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Integrating traditional and smart materials for sustainable rehabilitation of historic housing

Raed Salim Ahmed Alnumman[1*]
[1] University of Mosul Department of Architecture, Iraq

*Corresponding author E-mail: raeedalnumman@uomosul.edu.iq

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Abstract

Sustainable rehabilitation of historic buildings requires approaches that improve the environmental adaptability and preserve the architectural and material characteristics of the buildings. Traditionally constructed buildings of the Old City of Mosul utilize the characteristics of local materials and climatically sensitive architectural elements; however, the utilization of smart materials alongside these aspects has not been studied enough in terms of rehabilitation of the buildings. This paper presents a decision support framework in architecture for the combination of traditional and smart materials in the rehabilitation of traditional buildings. A design-driven approach with architectural and material aspects, in combination with a review of the literature, has been applied to derive four decision criteria: material compatibility, environmental performance potential, conservation considerations, and practical applicability. The framework is based on the relationships between architectural elements and traditional materials, as well as the issues and needs of these elements and materials, and smart material interventions in them. The proposed framework is applied to two traditional houses: Amin Bek Al-Jalili and Al-Tutunji, in order to see its applicability in case of different conservation conditions.

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Keywords: Architectural decision-support framework, Smart materials, Traditional materials, Sustainable rehabilitation, Old City of Mosul

1. Introduction

Traditions in architecture provide certain learning points about the adaptive nature of buildings to the local climate through the integration of space, form, and local materials. Normally, buildings in hot and dry areas use passive means to improve indoor environmental quality without depending heavily on mechanical means [1],[2]. Traditions in the materials and construction of such buildings are also a reflection of the correlation between the needs of the environment and the availability of local resources [3],[4]. These points make traditions in architecture very relevant to sustainability concerns in rehabilitation. However, improvements in the environmental qualities of heritage buildings cannot come at the expense of their materials, architecture, and cultural value. The old part of Mosul has distinct residential architecture that is informed by the climatic conditions, local materials, construction methods, and lifestyle of its inhabitants [5],[6]. Some of the key

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architectural features in these buildings include Iwans, Vaults, Domes and Sirdabs [5],[6]. The building materials include limestone, gypsum, timber, and Mosul alabaster [5],[6]. Architectural features such as the courtyard, thick walls, shaded transitional spaces, and underground chambers work collectively to ensure that passive environmental controls are achieved through means such as shading, ventilation, thermal storage and seasonal occupation patterns [6],[7]. Thus, the environmental responsiveness of these buildings depends on the relationship between the architectural form, space, and material construction.

The modern material technologies give opportunities for supplementing environmental technologies in case any specific rehabilitation requirement is identified. In the framework of the current research, the term "smart and advanced materials" relates to responsive materials, which are materials that can change their properties or behavior according to the environment, as well as advanced functional materials or material systems performing some specific environmental or protective function within the rehabilitation process of architectural heritage. It is essential to distinguish between these two groups of materials since not all interventions under analysis in the current paper are "smart" materials. Phase change materials (PCMs) can store and release heat depending on the temperature, [8],[9] while smart glass materials can change their optical properties, controlling solar radiation and natural light [10],[11]. Advanced insulation materials and protective technologies cannot be qualified as responsive materials but may perform some thermal or protective functions [12],[13].

Therefore, these materials will be referred to as smart and advanced materials, respectively, with some different functions performed. The interaction between traditional, advanced, and smart materials is an independent variable that has been studied in this research through a qualitative decision-making process, which is known as the architectural approach. The interaction between these two kinds of materials involves the choice of advanced and smart materials in addition to traditional materials in cases where there has been a need for the improvement of the environment.

It should be noted that in this research, the performance improvement of this kind of interaction has not been measured at all. Instead, this study assesses the suitability of proposed materials with respect to four criteria, including material compatibility, environmental performance potential, conservation philosophy, and feasibility of the intervention. These criteria help to identify a proper intervention with regard to the status of traditional materials and the architectural significance of the affected parts of the building.

However, the potential of these materials alone is not enough for the introduction of these interventions into historical buildings. The properties of the material and compatibility with the existing material, the importance of the architectural element for restoration, requirements of conservation, and realizable conditions for applying the material should be taken into account [13],[14]. Therefore, the selection of a material becomes an architectural and conservation decision and not only a technological one. Despite the documented environmental benefits, the material cannot be used if it implies significant alteration of the historical building or traditional maintenance techniques meet the needs of rehabilitation.

Although much has been known about the environmental aspects of vernacular and traditional architecture, [2],[3] and much more has been realized regarding the potential performance of modern materials [8],[12] it seems there is insufficient practical connection between these two areas of knowledge for architectural decision-making during the rehabilitation of historic buildings. Here, the main issue is not about which modern material performs better in terms of environmental performance, but rather whether there is a need for intervention, if there is an alternative material compatible with the traditional one, and under which conditions this material use will not affect the traditional one in a negative way. In terms of conservation principles, such decisions have to be based on the principle of retention and minimal intervention [14],[15]. The paper suggests a framework for architectural decision-making for the sustainable rehabilitation of historic houses in Old Mosul.

The first step of the proposed decision-making framework starts with an identification of an existing architectural element, its traditional material, original use, current state, and the necessity for rehabilitation or environmental enhancement. The four criteria for architectural decision-making related to the above element

are: material compatibility, environmental performance potential, conservation principles, and practicality of the intervention. A smart or advanced material intervention can be considered only if the need for rehabilitation or environmental enhancement is recognized. Two historic houses of different physical states - Amin Bek Al-Jalili House and Al-Tutunji House - were chosen as case studies for the selection of material interventions.

2. Research method

2.1. Research design

For this particular research, a design-oriented qualitative research methodology is employed in the development of the architectural decision-support framework for the rehabilitation of the traditional houses in the Old City of Mosul. The core of the research is the relationships between the architectural elements, the traditional materials, environmental functions, the requirements for conservation, and the potential interventions with smart materials. This framework has been developed through three research steps. First of all, the evidence relevant to the architecture and the materials has been collected from the existing literature, the sources for conservation, the documentation of the traditional houses in Mosul, and the visual observation of two case-study houses. Secondly, based on the collected evidence, the criteria for the selection and assessment of the interventions have been set. Lastly, the framework has been applied to two different traditional houses with different physical conditions for the examination of its potential usefulness for rehabilitation decisions on individual architectural elements [16],[17],[18].

2.2. Evidence and data sources

The study draws on three sources of evidence: literature review, architectural documentation, and direct architectural observation. Architectural observation was used to assess the existing physical conditions and architectural characteristics of the selected case-study buildings and to inform the evaluation of potential material interventions within the proposed decision-making framework. Literature and architectural documentation were employed to identify the features of traditional Mosul houses, local materials, passive environmental functions, conservation principles, and the properties of smart and advanced building materials. The literature on traditional architecture and the case-study houses helped identify architectural elements, materials, and functions [5],[6]. Information on conservation principles was used to interpret rehabilitation requirements and evaluate potential interventions [14],[15]. The literature on advanced building materials helped determine their potential environmental and protective functions [11],[12].

Information on the physical condition of the two case-study houses was obtained through field visits conducted by the researcher. The buildings were assessed through visual inspection of observable signs of deterioration relevant to architectural rehabilitation, including weathering, moisture damage, plaster deterioration, cracking, and timber aging. Photographs of these signs were taken in relation to the corresponding architectural elements. The observations were interpreted using the theoretical framework of conservation to determine the need for rehabilitation of each element [14],[15]. Condition assessment was qualitative and limited to visually observable architectural conditions. Structural analysis, laboratory testing, material analysis, and environmental measurements were not included in the assessment.

2.3. Development of the decision criteria

Four criteria were established for selecting interventions that would use smart materials. The criteria included material compatibility, environmental performance potential, conservation considerations, and the practicality of the intervention in question. Material compatibility is the ability of the proposed material to establish an appropriate physical and functional relationship with the existing material [13],[14]. The environmental performance potential criterion is related to the ability of the material to perform the necessary functions such as thermal regulation, insulation, and shading [10,14].

Conservation considerations refer to the conservation of the existing material and minimization of alterations to the historic building [14],[15]. In the context of the proposed framework, practical applicability can be described

as the ability to integrate the intervention without changes to the form and function of the architectural element. The four criteria provide a consistent approach to analyze the proposed interventions prior to their implementation into the decision-making process.

The criteria were used as qualitative screening criteria rather than a quantitative scoring system. The interventions that had scientific evidence of their environmental or protective functions (C2) and whose application was considered compatible with the existing material (C1), complying with conservation criteria (C3) and feasible with minimal alteration to the form and function of the architectural element (C4) were selected. When compatibility could not be confirmed by the available evidence, the intervention was designated as conditional, implying further investigation for compatibility with the material.

2.4. Development of the architectural decision-support framework

The system of decision support was developed by building connections between the decision criteria and architectural elements of the building. Each element was examined having in mind the existing materials, the initial purpose of the element, its current state and necessity of its restoration. Then, the proper smart material was selected having in mind the criteria mentioned above. The intervention was selected if it was able to perform its function while taking into account the existing materials and preservation requirements. In case of impossibility of finding compatibility, the intervention remained conditional, as explained in section 2.3. Consequently, seven stages of decision-making were formed, starting from the examination of the existing architectural element up to the decision about the intervention. They are shown in Table 1.

Table 1. Structure of the architectural decision-support framework

Step	Decision component	Main question
1	Architectural element	Which architectural element is being assessed?
2	Traditional material	What is the existing material?
3	Existing function	What function does the element perform?
4	Physical condition and rehabilitation needs	What rehabilitation need has been identified?
5	Conservation requirement	What should be retained or protected?
6	Smart-material option	Which material can respond to the identified need?
7	Proposed intervention	How can the material be introduced with limited alteration?

This sequence keeps the selection of smart materials linked to a specific architectural and conservation need rather than treating them as independent technological additions.

2.5. Case study selection

Two traditional structures located in the Old City of Mosul have been chosen for applying the decision-support framework: Amin Bek Al-Jalili House and Al-Tutunji House. The locations of the two buildings in the Old City are shown on the map in Figure 1. The two case studies have been chosen because they represent important spatial and construction qualities of the traditional Mosul houses [5],[6]. Both selected buildings are constructed from local materials and contain elements of the framework such as courtyards, stone walls, vaults, and interior spaces of traditional architecture. What is more, there are some differences in the state of preservation and conservation needs of the selected case studies. This enables the application of the framework under different conditions of the buildings in the same climatic and architectural environment.

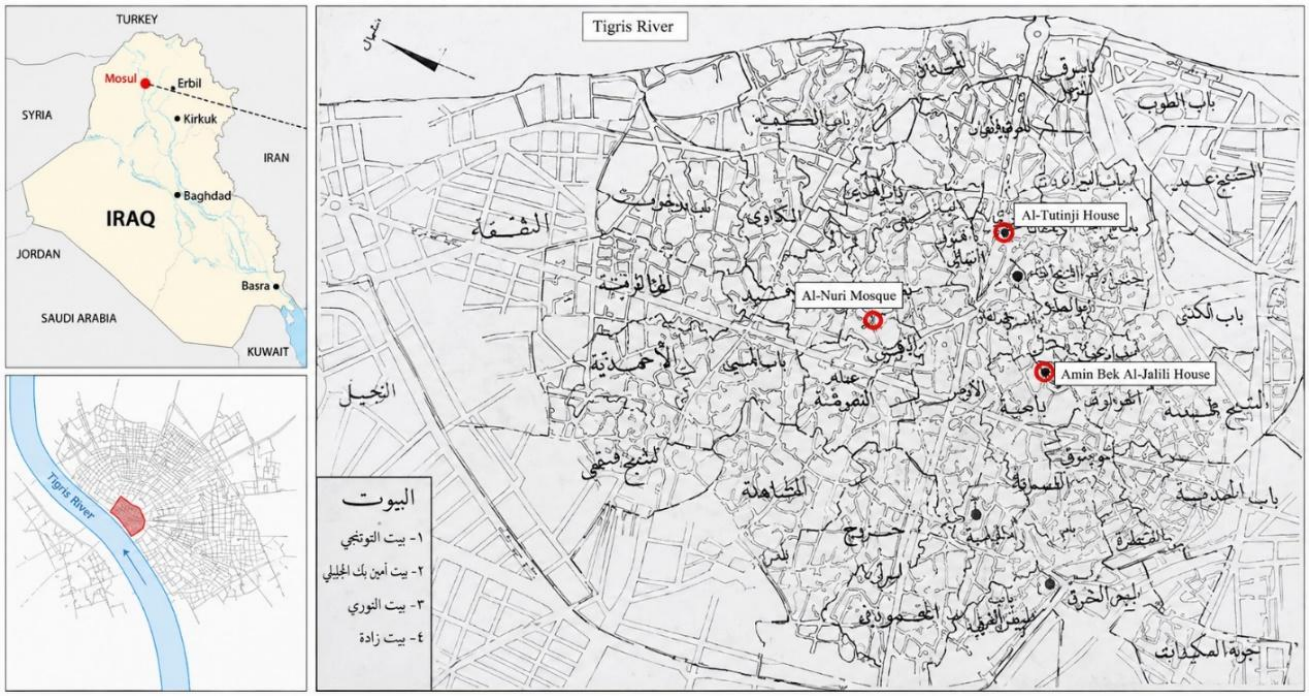


Figure 1. Location of the two case study houses within the Old City of Mosul [5]

2.6. Framework application and comparative assessment

A decision-support framework was applied to both cases while the architectural element was the unit of analysis in them. The first step of the evaluation process includes evaluation of the current building rather than any pre-defined smart material. Identification of the architectural element, its traditional material, function, condition, and the necessity of its rehabilitation is conducted within this step of the assessment process [5],[6]. These factors enable one to understand whether the architectural element should be retained, restored, protected, or improved only in terms of its limited function, due to the conservation approach [14],[15]. Suggestions of some smart or advanced materials come only after identification of a particular need. Four criteria are applied to the suggestions, and they include compatibility of the material (C1), its environmental performance potential (C2), conservation issues (C3), and practical applicability (C4).

There is literature support for the evaluation of thermal regulation, insulation, solar control, and material protection, while the conservation criteria allow one to decide on the preservation of the existing fabric with minimal changes [8],[11],[12]. Thus, the material is evaluated depending on the needs of the architectural element rather than a particular technology. The suggested material becomes an architectural intervention after defining its place and method of implementation. The intervention was accepted, considered conditionally, or rejected according to the qualitative screening rules suggested in Section 2.3.

In case the need could be satisfied by means of conservation, traditional repair, or maintenance, the intervention with a smart or advanced material was not suggested. The same procedure was performed in relation to Amin Bek Al-Jalili House and Al-Tutunji House. The comparison of the decisions was performed to see the difference between corrective rehabilitation and preventive conservation. The application sequence, guiding questions, and evidence used at each stage are summarized in Table 2.

Table 2. Application steps and evidence base of the architectural decision-support framework

Step	Framework component	Guiding question	Evidence/assessment basis
1	Architectural element	Which architectural element is being assessed?	Architectural documentation of traditional Mosul houses and the case study houses[5],[6]
2	Traditional material	What is the existing material or construction system?	Architectural and material documentation[5],[6]

Step	Framework component	Guiding question	Evidence/assessment basis
3	Existing function	What architectural or environmental function does the element perform?	Traditional and passive architectural evidence [2],[6]
4	Physical condition and rehabilitation need	What is the observed condition of the element, and what rehabilitation need does it indicate?	Researcher's field visits, visual condition assessment, photographic documentation, and conservation principles[14],[15]
5	Conservation requirement	What existing material, architectural character, or function should be retained or protected?	Conservation principles [14],[15]
6	Smart-material option	Which smart or advanced material could respond to the identified need while remaining appropriate to the existing element?	Assessment through C1-C4: material compatibility[13][14] ; environmental performance potential [8],[11],[12]; conservation principles [14],[15]; and practical applicability within the proposed framework. Material-specific evidence: PCM [8],[9]; advanced insulation [12]; secondary/Low-E glazing.[10],[11]; protective materials[13]
7	Proposed intervention	How can the selected material, where appropriate, be introduced with limited alteration to the existing architectural element?	Synthesis of the identified rehabilitation need, conservation requirement, and C1-C4 assessment within the proposed framework

The process in seven steps offers a trackable route from the assessment of the existing architectural element to the recommended rehabilitation measure. The four criteria for decision-making (C1-C4) are used in Step 6 to evaluate whether a potential advanced or smart material is suitable for the identified architectural need. In this regard, they are assessment filters rather than steps of the framework. The seven-step process was applied separately to each case study house. The decisions were then compared in order to understand how differences in physical condition and rehabilitation requirements were related to the priority of interventions. Comparative assessment is, therefore, used as an analysis step after the framework application rather than as another step of the framework.

3. Case study and architectural analysis

3.1. Architectural context of traditional houses in Mosul

The traditional architecture of the Old City of Mosul comprises mainly courtyard-type houses, whereby the main architectural elements include the courtyard, rooms, Iwans, arcades, and other spatial and structural elements such as sirdabs, vaults, and domes [5],[6]. The traditional architectural materials used are local limestone, gypsum, timber, and Mosul alabaster, depending on the function of the element in question.[5],[6] Thick walls, shaded spaces, courtyards, and underground rooms contribute to passive environmental responses through shading, ventilation, and thermal mass [6],[7]. The above architectural elements and principles provide the context for the analysis and assessment of the case studies. The houses were analyzed based on their architectural elements, traditional materials, existing uses, condition, and the need for rehabilitation.

3.2. Amin Bek Al-Jalili House

3.2.1. Architectural and material characteristics

The Amin Bek Al-Jalili House is a traditional courtyard house located in the Imam Awn Al-Din area of the Old City of Mosul, dating to 1747. The house has a Courtyard, Iwans, Arcades (Riwaqs), residential rooms, Sirdab, Vaults, Domes, and openings [5],[6]. The main architectural elements taken into consideration in the assessment of this house are shown in Figure 2. The house is constructed from local limestone, gypsum, Mosul alabaster, and timber.[5],[6] Stone masonry is used for enclosure purposes and contributes to thermal mass, while gypsum is used for internal finishing and timber for doors, windows, and architectural detailing. The courtyard, Iwans, Arcades, and Sirdab make up the spatial and passive design systems of the house [6],[7]. The architectural elements, materials, and uses are presented in Table 3 and Figure 2.

Table 3. Architectural elements, traditional materials, and existing functions in Amin Bek Al-Jalili House

Architectural element	Traditional material/construction	Existing function
External walls	Local limestone (Zakoor) with traditional mortar and plaster	Enclosure, thermal mass, protection
Internal wall surfaces	Gypsum (Juss) plaster	Surface finish, protection, interior character
Courtyard	Stone-paved/open space	Spatial organization, daylight, ventilation, microclimatic moderation
Iwan and Riwaq	Stone masonry and gypsum finishes	Shading, transitional space, connection with courtyard
Sirdab	Thick stone masonry	Seasonal cool space, thermal buffering
Roof	Traditional masonry construction with surface finish	Building enclosure, protection from climatic exposure
Vaults and domes	Masonry with gypsum finishes	Space enclosure, load transfer, architectural character
Windows and openings	Timber and traditional glazing	Daylight, ventilation, visual connection
Doors and timber elements	Timber	Access, privacy, enclosure, architectural character

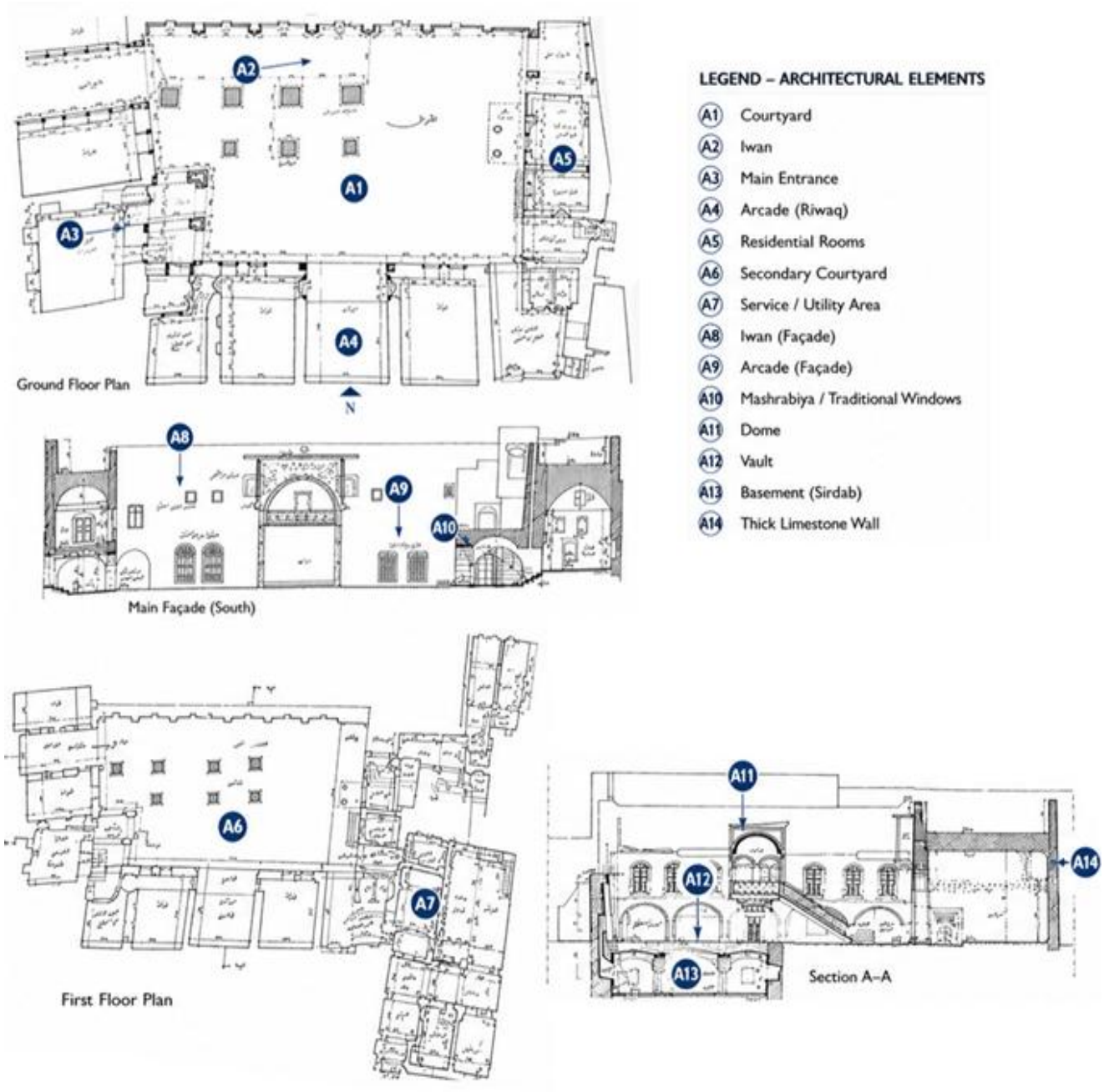


Figure 2. Architectural elements of Amin Bek Al-Jalili House identified for the case study assessment [5]

3.2.2. Physical condition and rehabilitation requirements

Assessment of the physical condition of Amin Bek Al-Jalili House showed varying levels of visible deterioration of its elements. These include weathering and moisture deterioration of limestone surfaces, deterioration of gypsum finishes, deterioration of roof surfaces, and ageing of timber elements. The physical condition of the principal elements is shown in Figure 3 and Table 4.

The rehabilitation requirements were determined according to the condition of each element before taking into account smart materials. Weathered stones require protection and local repair; deteriorated gypsum requires compatible repair, while sound historic plaster should be retained. Roof surfaces require protection where exposure has caused deterioration; aged timber requires maintenance and local treatment. The elements which are in good condition are retained without unnecessary intervention, in accordance with conservation principles [14],[15]. Table 4 shows the physical condition and rehabilitation requirements of the elements.

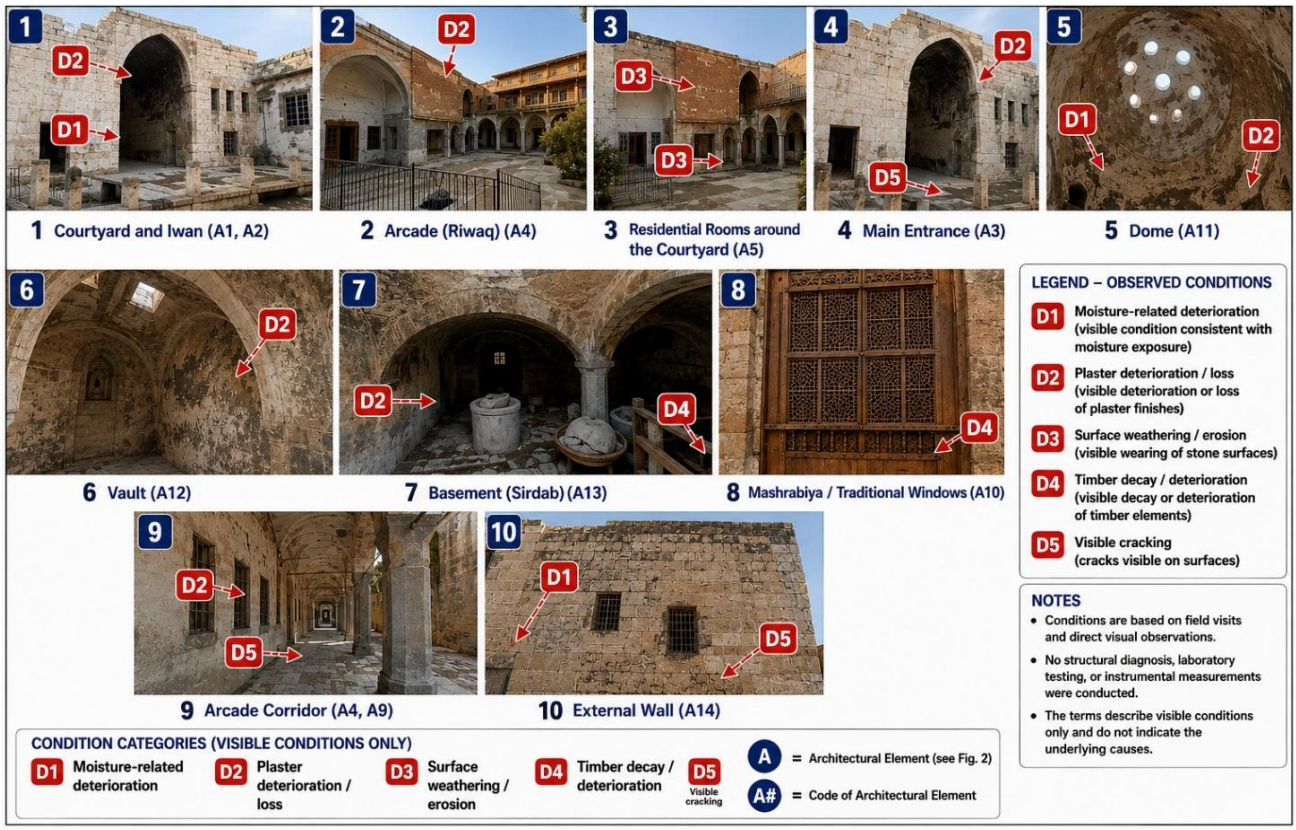


Figure 3. Observed physical conditions of the principal architectural elements of Amin Bek Al-Jalili House; Source: Author's field observations and photography

Table 4. Observed physical conditions and requirements in Amin Bek Al-Jalili House

Architectural element	Observed condition	Rehabilitation need
External limestone walls	Surface weathering and moisture exposure	Protect existing stone and reduce further moisture-related deterioration
Interior gypsum surfaces	Local deterioration and material loss	Repair damaged areas and retain sound traditional finishes
Roof surfaces	Surface degradation and climatic exposure	Protect existing construction and address exposed surfaces
Vaults and domes	Existing historic construction requiring continued protection	Retain original fabric and consider only limited intervention where a need is identified
Windows and openings	Existing elements with exposure-related concerns	Retain openings and improve protection where required
Timber doors and architectural elements	Ageing and weathering	Protect existing timber and limit further deterioration
Courtyard and associated surfaces	Existing traditional spatial element	Preserve spatial and material character; repair locally where required

3.3. Al-Tutunji House

3.3.1. Architectural and material characteristics

Al-Tutunji House represents the same courtyard-based residential tradition but provides a contrasting conservation condition for application of the framework. Its main elements include the courtyard, Iwans, and

arcades, residential rooms, Sirdab, vaults, domes, and traditional openings. These elements are identified in Figure 4. The house retains the principal material system of traditional Mosul dwellings, including local limestone, gypsum, Mosul alabaster, and timber [5],[6]. Because its architectural and material systems are comparable to those of the first case, the same element-based structure was used for the analysis. The courtyard, Iwans, arcades, and Sirdab also retain their roles within the spatial and passive environmental organization of the dwelling [6],[7]. Table 5 summarizes the architectural elements, traditional materials, and existing functions considered in the assessment.

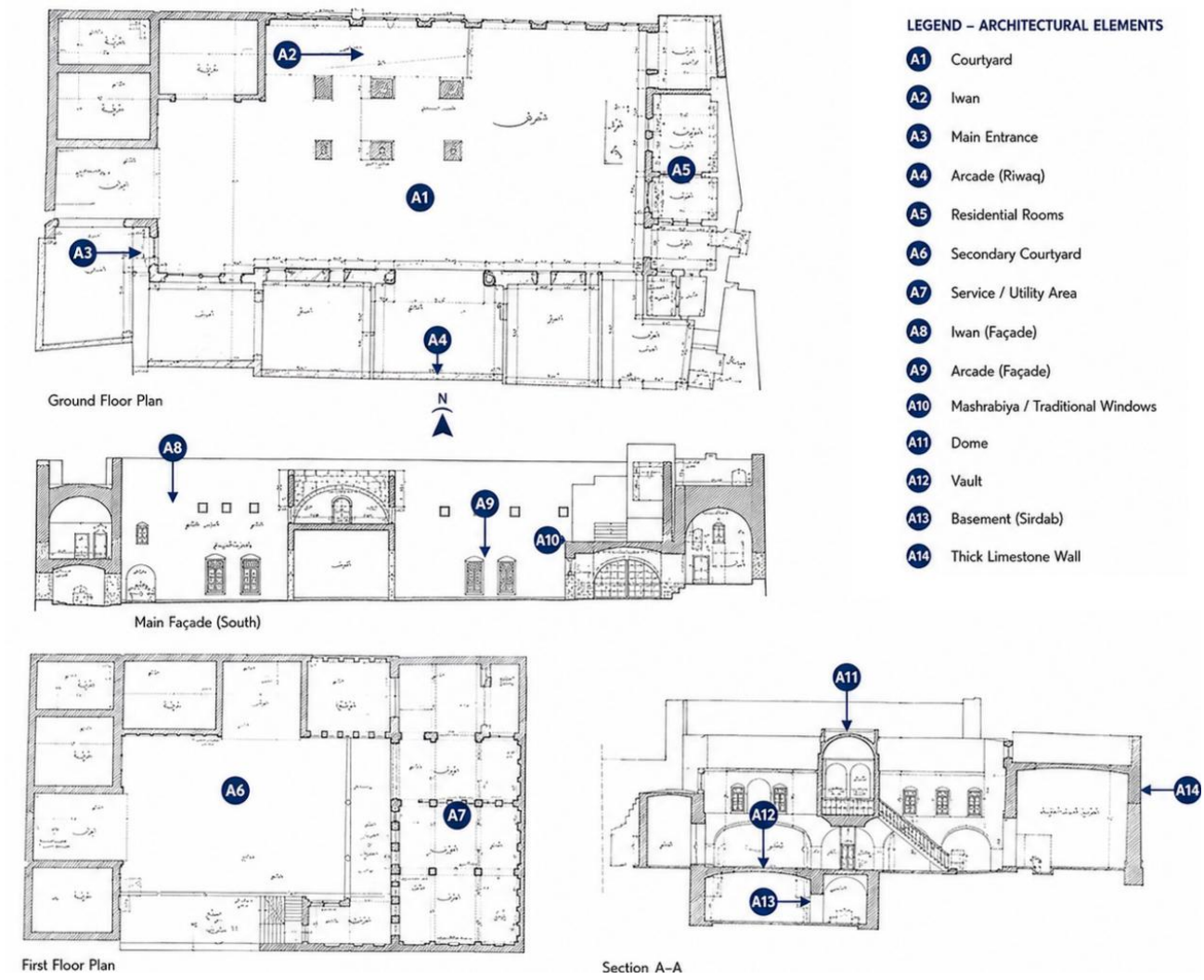


Figure 4. Architectural drawings of Al-Tutunji House showing the principal architectural elements considered in the analysis [5]

Table 5. Architectural elements, traditional materials, and existing Functions in Al-Tutunji House

Architectural element	Traditional material/construction	Existing function
External walls	Local limestone (Zakoor) with traditional mortar and plaster	Enclosure, thermal mass, protection
Internal wall surfaces	Gypsum (Juss) plaster	Surface finish, protection, interior character
Courtyard	Stone-paved/open space	Spatial organization, daylight, ventilation, microclimatic moderation

Architectural element	Traditional material/construction	Existing function
Iwan and Riwaq	Stone masonry and gypsum finishes	Shading, transitional space, connection with courtyard
Sirdab	Thick stone masonry	Seasonal cool space, thermal buffering
Roof	Traditional masonry construction with surface finish	Building enclosure and climatic protection
Vaults and domes	Masonry with gypsum finishes	Space enclosure, load transfer, architectural character
Windows and openings	Timber and traditional glazing	Daylight, ventilation, visual connection
Doors and timber elements	Timber	Access, privacy, enclosure, architectural character

3.3.2. Physical condition and rehabilitation needs

As determined from the field investigation, the Al-Tutunji House has a relatively better physical condition compared to the Amin Bek Al-Jalili House. The majority of its principal elements are well-preserved; deterioration is evident only through localized surface erosion, damage to the gypsum decorations, and aging of certain exposed elements. The observed condition of the principal elements is illustrated in Figure 5. Consequently, the rehabilitation needs of the property revolve around retention and preventive conservation. Elements in good condition should be protected, while localized deterioration should be addressed through limited repair. Localized damage to the exposed stones and timbers should be addressed through maintenance and localized treatment, and the damaged plasters should be repaired [14],[15].

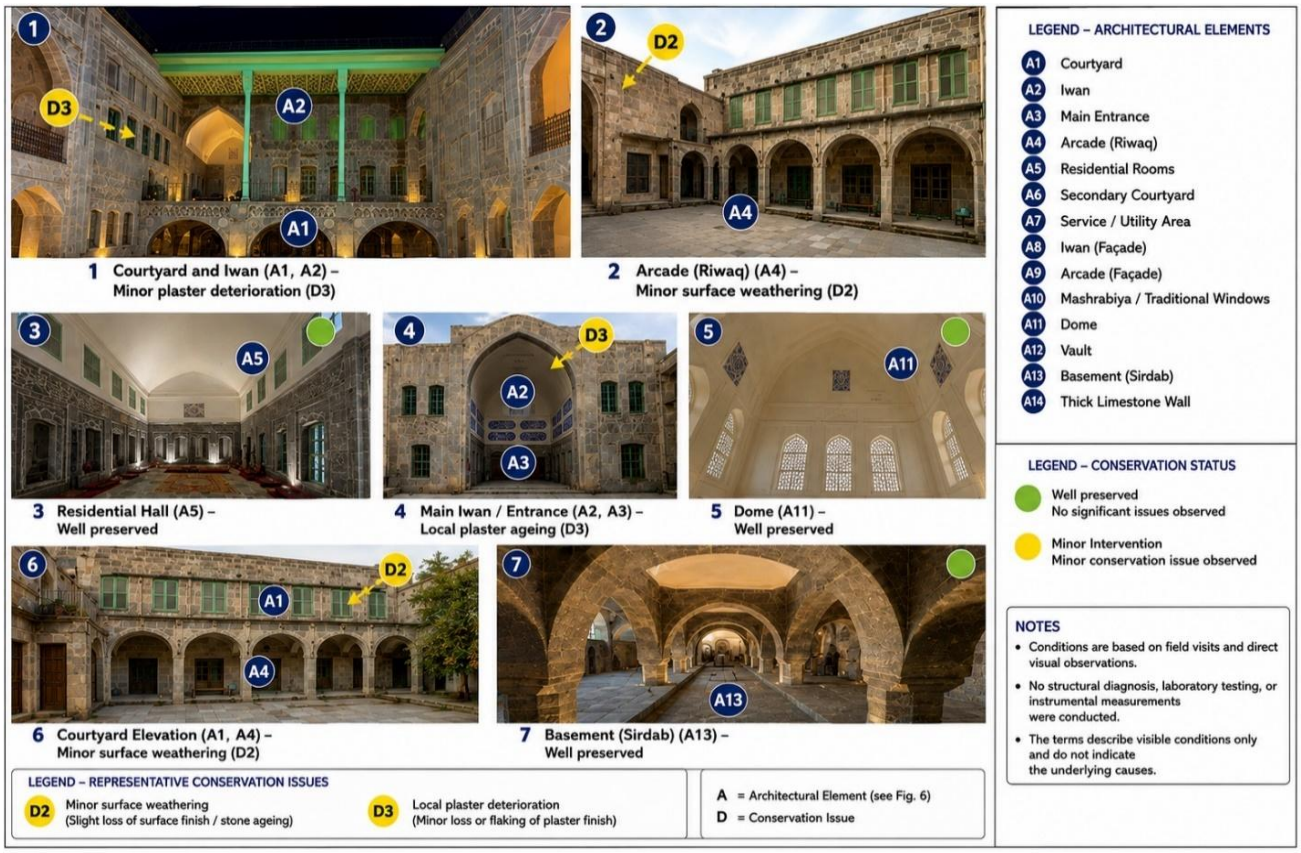


Figure 5. Observed physical conditions of the principal architectural elements of Al-Tutunji House; Source: Author's field observation and photography

Consider = potentially suitable subject to material-specific assessment.

Conditional = considered only where the corresponding environmental need is established.

Table 6 summarizes the observed physical conditions of the principal architectural elements and their corresponding rehabilitation needs.

Table 6. Observed physical conditions and rehabilitation needs in Al-Tutunji House

Architectural element	Observed physical condition	Rehabilitation need
External limestone walls	Minor surface weathering	Retain existing masonry and protect exposed stone
Interior gypsum surfaces	Localized plaster deterioration	Local repair and retention of sound traditional finishes
Roof surfaces	Generally sound condition	Continued protection and preventive maintenance
Vaults and domes	Well preserved	Retain original fabric; intervention only where a specific need is identified
Windows and openings	Generally good condition	Retain existing elements and maintain where required
Timber doors and architectural elements	Generally sound, with localized ageing	Maintenance and protection against further deterioration
Courtyard and associated surfaces	Well preserved	Preserve spatial and material character; local maintenance where required

3.4. Comparative assessment of architectural condition

Both houses exhibit similar architectural elements and traditional materials; however, the difference lies in their physical condition and rehabilitation requirements. Amin Bek Al-Jalili House shows greater deterioration when compared to its counterpart, especially with regard to exposed stones, gypsum finishes, roofs, and timbers. The comparison between the two houses is provided in Table 7 in the following order: architectural elements, traditional materials, existing use, physical condition, and rehabilitation requirements. Smart materials have not been selected at this stage.

Table 7. Comparative architectural, material, and rehabilitation assessment of the two case studies

Architectural element	**Traditional material/construction**	**Existing function**	**Amin Bek Al-Jalili House: condition and need**	**Al-Tutunji House: condition and need**
External walls	Local limestone (Zakoor), traditional mortar and plaster	Enclosure, thermal mass, protection	Surface weathering and moisture exposure → protection and localized repair	Minor surface weathering → retention and preventive protection
Internal wall surfaces	Gypsum (Juss) plaster	Finish, surface protection, interior character	Local deterioration and material loss → repair and retention of sound finishes	Localized deterioration → limited repair and retention
Courtyard	Stone-paved open space	Spatial organization, daylight, ventilation,	Traditional character retained →	Well preserved → continued

Architectural element	Traditional material/construction	Existing function	Amin Bek Al-Jalili House: condition and need	Al-Tutunji House: condition and need
		microclimatic moderation	preservation and local maintenance	preservation and maintenance
Iwan and Riwaq	Stone masonry and gypsum finishes	Shading, transition between open and enclosed spaces	Existing fabric requiring conservation → retain and repair where required	Generally sound → retention and preventive maintenance
Sirdab	Thick stone masonry	Seasonal use and thermal buffering	Existing traditional element → retain and protect	Generally preserved → retain and maintain
Roof surfaces	Traditional masonry construction and surface finishes	Enclosure and climatic protection	Surface degradation and exposure → protection and repair	Generally, sound → preventive protection and maintenance
Vaults and domes	Masonry and gypsum finishes	Enclosure, load transfer, architectural character	Historic fabric requiring continued protection → retain; limited intervention where needed	Well preserved → retain; intervention only where justified
Windows and openings	Timber and traditional glazing	Daylight, ventilation, visual connection	Exposure-related concerns → retention and protection where required	Generally good condition → retention and maintenance
Doors and timber elements	Timber	Access, privacy, enclosure, architectural character	Ageing and weathering → protection and localized repair	Generally, sound with localized ageing → maintenance and preventive protection

The comparison reveals that similar architectural elements may require different levels of intervention. While the Amin Bek Al-Jalili House calls for more active repair and protection, Al-Tutunji House demands more attention to retention and preventive conservation. These specific needs constitute the input data for applying the four decision criteria outlined in Section 4.

4. Application of the architectural decision-support framework

The decision support framework was used in evaluating the rehabilitation needs described in Section 3. Each potential intervention was examined according to four criteria: material compatibility (C1), environmental performance potential (C2), conservation principles (C3), and practical applicability (C4). Material solutions were retained only in cases where they responded to an identified need and met these criteria. The outcomes of the evaluation are discussed separately for each building and compared afterwards.

4.1. Application to Amin Bek Al-Jalili House

In the case of Amin Bek Al-Jalili House, there are certain needs concerning material deterioration, exposure, and protection. The framework was used element-by-element in order to differentiate between the needs of conservation and possible environmental improvement.

4.1.1. Element-based framework decisions

With regard to external limestone walls, the observed deterioration associated with exposure and moisture justifies considering a breathable protection treatment. The applicability of the solution is subject to its material compatibility and its impact on the appearance of the stone masonry.[13],[14]The case of interior gypsum finishes requires a different approach. The deteriorated historic plaster should first be repaired with appropriate

materials. PCM-enhanced plaster is only considered for renewed or non-decorative surfaces where a thermal-regulation need has been identified [8],[9].

Repair and protection are required for roof surfaces wherever there is deterioration. Advanced insulation might be considered where additional thermal insulation is required, although such a measure should only be considered where the measure would not involve any unnecessary changes to the historic material [12]. The same principle holds true for vaults and domes. When these elements are intact, and no environmental need is evident, the framework recommends conservation over additional insulation.

Existing windows and timber members should be conserved as well. Compatible treatments might be used for aging timber members, while secondary or Low-E glass depends upon an identified solar or thermal need as well as details that retain the existing opening [10],[11]. Courtyards should be conserved and maintained locally.

4.1.2. Decision matrix and spatial application

Figure 6 illustrates how the framework decisions relate spatially to the house. This is a spatial application of the framework, not a measure of building performance. Table 8 outlines the assessment of each element in terms of the C1-C4 criteria and its corresponding framework decision. These decisions range from conservation to repairs and conditional material interventions.

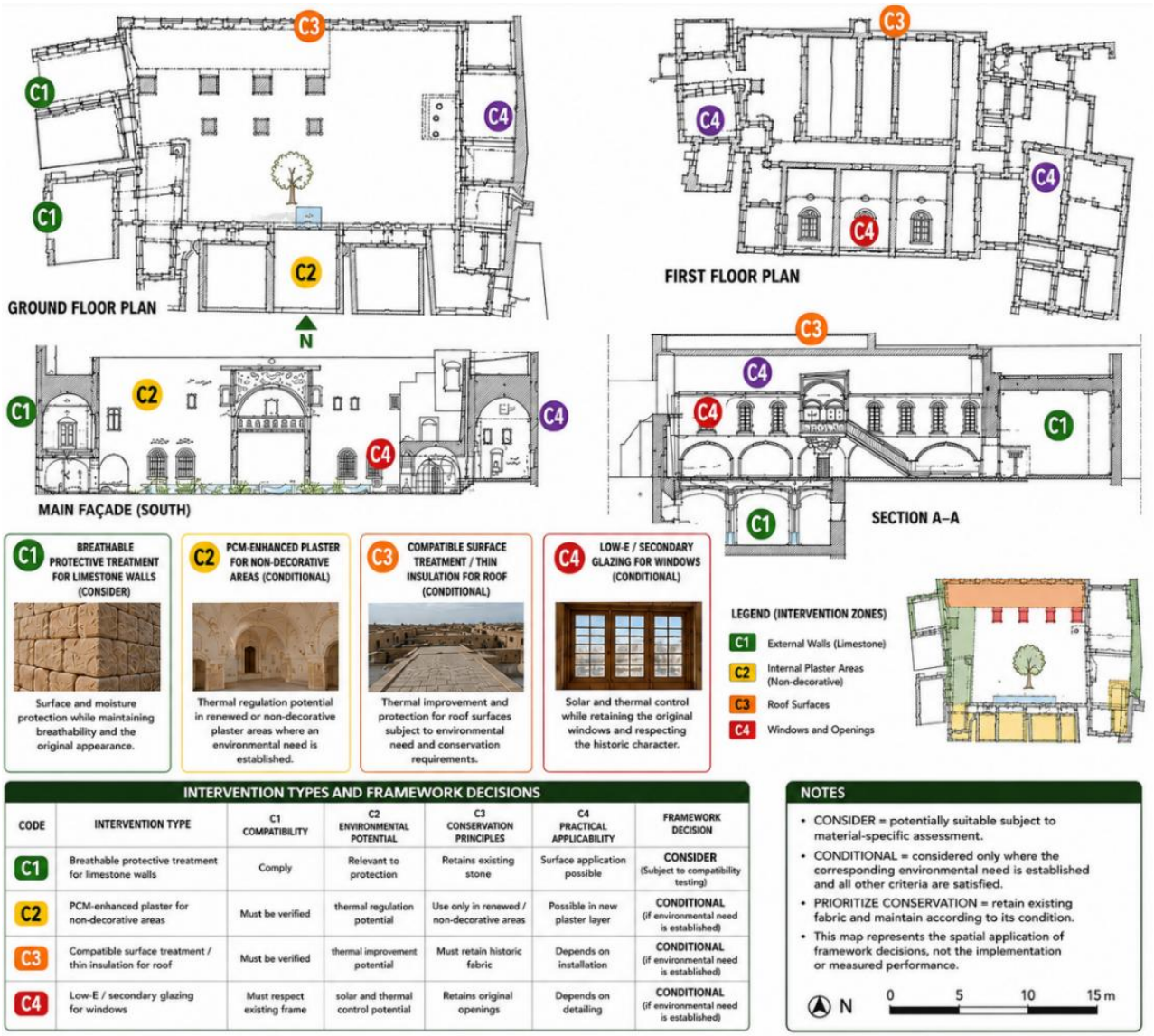


Figure 6. Spatial application of the decision-support framework to Amin Bek Al-Jalili House, showing the locations of proposed and conditional interventions; Source: Author's field observation and photography

Consider = potentially suitable subject to material-specific assessment.

Conditional = considered only where the corresponding environmental need is established.

Table 8. Decision-support framework application to Amin Bek Al-Jalili House

Architectural element	Identified need	Potential material/intervention	C1 Material compatibility	C2 Environmental performance potential	C3 Conservation principles	C4 Practical applicability	Framework decision
External limestone walls	Protect weathered stone and reduce further moisture-related deterioration	Breathable protective treatment	Must remain compatible with porous limestone [13],[14]	Relevant to surface and moisture protection	Retains existing stone	Limited surface application possible	Consider, subject to compatibility testing
Interior gypsum finishes	Repair deteriorated areas and retain sound historic plaster	Traditional compatible repair	High compatibility required [14],[15]	Environmental improvement is not the primary need	Retains sound original plaster	Local repair possible	Prioritize conservation and repair
Non-decorative renewed plaster areas	Additional thermal regulation, only where a need is established	PCM-enhanced gypsum plaster [8],[9]	Must be verified with existing gypsum	Documented thermal-regulation potential	Restricted to renewed or non-significant areas	Possible within a new plaster layer	Conditional
Roof surfaces	Repair degraded surfaces, improve protection, and consider additional thermal treatment where needed	Compatible surface treatment / thin insulation [12]	Must be verified	Documented thermal-resistance potential	Existing roof fabric should be retained	Depends on installation detail	Conditional
Vaults and domes	Retain historic fabric and provide additional thermal protection only where a need is established	Concealed advanced insulation [12]	Requires material assessment	Documented insulation potential	High conservation sensitivity	Limited applicability	Conditional / no intervention where unnecessary
Windows and openings	Retain existing openings and consider additional	Secondary / Low-E glazing [10],[11],[19]	Must respect existing frames	Documented solar-control potential	Original openings retained	Depends on reversible detailing	Conditional

Architectural element	Identified need	Potential material/intervention	C1 Material compatibility	C2 Environmental performance potential	C3 Conservation principles	C4 Practical applicability	Framework decision
	solar and thermal control where needed						
Timber elements	Protect ageing and weathered timber and limit further deterioration	Compatible protective treatment [13]	Must be compatible with existing timber	Relevant mainly to durability	Retains original timber	Limited surface treatment possible	Consider, subject to compatibility testing
Courtyard and associated spaces	Preserve existing spatial and material character and repair locally where required	Maintenance of existing materials and landscape	Existing materials retained	Existing passive role maintained	High conservation priority	Local maintenance possible	Prioritize conservation and local maintenance

4.2. Application to Al-Tutunji House

In the case of Al-Tutunji House, there are certain needs concerning material deterioration, exposure, and protection. The framework was used element-by-element in order to differentiate between the needs of conservation and possible environmental improvement

4.2.1. Element-based framework decisions

Limestone walls on the exterior side are mostly in need of preventive protection measures, with breathable treatment considered only where surface exposure demands it [13],[14]. The sound gypsum finishes should be preserved, while deteriorated spots require repair with compatible materials. The PCM plaster intervention is conditional and should be considered only for renewed or non-decorative spots where a thermal regulation need is identified [8],[9].

Roofs, vaults, and domes in most cases need preservation and preventive maintenance interventions. An advanced insulation measure should not be recommended solely based on its documented thermal properties [12]. While thermal properties may be among the factors to consider for this measure, they are not enough to justify an intervention in case the historic roof, vault, or dome is still sound [14],[15]. Therefore, the measure is conditional in case there is a need for thermal regulation and it can be installed in a compatible manner. Secondary or Low-E glazing should also be considered only where necessary for solar or thermal control and where it is possible to retain existing openings [10],[11],[19]. Wood elements should be maintained and protected where needed. Courtyard and adjacent rooms preserve their spatial and material characteristics. In case there is no need for any other intervention besides conservation and maintenance, no smart material needs to be used.

4.2.2. Decision matrix and spatial application

The results of the application of the decision framework to Al-Tutunji House are presented in Table 9. Figure 7 illustrates the spatial distribution of the decisions. The predominance of retention and conditional decisions is due to the better state of conservation of this house rather than to any change in the process of assessment.

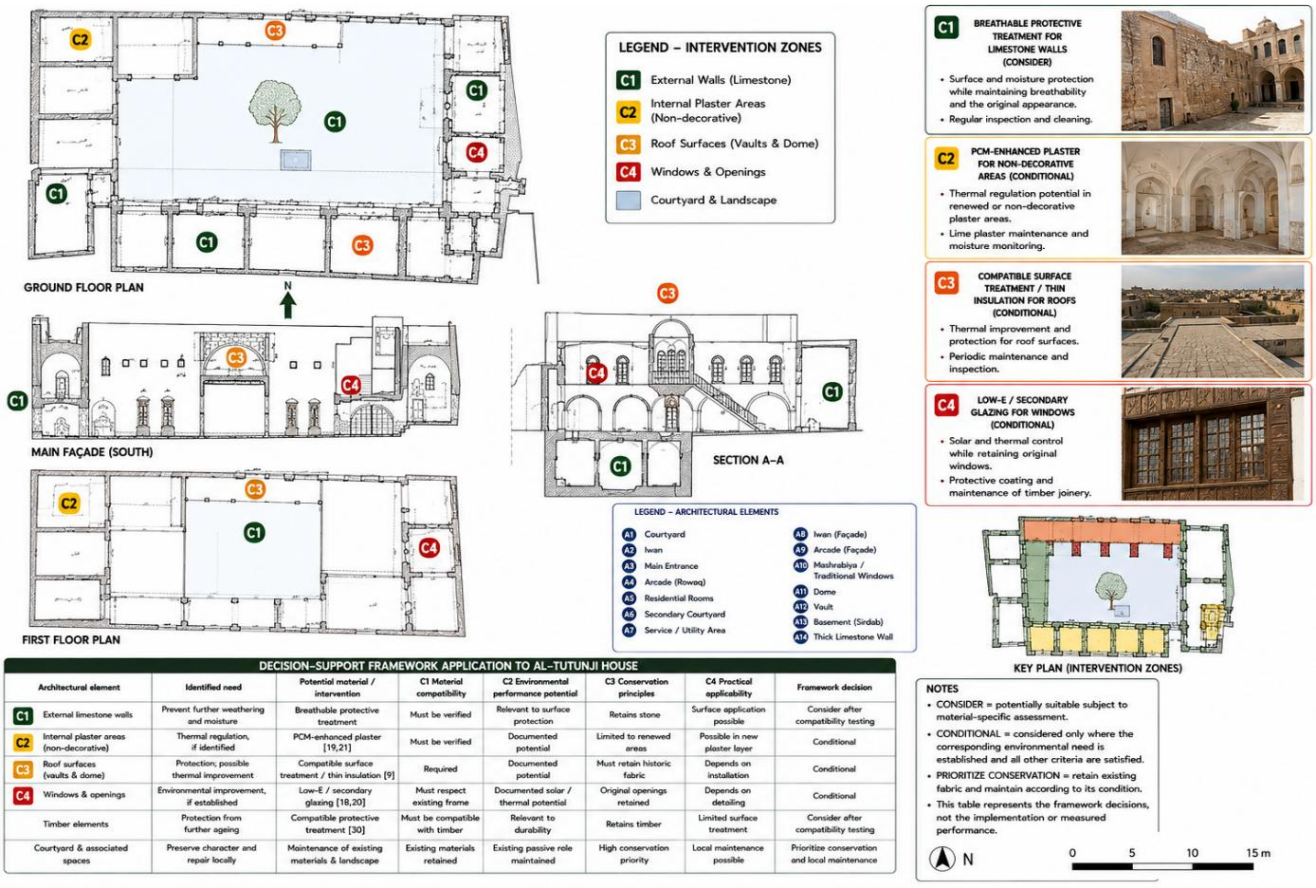


Figure 7. Spatial application of the decision-support framework to Al-Tutunji House, showing preventive and conditional intervention locations; Source: Author's field observation and photography

Consider = potentially suitable subject to material-specific assessment.

Conditional = considered only where the corresponding environmental need is established.

Table 9. Decision-support framework application to Al-Tutunji House

Architectural element	Identified need	Potential material / intervention	C1 Material compatibility	C2 Environmental performance potential	C3 Conservation principles	C4 Practical applicability	Framework decision
External limestone walls	Prevents further surface weathering and moisture exposure	Breathable protective treatment	Must remain compatible with porous limestone [13],[14]	Relevant to surface protection	Retains existing stone	Limited surface application possible	Considered subject to compatibility testing
Interior gypsum finishes	Local repair and retention of sound plaster	Traditional compatible repair	High compatibility required	Environmental improvement is not the primary need	Original plaster retained where sound	Local repair possible	Prioritize conservation
Non-decorative renewed plaster areas	Additional thermal regulation, only where a	PCM-enhanced gypsum plaster [8],[9]	Must be verified with existing gypsum	Documented thermal-regulation potential	Restricted to renewed or non-significant areas	Possible within a new plaster layer	Conditional

Architectural element	Identified need	Potential material / intervention	C1 Material compatibility	C2 Environmental performance potential	C3 Conservation principles	C4 Practical applicability	Framework decision
	need is established						
Roof surfaces	Preventive protection; possible environmental improvement	Compatible surface treatment / thin insulation [12],[19]	Must be verified	Documented thermal-resistance potential	Existing roof fabric should be retained	Depends on installation detail	Conditional
Vaults and domes	Retention and preventive conservation	Concealed advanced insulation [12]	Requires material assessment	Documented insulation potential	High conservation sensitivity	Limited applicability	No intervention unless a specific need is established
Windows and openings	Retention; possible solar and thermal control	Secondary / Low-E glazing [10],[11],[19]	Must respect existing frames	Documented solar-control potential	Original openings retained	Depends on reversible detailing	Conditional
Timber elements	Maintenance and protection from further deterioration	Compatible protective treatment [13]	Consider, subject to compatibility assessment	Relevant mainly to durability	Retains original timber	Limited surface treatment possible	Consider
Courtyard and associated spaces	Preserve existing spatial and material character	Maintenance of existing materials and landscape	Existing materials retained	Existing passive role maintained	High conservation priority	Routine maintenance possible	Prioritize conservation

5. Results and discussion

5.1. Comparison of decisions made in the frameworks

Using the same framework on both houses yielded different results in terms of intervention priorities. More effort must be made for repair and protection at Amin Bek Al-Jalili House, which appears to be more deteriorated, while Al-Tutunji House needs more retention and preventive conservation. This is especially apparent for exterior walls, finishes, roofs, and timber.

Moreover, one can see that even the material potential recorded in the documentation does not necessarily warrant any intervention. Use of PCM-enhanced plaster, advanced insulation, and secondary or Low-E glazing is still conditional, as it depends on the environmental need and conservation impact in both houses [8], [11],[12]. In contrast, traditional repairs or no intervention at all might be preferred in case of sound fabric. Table 10 illustrates the differences.

Table 10. Comparative framework decisions for the two case studies

Architectural element	Amin Bek Al-Jalili House	Al-Tutunji House	Comparative finding
External limestone walls	Protection and localized repair; breathable treatment considered	Retention and preventive protection; treatment considered	Same material option, but different intervention intensity

Interior gypsum finishes	Repair deteriorated areas; prioritize conservation and repair	Local repair; prioritize conservation	Conservation precedes material enhancement in both cases
Non-decorative renewed plaster areas	PCM-enhanced plaster conditional	PCM-enhanced plaster conditional	Accepted only where a thermal need is established
Roof surfaces	Repair/protection; thin insulation conditional	Preventive protection; insulation conditional	Physical condition changes intervention priority
Vaults and domes	Retention; insulation conditional / no intervention where unnecessary	Retention; no intervention unless need is established	Technical potential alone does not justify intervention
Windows and openings	Secondary/Low-E glazing conditional	Secondary/Low-E glazing conditional	Environmental need and conservation detailing govern selection
Timber elements	Protection/local repair; treatment considered	Maintenance/preventive protection; treatment considered	Same principle, different conservation intensity
Courtyard and associated spaces	Conservation and local maintenance prioritized	Conservation and maintenance prioritized	No additional material intervention required

From the comparison, it is clear that the framework does not create a standardized package of interventions for smart materials. The use of the same architectural element may result in varied decisions depending on the conditions and rehabilitation needs of the element. Thus, the framework filters between technological material potential and architectural needs.

5.2. Discussion

The use of the framework indicates that material selection for historic buildings should begin with architectural considerations rather than beginning with technological considerations. The architectural component, the material, the function, the physical state of the material, and the conservation need indicate whether the treatment is appropriate or not. This methodological procedure is in accordance with the principles of conservation, where the focus is on preserving the historic fabric and minimal intervention [14],[15]. It is apparent from the comparison that the existence of materials with documented technical capabilities does not necessarily indicate their utilization. The two case studies have shown how the approach is applied in different conservation conditions. The Amin Bek Al-Jalili House requires more repair and protection because of visible deterioration of stone surfaces, gypsum finishes, roof surfaces, and timber components. In contrast, the Al-Tutunji House is well preserved; therefore, retention and preventive conservation are important in this building.

The findings also make a distinction between conservation needs and environmental improvement. The case of deterioration of historic plaster, for instance, must first undergo a compatible repair prior to considering any additional function. The application of PCM-modified plaster continues to be a conditional choice in the case of renewed and/or non-decorative areas where thermal regulation is required [8],[9]. Insulation technology is another case in point.

The documented thermal performance of the latter [12] provides a basis for its consideration, yet it is insufficient to justify any intervention where historic roofs, vaults, and domes are in good condition [14],[15]. Glazing technology is also conditional upon environmental need and the preservation of historic openings [10],[11],[19]. Passive design considerations continue to play an essential role in this process. Courtyards, Iwans, arcades, thick masonry walls, vaults, domes, and Sirdabs represent the environmental response of traditional houses of Mosul. These contribute to shading, ventilation, thermal buffering, and seasonal usage of spaces.[6],[7] In other words, smart and advanced materials are viewed as secondary measures that complement the above-mentioned traditional systems.

This method is especially relevant to the issue of rehabilitation of the Old City of Mosul, because here physical rehabilitation should take place along with architectural identity and historical material that remains [20],[21]. The significance of the framework is not in introducing any new types of smart materials. It is clear from previous studies what the properties of PCM, advanced insulation, and smart glazing are [8],[11],[12]. What the framework contributes to is incorporating architectural aspects, traditional materials, existing use, physical condition, conservation needs, and material options into one decision process. Four criteria-material compatibility, environmental performance potential, conservation requirements, and practical feasibility-form the basis for prioritization of the interventions as well as their acceptance. This application of the framework does not prove the thermal or energy performance of the proposed interventions. Environmental performance within this framework refers to potential documented in the literature. Quantitative evaluation would require material testing and/or building performance simulation. In this context, the framework helps decide whether the intervention is needed, what materials can be used, and under what circumstances.

6. Conclusions

This research proposes an architectural decision-support framework aimed at guiding the integration of local traditional materials with smart and advanced materials in the context of rehabilitation of historic houses in the Old City of Mosul. The framework correlates architectural elements, traditional materials, current function, physical condition, and rehabilitation requirements with four decision criteria, including compatibility of materials, environmental performance potential, conservation considerations, and implementation feasibility.

The proposed decision framework includes a sequence of decisions starting with identifying the architectural element, its traditional material, current function, physical condition, and rehabilitation requirement. Following this, the proposed intervention is reviewed in terms of the above-mentioned decision criteria. Thus, the proposed decision sequence ties the analysis of existing architectural conditions with the choice of the intervention to make. In case material compatibility cannot be confirmed on the basis of collected evidence, the proposed intervention becomes conditional depending on further investigation.

Using the framework to analyze Amin Bek Al-Jalili House and Al-Tutunji House shows that the rehabilitation decisions have to be based on the condition and requirements of the existing architectural element rather than technological solutions predetermined in advance. While the former requires more effort in terms of repair and protection, the latter focuses on retention and preventive conservation. As a result, the same decision-making procedure yields different priorities of interventions in line with the condition of the existing building materials and architectural elements. Moreover, the findings prove that the use of smart and advanced materials can be considered as complementary interventions, rather than replacements of the existing architectural system. Selection of such materials needs to be driven not only by environmental benefits reported in the literature but also by material compatibility, conservation requirements, and practical feasibility. Depending on the condition of the architectural element and the results of the assessment, repair, maintenance, or lack of intervention might be more suitable. Thus, the main contribution of this research is the development of architectural decision-support approach for determining when an intervention is necessary, what material options are suitable and under what conditions they can be used. It should be noted that this research does not measure the thermal or energy performance of the proposed interventions. Further research should focus on the investigation of the

performance and compatibility of the selected materials through material compatibility testing, environmental measurements, and/or building performance modeling.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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