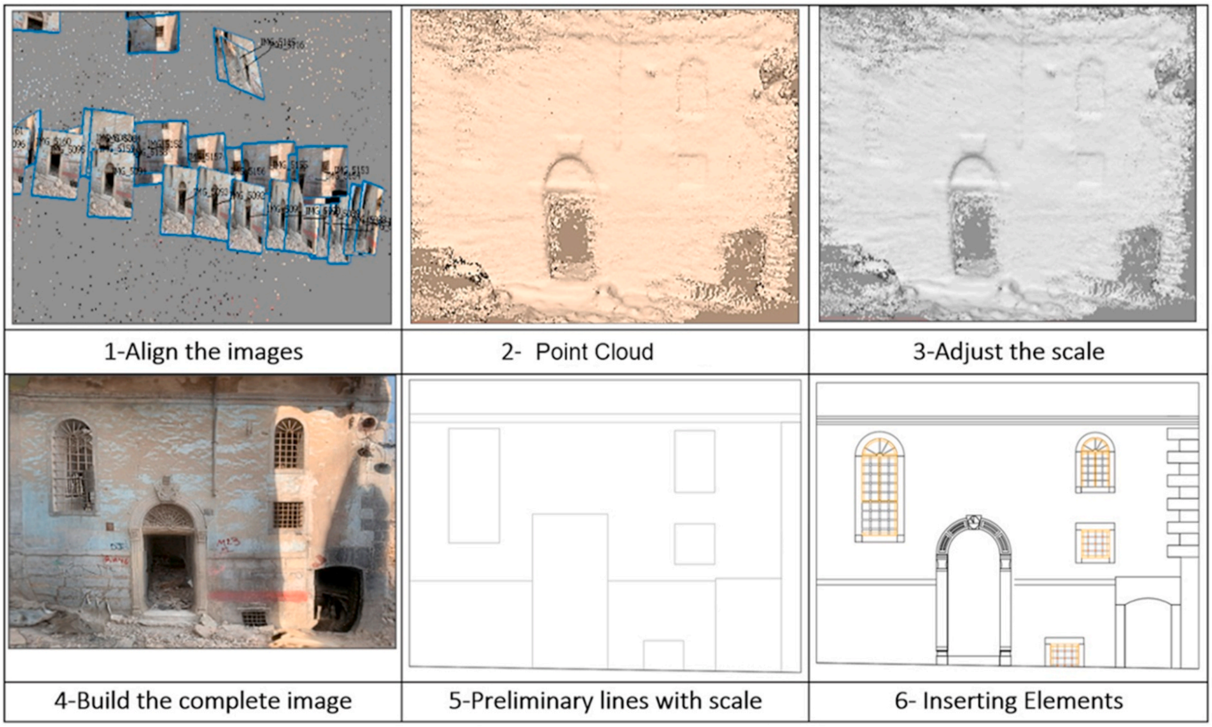


Fig. 2. stages of documenting facades (The researchers).

1978). Shape grammar rules can be generalized as constraints in construction processes to ensure consistency with the urban environment (Hsiao-Tung et al., 2023). One of the key features of Shape Grammar is the generation of models with distinctive characteristics through "specific patterns to unify design elements" (Godoi and Celani, 2008).

2.4.2. *Photogrammetry*

Photogrammetry is a highly accurate, flexible, and adaptable method within multi-scale image-based modeling techniques. It is utilized to derive metric information that accurately represents the scene from a set of photographs (Middleton et al., 2019).

2.4.3. *Parametric modeling*

Parametric modeling involves defining object properties using parameters that can automatically adjust within specific values. Fixed rules connect these parameters, so a change in one parameter affects the others according to specified constraints (Fu, 2018).

3. Case study

The heritage houses in the old city of Mosul, dating back to 1850, feature a unique architectural style shaped by factors like climate, religion, culture, economy, and construction needs (Al-Tayeb, 2008). This style, governed by specific rules, harmoniously integrates elements such as entrances, windows, etc., resulting in unified urban facades. These architectural elements are categorized based on function and form (Dewachi et al., 2010), including Entrances, Openings, Windows, Frieze, Madamic, Corbels, Arches, Corners, and Extensions (Mustafa and Hong, 2010).

3.1. *Applying the methodology*

The aforementioned procedures will be implemented during the empirical phase of this research endeavor.

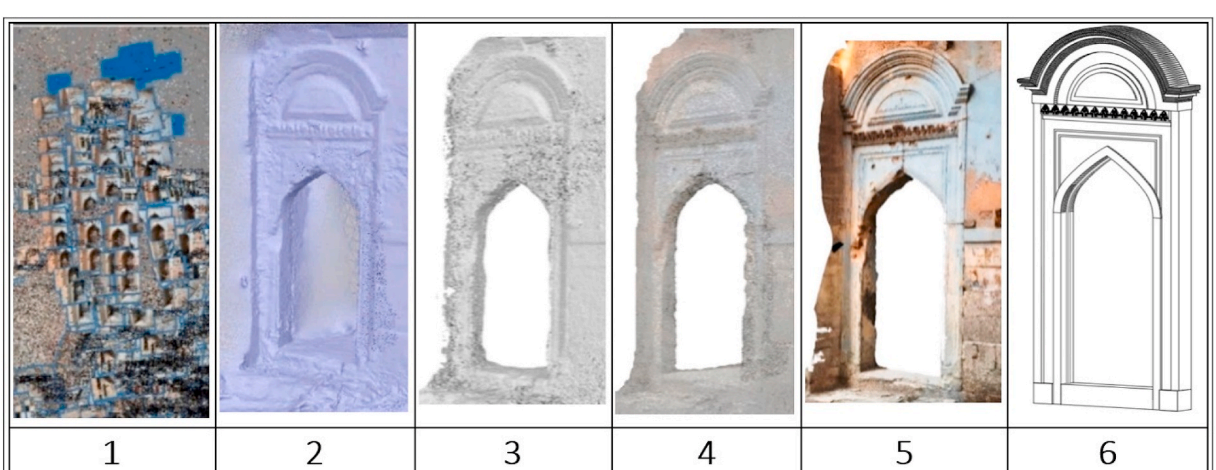


Fig. 3. Stages of data processing using photogrammetry of heritage architectural elements (The Researchers).

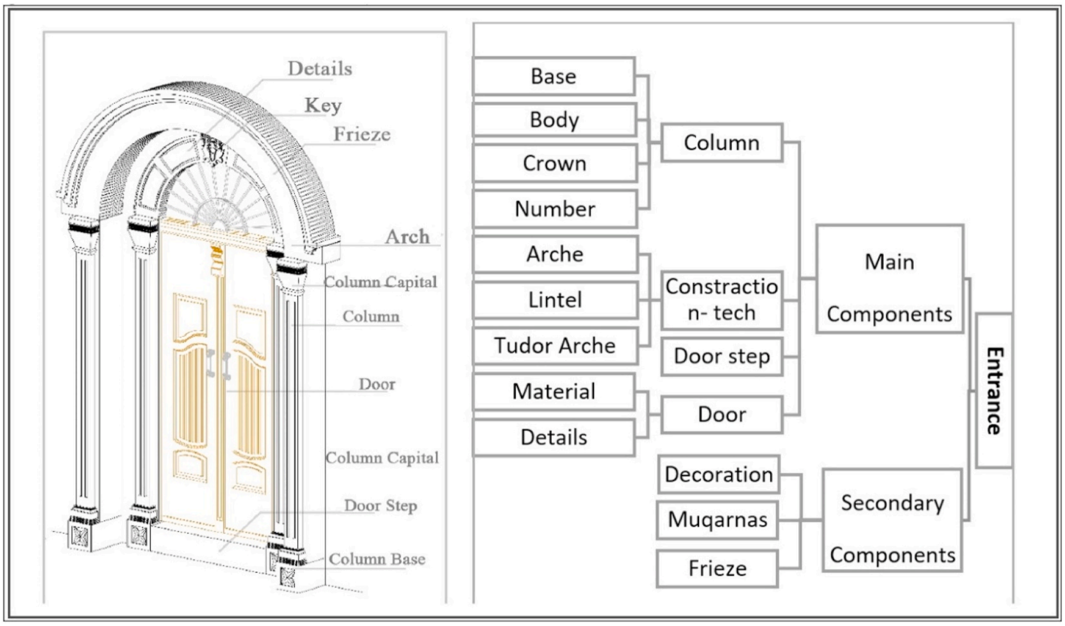


Fig. 4. The main and secondary components of the entrance (The Researchers).

3.1.1. *Documentation*

The documentation of the case study facades involved the utilization of a digital camera to describe meticulously and record data about 4000 facades of traditional Mosulian dwellings, which accounts for approximately 30% of the total facades (equivalent to around 12,000 housing units) (Directorate of Antiquities and Heritage in Mosul-2023). The documentation process encompassed two distinct types of data.

3.1.1.1. Facades documentation. From a pool of 4000 documented facades, a systematic sample of 760 interfaces was selected to capture the study case's essential formal and structural characteristics. These facades were categorized into 19 groups, each containing 40 facades

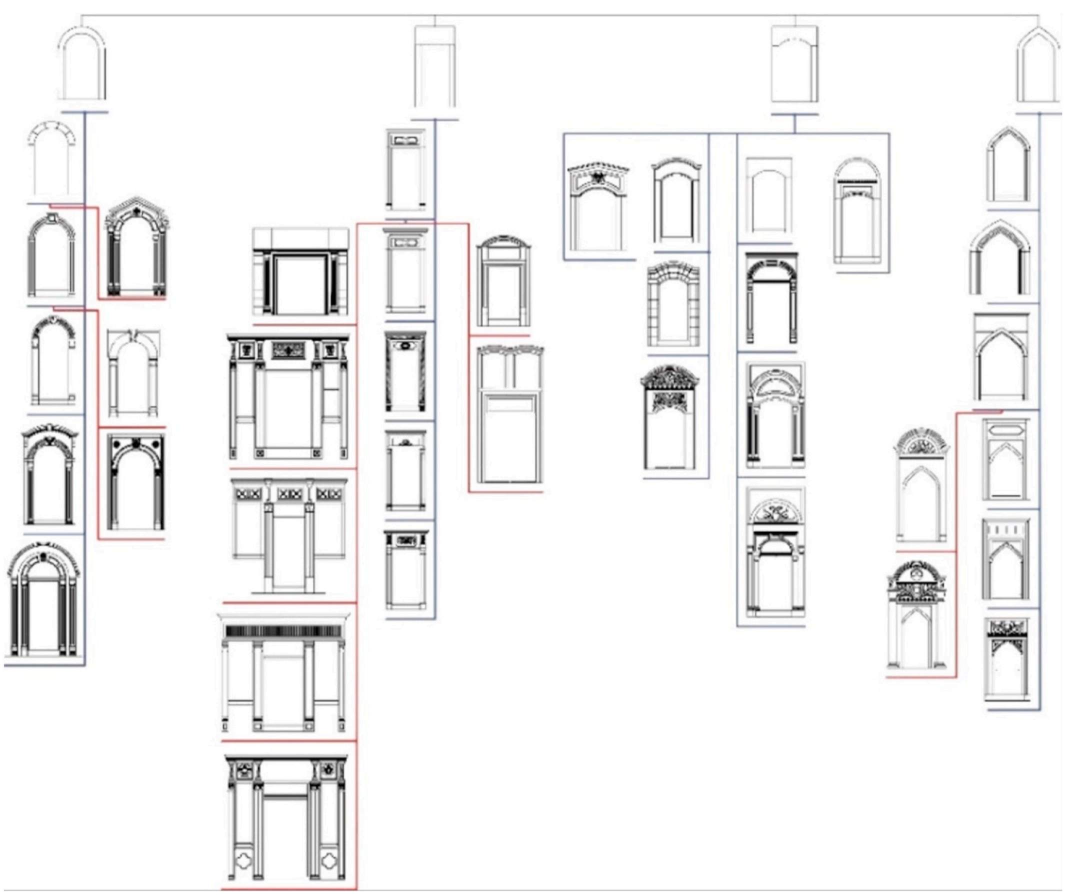


Fig. 5. genotype of entrances in the traditional mosul dwellings facades (The researchers).

Element	Vertical Level	Value	Horizontal Level	Value
Entrance (E)	• Corner Position (Ev-c) R1: W ≤ 3* Ew	Left Right	• Under the road level (Eh-a) R4: Eh > Level of Road	0.15-1.0
	• Centre Position (Ev-ce) R2: ½W ≡ ½Ew	½ W	• With the road level (Eh-w) R5: Eh ≡ Level of Road	0.0
	• Mid Position (Ev-m) R3: ½W-Ew ≤ Ew	½W-Ew	• Above the road level (Eh-u) R6: Eh < Level of Road	0.15-0.4

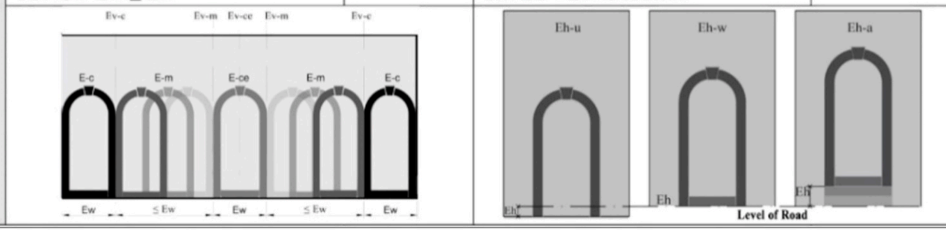


Fig. 6. euclidean rules of architectural heritage entrances (The researchers).

identified by a unique symbol. The documentation process involved (Fig. 2).

- Capturing high-resolution facade photographs with a digital camera, ensuring coverage overlap for suitable cloud point establishment.
- Using PhotoScan program to convert images into a cloud point-compatible.
- Generating comprehensive AutoCAD-format by amalgamating individual photos.
- Importing images into AutoCAD and adjusting scale using the Scale Reference feature.

3.1.1.2. Documenting the architectural elements. The process of documenting the architectural elements in this study involved using the photogrammetry technique, which ensured precise and accurate documentation. This process was carried out in two distinct phases. The initial phase encompassed conducting field surveys using a digital camera to capture high-resolution images of each element, with the number of images ranging from 50 to 200 depending on the level of detail and complexity. The subsequent phase involved office work, wherein the identified elements were modelled using the Photoscan program. The acquired data was then transformed into both 2D and 3D formats, as depicted in Fig. 3.

3.1.2. Derivation of the rules

The analysis of the documented facades will be conducted at Three levels.

3.1.2.1. Morphological analysis – genotype. The Genotype system has been widely employed in architectural studies to analyze the morphological structure of shapes, including their basic and secondary components, and to determine the relationships and characteristics of their phenotype (Mahdi and Ibrahim, 2016). The morphological analysis involves determining the genotype of the architectural heritage element by examining its morphological characteristics and primary and secondary components using 3D Shape grammar (Fig. 4) (Fig. 5).

3.1.2.2. Relational analysis. The term “relation" refers to the organization of elements on the facades. These relationships can be spatial and fall into three categories: Tri-Dimensional or Bi-Dimensional relationships within a specific level. Relationships could be classified as follows.

- Euclidean Relations: These relationships are based on quantitative geometry concepts and are categorized according to the organization with respect to a reference point, a line, or a coordinate system. This type of relationship will establish rules for the horizontal (H) and

Element			Rules	%
Entrance (E)	Window	Cellar Window	• RE2: if Eh1>Level of Road, then WCh≡ Level of Road	100%
		Bath Window	• RE2: if Eh2 > Level of Road, then WBh ≡ Eh1	80%
		Ventilation Window	• RE3a: = WVv= ½ WVv ≡ ½ Ev • RE3b: = WVh= Eh + (0.1-0.6)	100%
	Extension	Shanshool-Balcony	• RE4: if EX-S w< W, then EX-S h≡ Eh	100%
		Mass (Bath)	• RE5: EX-M h ≠ Eh	100%
	Frieze (F)		• RE6: Fh1≡ Fh2≡Eh1 • RE7: Fh2≡Eh1	100%
	Arches (A)		• RE8: ½Ew≡ ½Ad	100%

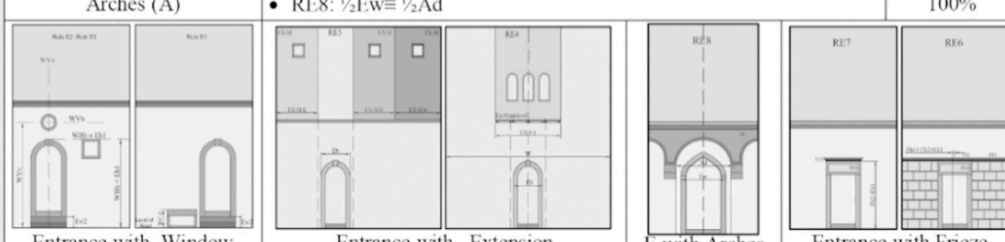


Fig. 7. typological rules of architectural heritage entrances (The researchers).

vertical (V) placement of elements on the facade using parameters. The objective here is to establish the rules governing the placement of architectural elements on the facades (Fig. 6).
- Topological Relationships: These relationships rely on non-quantitative geometry concepts to analyze the positioning of an object in relation to other objects. It involves arranging elements based on other elements, regardless of their types. Examples of topological relationships include Proximity, Closure, Succession, Interpenetration, and Division (Fig. 7).

3.1.2.3. Related analysis. This involves identifying the relationships between architectural elements at two levels.

- Style Relationships: This focuses on defining the usage of architectural element styles based on their morphology.
- Position Relationships: This involves deriving the rules for placing architectural elements in relation to each other.

This methodology was employed to analyze and prepare information about seven distinct architectural elements to facilitate the subsequent modeling stage.

3.2. *Parametric modeling*

In this stage, the formal and mathematical information obtained earlier will be utilized to create models that simulate the behaviour of architectural elements. This will be achieved by employing parameters that allow for quick, flexible, and efficient modification of these properties while preserving their formal and relational characteristics. The number of models that differ solely in parameter values can be reduced by utilizing parameters, thanks to the Family property of Building Information Modeling (BIM).

The subsequent stages outline the process of parametric modeling for the heritage elements.

- Modeling the primary component will involve utilizing instance properties, while the secondary components will be modelled using type properties.
- Mathematical properties determined by Shape Grammar will be modelled using parameters. Additionally, Shared Parameters will be employed to represent common properties shared among elements within the same family type, while Project Parameters will represent properties specific to a particular element. Parameters will be encoded to indicate the restrictions or properties of the corresponding part. For instance, the mathematical parameters of the Entrances element will be encoded.
- Determining the mathematical value restrictions of the elements, as well as establishing the relationships between components, will be accomplished through:
  - o Implicit constraints: This type determines the relationships of model components by the Reference Line and Reference Surface tools.
  - o Materials parameters: P-Material changes the elements' materials according to their values.
  - o Min/Max Values constraints: to specify the values range parameters using the following formula.

PEh-c Formula:= if (Height $<$ 2.5, 1.9, Height) (1)

- o Proportional constraints to determine the proportions of element components

If-And = if (and (Width $>$ 10, Width $<$ 20), Height = 30, Height = 36) (2)

Table 1
relational analysis of the architectural elements (source: Researcher).

Corbels	Arches	Corner	Frieze	Madamic	Services	Balcony	Shanshool	Basement W	Wc W.	Ventilation W.	Room	Entrance		
–	100%	–	41 %	18 %	100%	88	97%	55%	65%	100%	17.5%		Entrance	
–	100%	–	12.4%	72 %	–	–	100%	–	7.3 %	–		17.5%	**Room**	**windows**
–	100%	–	–	47%	–	–	–	–	–		–	100%	**Ventilation**	
–	100%	–	36%	15%	100%	–	–	–		–	7.3 %	65%	**Wc**	
–	–	–	80 %	75%	–	–	–		–	–	–	55%	**Basement**	
32%	–	67%	95%	–	–	–		–	–	–	100	97%	**Shanshool**	**Extension**
–	–	13%	12%	–	–		–	–	–	–	–	88 %	**Balcony**	
12%	–	30%	–	–		–	–	–	100%	–	–	100%	**Services**	
23%	65%	88%	100%		–	–	–	75%	15 %	47%	72 %	18 %	**Madamic**	
78%	100%	85%		100%	–	12%	95%	80%	36%	–	12.4%	41 %	**Frieze**	
23%	73%		85%	88%	30%	13%	67%	–	–	–	–	–	**Corner**	
–		73%	100%	65%	–	–	–	–	100%	100%	100%	100%	**Arches**	
	–	23%	78%	23%	12%	–	32%	–	–	–	–	–	**Corbels**	

Table 2
Relational analysis of styles of architectural elements (Source: Researcher).

Pointed		Segmental		Arch		Rectangular		Simple		Architectural element				ت
Ratio	No.	Ratio	No.	Ratio	No.	Ratio	No.	Ratio	No.					
6.7 %	4	13 %	5	**29%**	64	5.5 %	8	7 %	2	Simple	Marble	Room	windows	1
11.6%	7	24 %	9	6.2 %	7	**59.5 %**	88	10.8 %	3	Rectangular				
55 %	33	**49 %**	18	19.8 %	22	21.5 %	32	3.6 %	1	Arch				
16.6%	10	2.7 %	1	0.9 %	1	–	–	–	–	Segmental				
3.4%	2	2.7 %	1	20.7 %	23	0.5 %	1	–	–	Pointed	Wooden			
–	–	8.6 %	3	13.5 %	15	13.5 %	20	**78. %**	22	Rectangular				
6.7%	4	–	–	0.9 %	1	–	–	–	–	Pointed				
57 %	40	**80 %**	8	**66.3 %**	67	**53 %**	60	6.6 %	4	Square	Marble	ventilation		
5.7%	4	20 %	2	8.0 %	8	7.0 %	8	–	–	Rectangular				
11.5%	8	–	–	2.0 %	2	1.8 %	2	–	–	circular				
2.8 %	2	–	–	1.0 %	1	–	–	–	–	elliptical				
23.0 %	16	–	–	16.7 %	17	26.5 %	30	**66.4 %**	42	Wooden				
–	–	–	–	6.0 %	6	11.7 %	13	27 %	17	Without				
55.5 %	5	20 %	2	**62.4 %**	10	**70.0 %**	14	20 %	1	Rectangle	Marble	basement		
11 %	1	**80 %**	8	18.8 %	3	10 %	2	–	–	Segmental				
33.5 %	3	–	–	18.8 %	3	20.0 %	4	**80 %**	4	Wooden				
25.0%	5	**43.0%**	3	15.5 %	9	8.1 %	3	–	–	balcony			**Extension**	2
5.0 %	1	28.5%	2	1.7 %	1	2.7 %	1	–	–	tringle		shanshool		
25.0%	5	28.5%	2	**55 %**	32	**40.5 %**	15	–	–	Rectangle				
20.0%	4	–	–	–	–	10.8 %	4	–	–	Corner				
5.0 %	1	–	–	6.8 %	4	5.4 %	2	–	–	Trapezium				
13.8%	4	–	–	21.0 %	12	32.5 %	12	**100%**	16	Bathroom				
13.8%	4	9.0 %	1	22.2%	8	25.0 %	7	**80 %**	4	Simple			**Corner**	3
41.5%	12	36 %	4	**69. %**	25	**64.2 %**	18	–	1	One Floor				
17.1%	5	**46%**	5	8.4 %	3	10.8	3	–	–	Tow Floor				
13.8%	4	9.0 %	1	–	–	–	–	–	–	Combined			**Madamic**	4
4.3 %	2	17.6%	3	3.5 %	4	4.7 %	4	27.2 %	12	Low		Height		
13.0 %	6	–	–	**66.5 %**	75	**70.5 %**	60	**68.1%**	30	Medium				
43.5 %	20	23.6%	4	19.4 %	22	12.3 %	13	4.7 %	2	High				
39.2 %	18	**58.8%**	10	10.6%	12	12.5	8	–	–	All Height				
43.5 %	50	28.5%	16	**57. %**	125	**60.0 %**	90	**88 %**	44	Single			**Frieze**	5
56 %	65	**71.5%**	40	42.7 %	93	40.0 %	60	8.4 %	6	Multi				
–	–	–	–	27.3	3	**77.7%**	7	–	–	Simple			**Arches**	6
100%	6	**100%**	4	**72.7**	8	22.3%	2	–	–	Combined				
87.5%	14	**66.6%**	4	**70 %**	12	**50 %**	6	–	–	Simple			**Corbels**	7
12.5%	2	33.4%	2	29.5 %	5	**50 %**	6	**100 %**	1	Combined				

o Nested Statements: its formula:

If-And = if (and (Width > 10, Width <20), Height = 30, Height = 36) (3)

o Yes/No Condition: its formula:

IF with Yes/No condition = if (Medmac, <Fraize>, <without Fraize) (4)

o String Formatting: its formula:

= if (parameter a = 24″, "result 1", if (parameter a = 48″, "result 2", if (parameter a", "result 3", "Width not available: Please select a width of either 24, 48, or 72 cm")) (5)

- Placing the Element: To determine the precise locations of architectural elements within the facades, parameters and constraints will be employed according to the following guidelines:
  - o Horizontal parameters (Ph) and vertical parameters (Pv) will be utilized after establishing the implicit reference line. These parameters are shared among unified family models. For instance, the parameter for window height on the ground floor is denoted as Ph-WB, while the vertical parameter is represented as Pv-WB.
  - o The range of values for these parameters will be determined using conditional formulas. If the entered values fall outside the specified range, a message will be displayed to alert the user of the discrepancy.

4. Results

4.1. Relational analysis of element placement

This type of analysis yielded 35 relational rules that serve as constraints for determining the positioning of architectural elements as presented in Table 1.

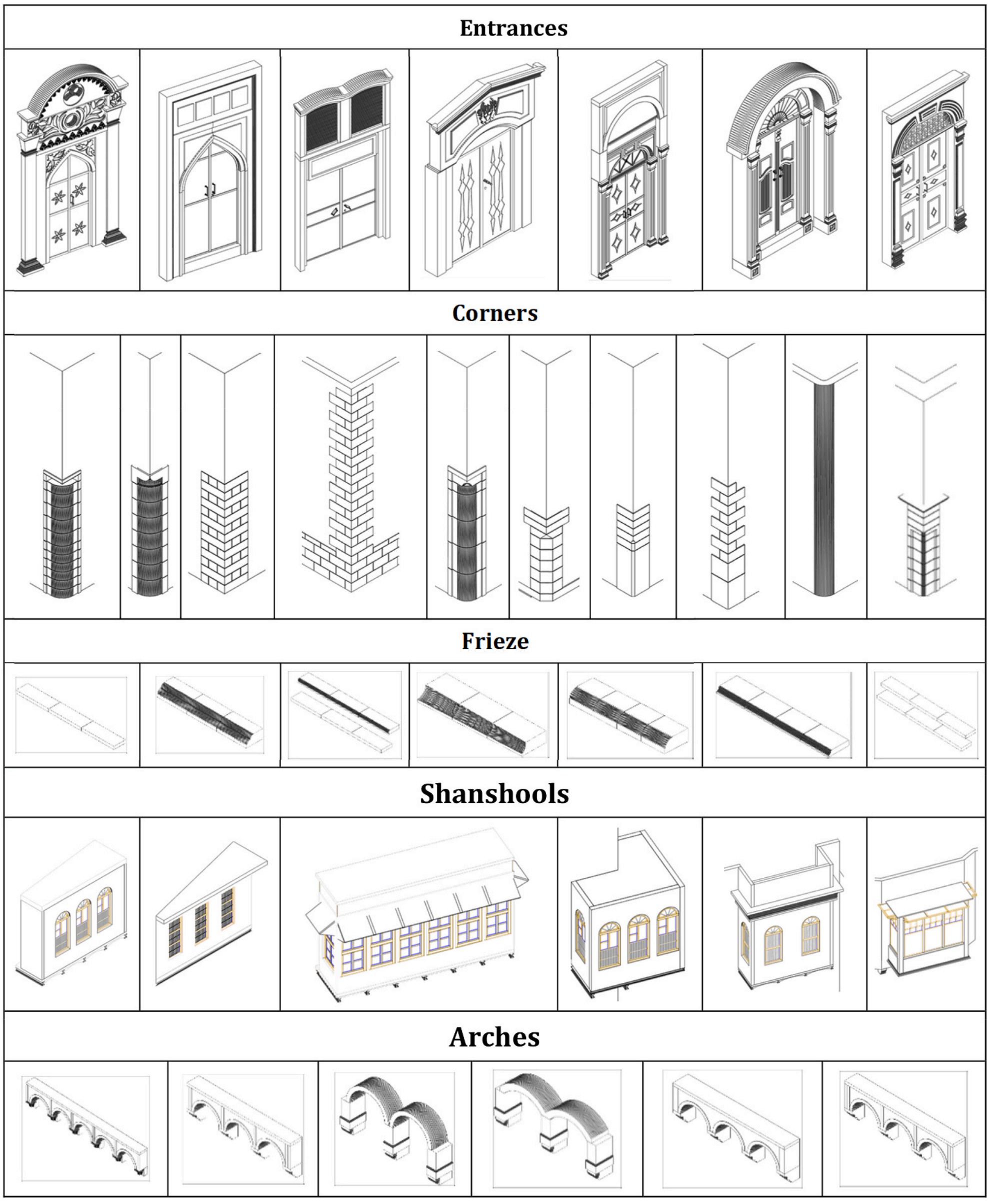
4.2. Relational analysis of styles of architectural elements

Relational Analysis of Architectural Element Styles demonstrate a significant correlation between the utilization of certain aspects and the presence of harmonious morphological characteristics (see Table 2).

5. Discussion

- Genotype analysis of architectural elements: The findings of this analysis reveal distinct styles that exhibit shared morphological characteristics and fundamental components. Each style encompasses elements that exhibit phenotypic variations in response to structural, aesthetic, or functional requirements.
- Analysis of element placement on facades: Examining architectural element placement on facades demonstrates a discernible pattern in the distribution of elements aimed at fulfilling functional, climatic, social (e.g., privacy), and aesthetic design requirements. Furthermore, this pattern indicates the designer's (local) understanding of facade structure and adherence to architectural design principles such as repetition, balance, etc.

Table 3
Samples of parametric objects of architectural elements of modelled HBIM Library.



- Relational analysis results: The Shape Grammar-based relational analysis elucidates the interrelationships between architectural elements in response to diverse requirements, operating at two levels:
  - o Relational analysis of element placement: This type of analysis yielded 35 relational rules that serve as constraints for determining the positioning of architectural elements within seven distinct groups.
  - o Relational Analysis of Architectural Element Styles: The findings of this study demonstrate a significant correlation between the utilization of certain aspects and the presence of harmonious morphological characteristics. This correlation can be attributed to implementing similar construction techniques, thereby indicating a conscious selection of facade elements based on aesthetic, functional, and economic considerations (see Table 2).
- The information modeling results were obtained using parametric modeling techniques. These techniques were employed to represent the mathematical and morphological characteristics of heritage elements accurately. The Family concept of architectural elements, which encompasses elements with typical structural or functional behaviour, was employed in this process. Parameters were used to capture these characteristics, while constraints were employed to model their relationships within predefined value ranges.
- The photogrammetric documentation process yielded significant results using various modern scanning techniques. These techniques facilitated the transfer of acquired data to digital models, thereby enabling the production of three-dimensional models of heritage elements through reverse engineering. This integration between computer-aided design (CAD) software and photogrammetry proved to be highly efficient in generating accurate representations of the scanned objects.
- The resulting HBIM library comprises parametric models of architectural elements that possess realistic simulation features. This library is a practical tool for urban conservation, particularly in the context of preventive conservation of urban facades. It facilitates the management of information pertaining to heritage facades. The library contains a total of 250 parametric models, which are

categorized into seven groups of architectural elements (as shown in Table 3).

- Integrating Building Information Modeling (BIM) as a representation system and Shape Grammar as an analysis and characterization system offers several advantages for historic buildings information modeling (HBIM). This approach represents a critical advancement in leveraging parametric modeling approaches' capabilities within the urban heritage conservation domain. It enables the creation of digital libraries containing heritage elements and virtual city models. These resources provide specialists with real-time access to information, thereby circumventing the information management challenges associated with traditional approaches.

6. Conclusion

The study employs mathematical, morphological, and relational analyses to examine the facades of heritage dwellings. It concludes that despite variations in the size and area of residential units, a cohesive architectural style exists in the local context. This unity can be attributed to the structural, climatic, functional, and economic requirements that have influenced the design of urban facades, resulting in distinct characteristics. Furthermore, the study demonstrates the efficacy of the proposed methodology in digitally representing heritage elements and facades. The utilization of parametric modeling enables the incorporation of various architectural features through parameters and constraints. Additionally, it facilitates the representation of multiple levels of information using the Level of Detail (LoD) concept. This approach creates a virtual environment that supports the management and exchange of information among conservation specialists. By utilizing a unified database, this integrated environment aids decision-making processes, which are crucial for the preventive conservation of urban facades.

CRediT authorship contribution statement

Khalid Ahmed Hussein: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Araz Rajab Abrahim:** Supervision, Software, Resources, Formal analysis. **Ameer Sulaiman Mohammed:** Writing – original draft, Visualization, Investigation, Formal analysis. **Karzan Abdulazeez Ali:** Software, Resources, Investigation, Formal analysis, Data curation.

Declaration of competing interest

I hope this letter finds you well. I am writing to officially declare that the co-authors and I, Khalid Ahmed Hussein, Araz Rajab Abrahim, Ameer Sulaiman Mohammed, and Karzan Abdulazeez Ali, of the research paper titled “Digital Preservation of Heritage Urban Facades: An Integrated Approach Using Historic Building Information Modeling and Shape Grammar Analysis" have no conflicts of interest with regards to the publication of this manuscript.

We affirm that we have disclosed all financial and personal relationships with any individuals or organizations that could be perceived as potential conflicts of interest. This includes but is not limited to, financial support, employment, consultancy, intellectual property, and any other relationships that could be perceived as influencing the work presented in the paper. Furthermore, we confirm that the research presented in the paper is conducted in an unbiased and ethical manner, and the results and conclusions are based solely on the merit of the research.

In accordance with the guidelines of the Journal of Digital Applications in Archaeology and Cultural Heritage (DAACH), we have completed the conflict-of-interest disclosure statements as part of the submission process. We have provided all relevant information to the best of our knowledge. Should any potential conflicts arise during the review process or after publication, we commit to promptly notifying the editorial board and taking appropriate measures to address the situation.

Thank you for considering our declaration. Please contact us if you require any additional information or clarification.

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