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From Condition Assessment to Sustainable Conservation Prioritisation: An Element-Level Framework for Traditional Earthen and Stone Heritage

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Abstract

Sustainable conservation of traditional buildings depends on decisions that prolong the service life of historic fabric while using scarce material, financial and skilled-labour resources efficiently. This study presents an element-level decision-support framework that integrates five established components—field documentation, material-specific vulnerability assessment, EN 16096-informed condition and urgency classification, heritage-significance assessment and conservation prioritisation—within one traceable workflow. The contribution lies in their transparent integration, not in the components themselves: each element carries one identifier through all steps; condition, urgency, significance and evidential uncertainty remain separately visible; and interventions are sequenced by an ordered rule without a composite score. Heritage significance is assigned through a rubric with explicit evidence and decision rules, including provisions for borderline cases. A pilot application to a traditional multi-storey house in the UNESCO-listed Old City of Sana'a, Yemen, identified moisture and drainage failure as a cross-cutting driver, placed preventive drainage and roof works first, and retained an unassessed brick element as a pending diagnostic requirement. Links to environmental, resource, cultural and social sustainability, preventive conservation and resilience are articulated conceptually and not quantified. The single-building, single-assessor design and the absence of laboratory testing limit the evidence to operability and internal coherence; reproducibility and generalisability require multi-building, multi-assessor testing.

Keywords: heritage conservation; sustainable conservation; preventive conservation; condition assessment; heritage significance; EN 16096; conservation prioritisation; earthen architecture; old city of Sana'a

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1. Introduction

Conservation of historic buildings is increasingly understood as a contribution to sustainable development rather than a separate activity. Reuse of existing buildings generally offers environmental savings over demolition and new construction, especially

where new material inputs are minimised [1]; repairing and retaining historic fabric also sustains the cultural identity and social continuity embodied in the built environment. Heritage is recognised in the Sustainable Development Goals, whose Target 11.4 calls for strengthened efforts to protect and safeguard the world's cultural and natural heritage [2], and policy guidance sets out how heritage practice can contribute to these goals [3]. Sustainability is, however, rarely examined as a property of the decision process itself. How limited resources are allocated across a deteriorating building (which elements are treated first, which are repaired rather than replaced, which are monitored, and which need further diagnosis) largely determines whether conservation preserves historic fabric or generates repeated, premature or unnecessary intervention. That decision point is the focus of this paper.

The conservation of historic buildings depends on identifying deterioration mechanisms accurately, evaluating their severity consistently, and translating condition information into intervention priorities. This is particularly demanding in traditional buildings of earthen materials, stone, timber and lime-based finishes, where deterioration is rarely confined to a single material or component [4–6]. Moisture ingress, structural movement, material ageing, biological activity and inappropriate earlier repairs interact across elements, creating decay patterns that descriptive visual inspection alone cannot resolve. Conservation practice has moved from descriptive documentation towards integrated digital and information-based approaches, and recent HBIM studies link geometric documentation with material condition, defect information and conservation data [7–10]. Established instruments such as the Monument Damage Diagnostic System, damage-indexing methods and EN 16096:2012 [11] provide structured means of recording and classifying conditions, but their application to traditional composite buildings remains difficult when assessment must simultaneously account for material vulnerability, architectural significance, intervention urgency and limited field resources. In fragile, resource-constrained urban environments decisions are often made without laboratory testing, advanced diagnostics or continuous monitoring, so field documentation remains the primary source of evidence; measured surveys, photographic recordings and visual interpretation have established geometric and condition baselines in Saudi [12–14] and European [15,16] heritage contexts. Yet documentation alone may yield fragmented, building-specific judgements unless it is embedded in a transparent and repeatable decision structure, and classification at building scale can conceal differences between walls, roofs, ceilings, finishes, openings and drainage components. The Old City of Sana'a, Yemen, is a particularly relevant context: its multi-storey houses combine stone masonry, earthen construction, timber systems and lime- or gypsum-based finishes and are exposed to moisture, rainfall, inadequate drainage, ageing, inappropriate repairs and the wider pressures on a fragile historic city. The available literature on them remains divided between descriptive studies of traditional materials and architecture, standardised condition-assessment approaches, and broader conservation-prioritisation practice [17].

None of the five components on which such decision-making rests is claimed here as new. Field documentation, material-specific deterioration knowledge, standardised condition and urgency classification, value-based significance assessment and conservation prioritisation are each established in the literature (Section 2), and recent HBIM-based studies have already connected several of them within information-rich digital environments [18–20]. The contribution is narrower and lies in the integration. Applied separately, the components leave specific questions open: condition surveys provide no rule for combining condition with significance or for sequencing interventions by causal dependency; material research explains but does not rank deterioration; value-based approaches establish why fabric matters but not how significance and urgency are combined without one obscuring the other; and HBIM workflows store such information but depend

on geometric capture, modelling software and expertise that may be unavailable (Table 1). Sustainability is a further gap. Documentation-led frameworks are sometimes presented as contributions to sustainable conservation [7,21], and prioritisation methods linked to sustainable development and resilience exist for historic areas exposed to natural and climate-change hazards [22], but how a prioritisation procedure itself contributes to sustainable outcomes has received little explicit attention.

The framework proposed here provides four properties that the separate use of these components does not secure: (i) one element identifier is carried from survey to sequence, so every priority is traceable to its evidence; (ii) condition, urgency, significance, causal dependency and evidential status are recorded as separate variables and not merged into a composite score; (iii) an ordered sequencing rule (urgency, then causal and structural dependency, then significance and condition) lets a low-significance preventive element, such as a drainage component, precede a high-significance element that it protects; and (iv) missing evidence persists as a "pending investigation" status instead of being resolved by assumption. The framework comprises five steps: (1) field documentation; (2) material-specific vulnerability assessment; (3) element-level condition and urgency classification informed by EN 16096:2012; (4) heritage-significance integration; and (5) conservation prioritisation and sequencing. It is a decision-support structure, not a replacement for conservation expertise or for data-rich HBIM systems.

These properties also define the framework's relationship to sustainability. Element-level assessment narrows the scope for blanket replacement of sound fabric; a separate significance rating protects authenticity and cultural continuity where they matter most; dependency-based sequencing places the removal of causes (here, rainwater management) ahead of or alongside repair, reducing recurrence; recorded evidential gaps allow diagnosis to precede irreversible intervention; and the field-only workflow can be applied where laboratory, digital and financial resources are limited. These relationships are developed in Sections 3.5, 5.7 and 7.2. They are conceptual: no life-cycle, cost or monitoring analysis was undertaken (Section 7.5).

Table 1 compares the framework with EN 16096:2012 and recent HBIM-based condition-assessment studies [18,19], distinguishing what is adopted (the condition and urgency survey logic), adapted (the CC1–CC5/UC1–UC4 coding applied at element level) and newly proposed as an integration (significance as an independent variable, causal-dependency sequencing and transparent treatment of data gaps).

Table 1. Comparison of the proposed element-level framework with EN 16096:2012 and recent HBIM-based condition-assessment studies.

Dimension	EN 16096:2012 (Existing Condition-Survey Standard)	Recent HBIM-Based Frameworks [18,19]	Proposed Framework (This Study)
Assessment unit	Typically applied at building or building-component level; does not itself prescribe element segmentation rules	Individual building elements/components represented within a 3D digital model	Individual building elements, segmented using an explicit two-tier system/material rule (Section 3.2)
Condition classification	Normative, multi-level condition categories (not identical to the CC1–CC5 scale used here)	Condition typically recorded as linked attribute data within the model	Author-adapted CC1–CC5 scale, informed by EN 16096:2012 principles (Table 2)
Urgency classification	Normative urgency categories inform intervention timeframe	Not a uniformly defined, standard output across HBIM studies	Author-adapted UC1–UC4 scale with explicit decision rules (Sections 3.2 and 5.3)

Heritage significance	Not addressed by the standard	Addressed inconsistently; not a core structural output in [18,19]	Explicit Step 4 output, assessed independently of condition/urgency via a three-dimension rubric
Causal/structural dependency	Not addressed	Representable geometrically, but not itself a decision rule	Explicit sequencing rule applied in Step 5 (Section 3.2)
Uncertainty/data-gap handling	Not addressed	Not typically a discrete, traceable output	Explicit "pending investigation" status retained and propagated through the workflow (e.g., BU-1)
Resource requirements	Field survey only; no digital modelling required	Requires 3D modelling software, geometric capture (e.g., point-cloud or photogrammetry), and specialist BIM expertise	Field-operable; does not require a 3D BIM environment (Section 7)
Decision-support function	Screening/condition-classification instrument	Visualisation and information-management platform	Explicit, auditable prioritisation and intervention-sequencing output (Step 5)

Table 2. Condition Class (CC) and Urgency Class (UC) definitions.

CC	Category	Description (Extent of Damage)	UC	Category	Timeframe
CC1	No symptoms	No visible evidence of substantial material deterioration or functional change.	UC1	Long term	After 3 years
CC2	Minor symptoms	Superficial or localised deterioration without significant material loss or functional impairment.	UC2	Intermediate term	Within 1–3 years
CC3	Moderate symptoms	Clearly observable deterioration with partial material loss and/or localised functional impairment, but without evidence of imminent failure.	UC3	Short term	Within 1 year
CC4	Major symptoms	Serious deterioration, substantial material loss, instability, or danger of local failure requiring prompt intervention.	UC4	Urgent and immediate	Within 3 months
CC5	Total loss	Near-total or total physical loss, collapse, or complete functional failure of the assessed element.			

The framework is applied through a pilot study of a traditional multi-storey residential building in the UNESCO-listed Old City of Sana'a. The pilot is used to examine whether the proposed sequence can be implemented under real field conditions and whether element-level assessment can provide a more differentiated basis for conservation prioritisation than whole-building classification. Accordingly, the study addresses the following research questions:

How can material-specific vulnerability, standardised element-level condition assessment, and heritage significance be integrated into a transparent framework for prioritising conservation interventions in traditional historic buildings?

In addition, how can the resulting element-level prioritisation be related, conceptually and without quantitative impact analysis, to environmental, resource, cultural and social sustainability, preventive conservation and resilience, and what evidence would be needed to verify those relationships?

The study has four objectives: to develop a structured element-level assessment and prioritisation framework; to specify a reproducible protocol for the heritage-significance step; to demonstrate the framework through a pilot building in the Old City of Sana'a; and to articulate how the resulting prioritisation relates to sustainability, identifying the limits and requirements for replication and verification. Its contribution lies not in documenting a single house, nor in proposing any single new component, but in the transparent integration through which field evidence becomes conservation priorities, supporting consistent, auditable and resource-sensitive decisions in traditional and resource-constrained contexts.

2. Literature Review

2.1. Standardised Condition Assessment in Built Heritage

Accurate condition assessment is fundamental in conservation because intervention decisions depend on the systematic identification and interpretation of deterioration. Early practice relied heavily on descriptive inspection and expert judgement; the need for comparable procedures led to structured diagnostic systems. The Monument Damage Diagnostic System introduced a hierarchical method with structured damage terminology and decision-tree logic to support, not replace, professional judgement [23], and Fitzner and Heinrichs [24] developed quantitative stone-damage mapping based on weathering forms, damage categories and numerical indices. EN 16096:2012 provides a structured framework for condition survey and reporting and supports the classification of condition and urgency [11]. Such instruments improve transparency and comparability, but their usefulness depends on the scale of application. Whole-building classifications suit inventory-level screening but can conceal large differences between a roof, load-bearing wall, plaster finish, timber ceiling and drainage component in the same building; for conservation planning at building scale, element-level assessment offers greater diagnostic resolution. Recent HBIM research shows a similar transition, associating deterioration, defects, material properties and intervention data with individual components rather than detached descriptive records, which improves traceability and supports monitoring and decision-making [25,26]. Assessment also presupposes documentation that is fit for purpose: guidance on heritage recording treats the level of detail, accuracy and control of a survey as matters to be specified in relation to its intended use [27,28].

2.2. Material-Specific Vulnerability in Traditional Construction

Traditional buildings combine materials whose deterioration mechanisms differ substantially. Earthen construction, stone, timber and lime-based finishes respond differently to moisture, temperature variation, structural movement, biological activity and inappropriate repair materials. Earthen architecture is particularly sensitive to prolonged water exposure, capillary moisture, erosion and loss of cohesion, and the earthen-construction literature identifies moisture management, compatible repair materials and preventive maintenance as fundamental to durability [29]. Stone deterioration results from interacting physical, chemical and biological processes, including salt crystallisation, scaling, cracking and joint deterioration [30], which may arise from water penetration, thermal cycles, atmospheric exposure and incompatible repairs [30,31]. Baik et al. [21] developed a four-dimensional Historical Building Defect Information Modeling framework for deteriorated historic stucco, illustrating how deterioration can be documented as structured evidence supporting treatment selection. Timber is vulnerable to deformation, biological degradation, moisture-related loss of strength and structural failure under prolonged wetting or inadequate maintenance. These vulnerabilities are climate sensitive: changes in moisture availability, temperature, rainfall and biological activity can significantly alter

the rate and character of deterioration in heritage materials [32]. Local climatic and material knowledge should therefore inform condition assessment, rather than assuming that a standardised classification system alone explains deterioration.

Accordingly, material vulnerability and standardised condition classification should be treated as complementary analytical layers: the first explains why an element is vulnerable and how deterioration develops, while the second provides a structured means of recording condition severity and intervention urgency.

2.3. Traditional Building Heritage in the Old City of Sana'a

The Old City of Sana'a is one of the most distinctive historic urban environments of the Arabian Peninsula. Its multi-storey houses combine stone masonry at lower levels, earthen or fired masonry in upper storeys, timber structural systems and lime- or gypsum-based finishes, closely tied to the city's architectural identity, climatic adaptation and construction traditions. Studies of the tower house describe it as an example of sustainable architecture, highlighting the relationship between local materials, multi-storey spatial organisation and climatic adaptation. References [33,34] discuss heritage, urban identity and conservation in Sana'a, and other work has examined the continuity of traditional residential typologies and the cultural significance of their spatial organisation, façades and construction techniques [34]. Comparable challenges of documenting and conserving traditional masonry, earthen and composite heritage are reported elsewhere on the Arabian Peninsula, for example in Historic Jeddah and AlUla, where traditional-material knowledge is combined with systematic architectural documentation [12,13]. Sana'a's building stock is meanwhile exposed to environmental stress, insufficient maintenance, inappropriate interventions and conflict-related pressures [35]. Much of the existing literature remains descriptive, typological or focused on documenting damage; procedures that translate observed deterioration into structured, element-level priorities have received comparatively little attention.

2.4. From Condition Assessment to Conservation Prioritisation

Condition assessment alone does not determine conservation priority. Heritage-information frameworks emphasise that documentation achieves its greatest value when geometric and condition information is transformed into actionable management knowledge, and HBIM research increasingly incorporates deterioration records, material properties, structural information and conservation requirements to support intervention planning [7,21]. Two elements may show comparable deterioration yet differ in structural importance, architectural contribution, historical significance, authenticity or function, so decisions require a means of interpreting technical condition alongside heritage value. Value-based approaches have long emphasised that intervention should consider authenticity, cultural significance and architectural character, not only material survival [36], and international conservation principles stress minimum intervention, compatibility and the preservation of culturally significant fabric [37]. Where resources are limited, as in fragile or conflict-affected environments, prioritisation becomes essential because not all deterioration can be addressed at once: [38] highlights, in the Yemeni context, the need to consider significance alongside physical condition, and [39] demonstrate the value of explicit, repeatable assessment protocols for comparable and actionable data in conflict-affected heritage environments. A methodological challenge remains in combining technical condition and heritage value without obscuring their independent meanings. Simplified composite scores can hide whether an intervention is prioritised because an element is structurally urgent, historically significant, materially vulnerable or some combination of these; a transparent framework should retain each dimension while supporting a practical intervention sequence.

2.5. Existing Applications of EN 16096 and the Need for Element-Level Assessment

The application of EN 16096 in Sana'a provides an important precedent: [38] applied condition, urgency and recommended-intervention classifications to a sample of historic buildings in the Old City, demonstrating the usefulness of standardised assessment for a relatively large group of structures. The classification was, however, reported principally at building level rather than element by element. This is valuable for inventory management and comparative screening but offers limited resolution for planning interventions within a building where a critically deteriorated timber roof, moderately damaged stone masonry, superficially deteriorated plaster and functional drainage elements requiring immediate maintenance may coexist. A single overall classification risks obscuring the differences that determine the type, timing and sequence of intervention. Preventive and planned conservation approaches, which direct inspection and maintenance towards the causes and progression of deterioration over time, offer a related precedent [40]. Element-level assessment therefore represents a logical extension of standardised condition-survey practice, enabling each component to be assessed independently within a common classification structure.

2.6. Sustainability Dimensions in Conservation Decision-Making

Six sustainability dimensions are distinguished here as working definitions, not as definitions drawn from a single source. Environmental sustainability concerns the material, energy and waste implications of intervention, in particular avoidable replacement of historic fabric; reuse of existing buildings generally offers environmental savings over demolition and new construction, especially where new material inputs are minimised [1]. Resource sustainability concerns the efficient use of limited financial, material and skilled-labour inputs. Cultural sustainability concerns the continuity of authentic fabric, craft knowledge and significance, and social sustainability the continued use, care and meaning of the built environment for those who inhabit and manage it; both are central to the relationship between heritage and the Sustainable Development Goals [3]. Preventive conservation concerns reducing the rate and recurrence of deterioration by acting on its causes [40], and resilience the capacity of a building and its management to absorb environmental and institutional stress without loss of significance [22].

HBIM-based documentation frameworks are frequently presented as contributions to sustainable conservation [7,21]. Prioritisation methods linked to sustainability and resilience also exist, typically as multi-criteria indices [22,41], but how a prioritisation procedure with separately visible variables contributes to sustainable outcomes is less explicitly developed. Sana'a's tower houses are described as sustainable architecture grounded in local materials and climatic adaptation [33], so loss or premature replacement of their fabric also entails loss of that embodied logic. Earthen architecture depends on moisture management, compatible repair and preventive maintenance for durability [29], and climate-related changes in moisture, rainfall and temperature affect decay in heritage materials [32]; preventive moisture control therefore has a resilience dimension as well as a technical one.

This study therefore treats sustainability as a set of conservation consequences that follow from identifiable features of a prioritisation workflow, not as a measured outcome (Sections 3.5, 5.7 and 7.2).

2.7. Research Gap and Conceptual Basis of the Proposed Framework

The reviewed literature identifies several mature but only partially overlapping approaches. Standardised condition-assessment instruments provide structured procedures for recording deterioration and intervention urgency [11,23,24], while material-conservation research explains the vulnerability of earthen construction, stone, timber and

traditional finishes [30,32]. Value-based conservation approaches demonstrate that intervention decisions must consider cultural and architectural significance in addition to physical condition [37,38]. Multi-criteria methods have been used to prioritise heritage interventions by aggregating weighted indicators into a risk or prioritisation index, including for resilience to natural and climate-change hazards [22,41]; such indices rank efficiently but combine condition, value and hazard into a single number. More recently, digital heritage studies have integrated historical records, condition-survey information, deterioration mapping and intervention requirements within HBIM environments. Chelaru et al. [18] linked point-cloud data, historical information, condition assessment and intervention-priority criteria within an HBIM model, while Zanni et al. [19] developed an OpenHBIM methodology combining material-deterioration assessment with intervention prioritisation. These studies demonstrate the maturity of information-rich digital decision-support systems. The gap addressed here is therefore twofold and deliberately narrow. The first is methodological: a lightweight, field-operable workflow that retains material vulnerability, element-level condition and urgency, heritage significance, causal dependency and incomplete evidence as separate and auditable outputs, and specifies how they are combined into a sequence, where full HBIM implementation, laboratory testing or advanced monitoring may not be feasible. The second is conceptual: an explicit account of how such a procedure relates to environmental, resource, cultural and social sustainability, preventive conservation and resilience (Section 2.6), stated so that each relationship can be examined and, in future work, tested.

The present study addresses this gap by proposing an integrated five-step framework that links:

- field documentation;
- material-specific vulnerability assessment;
- element-level condition and urgency classification informed by EN 16096:2012;
- heritage-significance assessment; and
- conservation prioritisation and intervention sequencing.

The framework is intended to function as a transparent decision-support process rather than as a replacement for conservation expertise. Its contribution lies not in any single component but in making the relationship between observed deterioration, material behaviour, technical urgency, heritage significance and intervention priority explicit and auditable, thereby making the conservation and sustainability consequences of each priority open to scrutiny. The pilot application in the Old City of Sana'a is subsequently used to examine the practical operability of this integrated workflow under real field conditions.

3. Methodology

3.1. Research Design and Framework Development

This study adopts a methodological development and pilot-application design whose principal output is an integrated decision-support framework for assessing material deterioration and prioritising interventions in traditional historic buildings. The pilot building demonstrates and evaluates the framework's operability and is not treated solely as a case study. The framework responds to the gap identified in Section 2: condition-assessment approaches [11,23,24] structure the recording of deterioration, material-conservation research [29–32] explains vulnerability, and value-based approaches [36] emphasise significance, but these are not always integrated in one transparent workflow supporting element-level prioritisation. Three requirements guided development: the process had to be explicit enough for the same sequence to be applied in later surveys; it had to remain applicable where laboratory analysis, continuous monitoring and advanced instrumentation are limited; and its outputs had to make the conservation consequences of

each priority interpretable in sustainability terms (material retention, efficient use of limited resources, prevention of recurrent damage, continuity of cultural value) [1–3,22,40,41] without presupposing quantitative impact analysis that the pilot data could not support (Section 3.5).

Accordingly, the proposed methodology relies primarily on field-based evidence obtained through systematic visual inspection, photographic documentation, measured architectural survey, material identification, and condition assessment. These observations are progressively transformed into conservation priorities through five sequential analytical steps:

Step 1—Field documentation.
Step 2—Material-specific vulnerability assessment.
Step 3—Element-level condition and urgency classification.
Step 4—Heritage significance integration.
Step 5—Conservation prioritisation and intervention sequencing.

Each step produces a discrete and traceable output so that deterioration evidence, technical urgency, heritage significance, and intervention priority remain independently identifiable throughout the decision-making process. Figure 1 summarises the proposed five-step framework for element-level condition assessment and conservation prioritisation.

Use of Generative Artificial Intelligence

A generative artificial intelligence tool developed by OpenAI was used during manuscript preparation and revision to assist with language refinement, text organisation, and editorial restructuring. The AI tool was not used for data generation, field-data analysis, condition classification, heritage-significance assessment, or conservation decision-making. All AI-assisted content was critically reviewed, verified, and revised by the authors, who take full responsibility for the scientific content and conclusions of the manuscript.

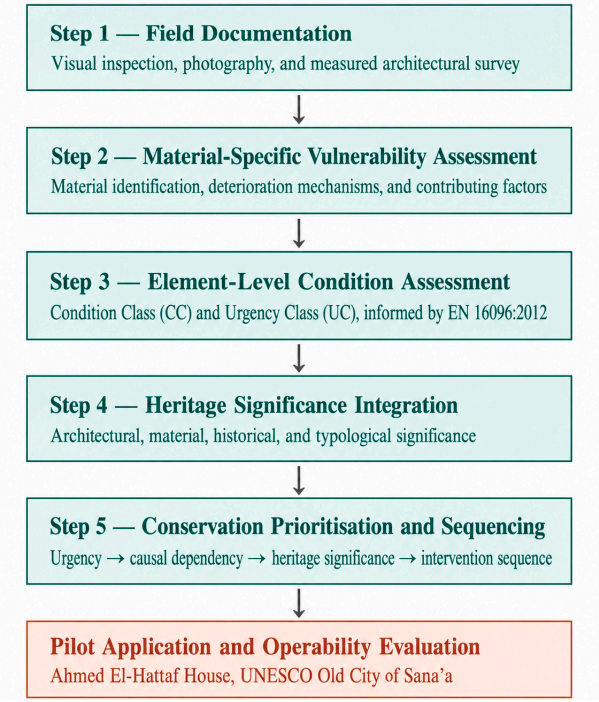

Figure 1. Proposed five-step framework integrating field documentation, material-specific vulnerability, element-level condition assessment, heritage significance, and conservation prioritisation, followed by pilot application and operability evaluation.

3.2. Proposed Five-Step Assessment Framework

The framework follows a sequential process in which information generated at each stage provides the evidence required for the subsequent stage.

Step 1—Field documentation

Step 1 establishes the physical, architectural and material baseline of the building through systematic visual inspection, photographic recordings and measured architectural surveys. Observations are recorded by identifiable building element (wall segments, roof areas, ceiling bays, plaster surfaces, openings, drainage components and other materially or functionally distinct components) and not for the building as a whole. The step follows the principle that recording should be fit for purpose: the level of detail, accuracy and control of a survey should be specified in relation to the decisions it must support [27,28]. Here the purpose is element-level condition assessment and prioritisation, not a high-precision metric record for archival or reconstruction use.

Elements were segmented using a two-tier rule: the building was first divided by principal building system (roof, walls, doors, windows, floor, and other structural elements); within each system, elements were further separated by material or construction layer (e.g., within a wall: masonry, plaster, and timber components) where these layers exhibited materially distinct deterioration behaviour. Repeated, materially and functionally homogeneous sub-components exposed to comparable conditions (e.g., individual window or door units) were aggregated into a single element entry (e.g., WD-1), whereas components exhibiting spatially distinct damage patterns (e.g., the south-façade versus corner stone masonry) were retained as separate entries (W-S, W-C) even where the underlying material was identical. Photographic records are organised according to element location, façade orientation, storey level, and material type, while measured plans, sections, and elevations provide the geometric reference required to locate deterioration spatially. The output of Step 1 is therefore an element-referenced documentation dataset linking the location of each component to its material, observed condition, and supporting photographic or measured evidence.

Pilot implementation: The field survey of the pilot building comprised two site visits in June 2022. The building was visited a further six times during the conservation works and twice after their completion. Linear and spatial measurements were taken with an Exeo H6 handheld laser distance meter (Shenzhen Kace Technology, Shenzhen, China); photographs were taken with a smartphone camera (Samsung Galaxy Note 10, Samsung Electronics, Suwon, Republic of Korea) and organised by element and façade; and measured plans, sections and elevations were drawn in AutoCAD 2024 (Autodesk Inc., San Rafael, CA, USA) at a scale of 1:100 from the field measurements, with visual condition mapping recorded directly on the drawings. The AutoCAD survey files are retained by the authors.

No formal survey-control, redundant-measurement, closure-adjustment or independent AutoCAD-validation procedure was undertaken. The drawings were prepared directly from the field measurements and are therefore used only as a spatial reference for element identification and condition mapping, rather than as metrically controlled survey products.

Accuracy and fitness for purpose: This is a rapid, low-cost documentation level. It is adequate for locating, describing and classifying deterioration on identified elements, but it is not equivalent to a metric survey specified to conservation-record standards, which relies on survey control, stated tolerances and independent checks [27,28]. No survey control network, total station, GNSS control, photogrammetry or laser scanning was used, and the positional accuracy of the drawings was not independently quantified. The drawings therefore represent geometry within the tolerance of handheld measurement and serve to locate and relate elements, not to extract dimensions for structural calculation or reconstruction. Photographs were used as visual evidence of condition and not for

photogrammetric measurement. The suitability of smartphone imaging for façade documentation and deterioration mapping has been examined in the literature [42,43]; consumer cameras lack calibrated optics and controlled geometry, so where images are to be used metrically, established rules for simple photogrammetric documentation [44] and current guidance on photogrammetric survey [45] should be followed. Metrically controlled documentation (calibrated imaging or laser scanning with control) is therefore the appropriate route for replication where dimensional accuracy is required (Section 3.6). Terrestrial photogrammetry, UAV imagery and laser scanning with ground control points were not employed in this pilot.

Step 2—Material-specific vulnerability assessment

The second step interprets observed deterioration according to the characteristic behaviour and vulnerability of the material from which each element is constructed. The principal material categories considered in the framework are stone, earthen masonry, timber, and traditional lime- or gypsum-based finishes, reflecting the principal materials encountered in Sana'a's traditional architecture. Observed deterioration is interpreted using the physical, chemical, and biological deterioration mechanisms established in the conservation literature. Visible manifestations may include cracking, material loss, surface erosion, deformation, spalling, moisture staining, joint deterioration, or biological colonisation. These observations are consistent with recent digital heritage studies in which surface deterioration and material defects have been mapped as structured conservation information [12,21]. Where supported by field evidence, plausible contributing factors are also recorded, including prolonged moisture exposure, inadequate drainage, structural movement, loss of material cohesion, or incompatible previous interventions. A distinction is maintained between observed deterioration and interpreted cause. Because laboratory material characterisation was not undertaken during the pilot application, causal interpretations remain field-based diagnoses rather than confirmed physicochemical determinations.

The Step 2 output records, for each assessed element:

- material type;
- observed deterioration;
- deterioration mechanism;
- apparent contributing factor; and
- supporting field evidence.

This stage provides the material-specific interpretation required before assigning formal condition and urgency classifications.

Step 3—Element-level condition and urgency classification

Following field documentation and material interpretation, each assessable building element is independently classified according to its physical condition and urgency of intervention. EN 16096:2012 is used as the principal reference for structuring the condition survey and the assessment of intervention urgency within built cultural heritage. Rather than assigning one condition category to the building as a whole, the proposed framework applies classification at the level of individual building elements. This element-level approach allows deterioration conditions within the same building to be differentiated. For example, a timber ceiling, stone wall, plaster surface, roof area, and drainage system may exhibit substantially different levels of deterioration and therefore require different intervention timeframes. For each element, two principal attributes are recorded:

- Condition Class (CC): representing the observed severity and extent of deterioration;
- Urgency Class (UC): representing the required timeframe for conservation response.

The classification is based on evidence established in Steps 1 and 2. The CC and UC scales are defined in Table 2.

The framework distinguishes the EN 16096-informed condition-survey structure from the supplementary prioritisation procedure introduced here, which is treated as part of the proposed framework and not attributed to the standard. Elements for which the evidence is insufficient are not assigned an assumed condition class but are retained as unclassified or pending investigation, so that incomplete survey coverage remains visible. The Step 3 output is an element-level table linking element identity, material type, Condition Class, Urgency Class and supporting evidence.

EN 16096:2012 provides the principal methodological reference for the condition-survey structure adopted in this study. In particular, Clause 4.4.4 defines condition classification at component level, while Clauses 4.5.1 and 4.5.2 address risk assessment and recommendations, respectively. The normative EN 16096 condition scale comprises CC0–CC3. EN 16096-based implementation guidance has subsequently extended this logic in some heritage-documentation applications by introducing an additional total-loss category and urgency coding. The five-level Condition Class (CC1–CC5) and four-level Urgency Class (UC1–UC4) used in the present study are therefore author-defined adaptations for element-level application rather than a verbatim reproduction of the EN 16096 categories. Accordingly, the framework is consistently described as "informed by EN 16096:2012" rather than "in accordance with EN 16096:2012."

The CC categories are applied qualitatively on the basis of field-observable severity, extent, and functional consequence. Percentage-loss thresholds are intentionally not used because the original field campaign did not include systematic quantitative measurement of damaged surface area or material volume. This avoids introducing retrospective numerical precision that is not supported by the field dataset.

For the pilot application, Urgency Class was assigned using explicit decision rules. UC4 was reserved for elements presenting immediate safety concerns, active failure, or an ongoing deterioration mechanism capable of causing substantial additional loss if not addressed promptly. UC3 was assigned where deterioration was active and required intervention within approximately one year but did not constitute an immediate safety concern. UC2 was assigned to deteriorated but comparatively stable elements for which intervention could reasonably be deferred for one to three years without expected substantial short-term loss. UC1 was reserved for elements requiring only long-term monitoring or routine maintenance. Condition Class was assessed independently on the basis of the observed severity, extent, and functional consequence of deterioration within each identified element.

Step 4—Heritage significance integration

Technical deterioration alone does not determine conservation priority. Two elements exhibiting comparable levels of physical deterioration may differ significantly in terms of architectural contribution, material authenticity, historical significance, and typological significance.

Step 4 therefore introduces heritage significance as a separate analytical dimension.

The assessment considers three principal dimensions:

- Architectural contribution, referring to the role of the element in defining the building's form, façade composition, spatial organisation, or decorative character;
- Material and construction significance, referring to the extent to which the element represents traditional materials, craftsmanship, or construction techniques;
- Historical and typological significance, referring to the element's contribution to the interpretation of the building's historic development and traditional residential typology.

Structural and functional criticality is assessed separately in Step 5 and is not treated as a component of heritage significance. This distinction prevents technical necessity from being conflated with cultural value.

Assessor and evidence. In the pilot, heritage significance was assigned by a single assessor within the research team, working from the documentary record established in Step 1: measured plans, sections and elevations; the element-referenced photographic records; direct field observation of materials, jointing and construction technique; and published descriptions of the traditional Sana'ani building typology (Section 2.3). Evidence was used in a stated order of precedence. Direct observation and measured documentation were treated as primary evidence, while published typological descriptions were used to interpret what was observed. No archival, cadastral or waqf records were consulted, and the pilot did not include an independent heritage specialist or stakeholder panel.

Three-level rubric. The definitions of the three levels are retained from the pilot. High significance is assigned where an element is character-defining in at least two of the three dimensions, or where its loss would substantially diminish the building's recognised traditional character. Medium significance is assigned where an element makes a clear but secondary contribution to one or more dimensions and could be repaired or partially replaced without substantial loss of character. Low significance is assigned to functional or routinely replaceable components with limited documented architectural, material, historical or typological value. To make these definitions reproducible, they are operationalised through the dimension-level criteria in Table 3 and the decision rules below.

Table 3. Dimension-level criteria for the heritage-significance rubric (Step 4).

Dimension	Indicators and Primary Evidence	Character-Defining (CD)	Contributory (C)	Limited (L)
Architectural contribution (A)	Role in façade composition, massing, spatial organisation or decorative character. Evidence: measured drawings, façade photographs, field observation.	The element forms or carries a feature that defines the building's recorded form, façade composition or decorative character (e.g., the principal façade, hizam bands, gypsum ornamentation).	The element supports such a feature from a secondary position (e.g., secondary elevation; partly concealed or interior location).	No identifiable contribution beyond enclosure, protection or function.
Material and construction significance (M)	Traditional material (stone, timber, fired clay brick, lime or gypsum finish), traditional jointing and construction technique, presence of historic rather than replaced fabric. Evidence: field observation; comparison with typological descriptions (Section 4.2).	The element is a principal carrier of historic fabric made with traditional materials or techniques characteristic of the building tradition.	Traditional material or technique is present but secondary within the element's system or is partly altered or replaced.	Contemporary or generic material, or no evidence of traditional technique.

Historical and typological significance (H)	Contribution to reading the building's development and its traditional residential typology (e.g., material sequence from stone ground floor to brick upper storeys; vertical organisation of functions). Evidence: measured plans, documented spatial organisation, typological descriptions.	The element is a diagnostic feature of the documented typology or building history.	The element supports interpretation of the typology or history without being diagnostic.	No documented contribution.

Decision rules. Each dimension is first rated CD, C or L from the evidence indicated in Table 3, and the rating is recorded with its source. The overall level is then assigned by the following rules, applied in order:

- H1: two or more dimensions rated CD → High.
- H2: exactly one dimension rated CD, and the assessor documents that loss or replacement of the element would remove a feature recorded in the survey as defining the building's recognised traditional character → High; the justification is recorded in the basis for the rating.
- M1: one dimension rated CD without satisfying H2, or at least one dimension rated C, and the element could be repaired or partly replaced without substantial loss of character → Medium.
- L1: all dimensions rated L and the element is functional or routinely replaceable → Low.

Uncertain and borderline cases. First, a dimension for which the evidence is insufficient is recorded as "not demonstrated" and treated as not met; value is not assumed in the absence of evidence. Second, where two adjacent levels remain defensible after rules H1–L1, the level best supported by the primary evidence is assigned, the alternative level is reported with the reason, and its effect on the within-phase sequence is checked (Section 5.4). Third, ratings that rest on a single documented dimension (H2 cases), and ratings of elements whose condition could not be assessed, are flagged so that the dependence of the sequence on judgement remains visible.

Status of the protocol. The three-level definitions were applied in the pilot as originally formulated; the dimension-level criteria, evidence rules and borderline provisions were formalised afterwards, and the recorded basis of each pilot rating was read against them as a documentary consistency check (Section 5.4). The protocol is a transparent decision procedure, not a validated scoring instrument, and has not been tested by independent assessors.

Step 5—Conservation prioritisation and intervention sequencing

The final step translates the outputs of the preceding stages into a practical intervention sequence. Urgency Class remains the primary determinant of intervention timeframe. Elements are therefore first grouped according to their assigned Urgency Class. Within each urgency category, sequencing is refined according to causal and structural dependency, heritage significance, Condition Class, and the need to prevent further deterioration. No composite numerical score is used to override or combine these dimensions. This hierarchical structure preserves the meaning of each assessment variable while still producing a transparent intervention sequence.

Within each urgency category, the sequence of intervention considers:

- structural and functional dependency;

- causal relationships between deteriorating elements;
- heritage significance;
- condition severity; and
- the need to prevent further deterioration.

This is particularly important where a comparatively low-value element plays a critical preventive role. For example, a drainage component may have limited architectural or historical significance, yet its failure may actively accelerate deterioration in a highly significant timber roof or masonry wall. In such circumstances, preventive intervention may need to precede direct treatment of the higher-value element. The prioritisation hierarchy used in this study is therefore expressed as shown in Figure 2:

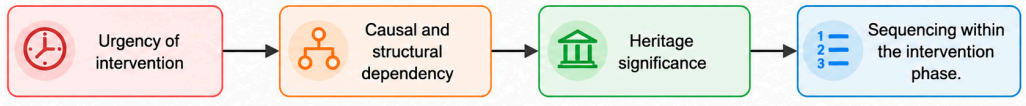

Figure 2. The prioritisation hierarchy used in this study.

The final Step 5 output is a sequenced intervention matrix identifying the intervention phase, timeframe, element, principal condition, heritage significance, and rationale for prioritisation. This structure enables the reasoning behind each intervention priority to remain transparent and auditable and allows priorities to be revised if new information becomes available. Because phase membership is fixed by Urgency Class alone, the significance rating affects only the order of elements within a phase; a one-level change in any significance rating therefore cannot move an element from one phase to another.

3.3. Pilot Case Selection and Field Data Collection

The framework was applied to the Ahmed El-Hattaf House in the UNESCO-listed Old City of Sana'a, Yemen. The building was selected because it met three criteria: it combines several materials characteristic of the local building stock (stone masonry, timber structural components, earthen construction and traditional finishes), which suited testing the material-vulnerability step; it showed a broad range of deterioration conditions (masonry cracking and joint deterioration, surface deterioration of finishes, deformation and partial failure of timber ceiling and roof systems, and drainage defects), which suited element-level classification; and it was physically accessible for repeated field documentation under the prevailing local conditions. The pilot examines whether the complete sequence can be implemented under real field conditions and whether element-level assessment generates differentiated and actionable priorities.

- Field data collection comprised systematic visual inspection, photographic documentation and measured architectural documentation, as specified in Step 1 (Section 3.2), and observations were cross-referenced with the material categories and deterioration mechanisms of Step 2. Access was granted by the owner, and work followed the prevailing local safety conditions.

The principal field survey took place in June 2022 and comprised two site visits; six further visits were made during the conservation works and two after their completion. The element-level assessment and prioritisation matrix were developed from the field dataset before and during the conservation works reported in Section 6, so the framework was applied prospectively and not reconstructed after the works. Because exact dates were not systematically retained for every intervention, none has been assigned retrospectively.

3.4. Framework Application and Evaluation

The pilot application followed the five-step sequence described in Section 3.2 without altering the order of the analytical stages to accommodate the specific characteristics of the building. The framework was evaluated according to its practical operability. For the purposes of this study, operability refers to the ability of the framework to be implemented sequentially under actual field conditions and to produce coherent, traceable outputs capable of supporting conservation decision-making.

The framework was considered operational if it could:

- progress systematically from field documentation to conservation prioritisation;
- produce a distinct and traceable output at each methodological step;
- distinguish between deterioration conditions affecting different building elements;
- differentiate material vulnerability from general condition severity;
- retain technical urgency and heritage significance as independently visible dimensions;
- make explicit, for each heritage-significance rating, the evidence, dimension-level judgements and decision rule on which it rests;
- identify incomplete or uncertain assessment data explicitly rather than conceal them;
- recognise causal dependencies between building elements;
- distinguish, when relating priorities to sustainability, between effects observed in the pilot, effects that are plausible but unverified, and effects that were not examined; and
- generate a transparent and interpretable intervention sequence.

This evaluation focuses specifically on whether the proposed workflow can function as intended.

The pilot does not establish statistical generalisability, predictive accuracy, or whether independent assessors would assign identical classifications; operability, not generalisability, is evaluated, and broader validation requires replication across buildings, material conditions and assessment teams. Elements that could not be classified reliably were retained as pending diagnostic requirements, so that missing information is not read as satisfactory condition. Nor does the pilot verify the sustainability benefits discussed in Sections 3.5 and 7.2, which are interpreted conceptually.

3.5. Sustainability Dimensions and Their Operationalisation

Section 2.6 distinguished six sustainability dimensions. Because the pilot generated no life-cycle, cost or monitoring data, the framework calculates no sustainability indicators; instead, Table 4 maps each dimension to the relevant framework feature, the mechanism of contribution and the evidence status. Every sustainability statement is graded as observed in the pilot record, plausible from the workflow's design or the literature but unverified, or not examined, and no statement of magnitude is made, because none was measured. Verification would require comparative life-cycle or embodied-carbon assessment of repair and replacement scenarios, cost and labour records, post-intervention monitoring and elicitation of stakeholder values (Section 7.5).

Table 4. Conceptual mapping between framework features and sustainability dimensions, with the evidence status of each link.

Dimension	Relevant Framework Features	Mechanism of Contribution	Evidence Status in This Study
Environmental	Element-level assessment (Steps 1–3); preference for repair and compatible material (Step 5; Section 4.4).	Intervention is directed to the failing element, narrowing the scope for blanket replacement of sound fabric and the associated material demand and waste.	Plausible. The pilot record shows sectional rebuilding, renewal and repair (W-S, W-C, plaster, WD-1) alongside replacement of failed elements (C-1, R-1). No life-cycle or embodied-carbon data.
Resource	Urgency-based phasing; ordered sequencing rule; "pending investigation" status; field-only workflow (Steps 3 and 5).	Scarce funds, materials and skilled labour are directed first to urgent and causally upstream interventions; intervention is deferred where evidence is insufficient; no BIM or laboratory infrastructure is required.	Plausible. The pilot produced three phases and one deferred element. No cost, time or labour records.
Cultural	Heritage significance as a separate variable (Step 4); differentiated treatment of authenticity.	Historic fabric and craft are protected where significance is highest; pragmatic solutions are confined to low-significance functional elements; traditional materials and techniques remain in use.	Observed in part. Matched timber, stone and lime-based materials were used for high-significance elements; galvanised gutter sections (G-1) were an explicit exception. Significance was rated by a single assessor.
Social	Auditable sequence with recorded rationale; low-technology field workflow; residential building type.	A transparent rationale can support communication with owners and authorities and keep vernacular dwellings maintained and usable; the workflow could be extended to participatory valuation.	Plausible. Owner, resident and community outcomes were not assessed. Occupancy, community outcomes and stakeholder views were not assessed.
Preventive conservation	Logging of mechanism and contributing factor (Step 2); causal-dependency rule (Step 5); UC1 monitoring and maintenance class.	Causes of deterioration (here, rainwater management) are addressed before or together with direct repair of the fabric they threaten, reducing the likelihood of recurrence.	Observed in the sequence: G-1, R-1 and C-1 were treated as one Phase 1 unit. Effectiveness was not monitored after intervention.
Resilience	Moisture identified as cross-cutting driver (Step 2); revisable matrix; visible uncertainty.	Reducing exposure to rainfall and moisture addresses a climate-sensitive deterioration pathway [32]; the matrix can be re-ranked as conditions or evidence change.	Plausible. Not tested against climatic or hazard events; no monitoring.

3.6. Methodological Limitations

The methodology is subject to the following limitations, which define the boundaries of the claims made in this study.

Single building. The framework was applied to one pilot building. This shows that the sequence can be executed under field conditions and yields internally coherent outputs, but not that equivalent results would be obtained for other typologies, materials, deterioration levels or contexts. The building was also selected partly for its material

diversity, broad range of deterioration and accessibility (Section 3.3), which favours demonstration over stress-testing.

No independent evaluators. Condition Class, Urgency Class and significance ratings were assigned by the research team, who also developed the framework, without independent parallel assessment. Inter-rater reliability was not evaluated; explicit rules make disagreement detectable but do not show that it would be small.

No laboratory verification**.** Deterioration was assessed from field-observable evidence; no mineralogical, chemical, moisture, salt-content, mechanical, structural or hygrothermal testing was carried out. Mechanisms and contributing factors are therefore field diagnoses, and some, such as the role of moisture in the south-façade stone decay and of member dimensions in timber deformation, remain hypotheses. Targeted laboratory testing should supplement the workflow where decisions depend on precise identification of a mechanism.

Documentation level. Measured drawings and photographs were produced with low-cost equipment, without survey control or independently quantified accuracy (Section 3.2, Step 1). They suffice for locating and classifying deterioration but not for metric extraction.

Significance and sustainability. The significance rubric was specified and applied by a single assessor without stakeholder input and is not a validated scoring instrument; ratings that rest on a single dimension, or on documentary evidence without a condition assessment, are most sensitive to judgement (Section 5.4). Sustainability relationships are conceptual: no life-cycle, cost, labour or post-intervention monitoring data were collected.

The study therefore makes a bounded claim: the pilot demonstrates operability and internal coherence, not reproducibility, robustness, transferability or sustainability benefits. Element identifiers, evidence provenance, recorded rating bases and visible pending-investigation status are intended to make these properties testable by others (Section 7.5).

4. Background: Traditional Building Materials and Deterioration Mechanisms in the Old City of Sana'a

This section establishes the material and typological background needed to apply Step 2 (Section 3.2) independently of any single building; the materials, mechanisms and conservation approaches below form the diagnostic vocabulary applied to the pilot building in Section 5.

4.1. Geographic and Climatic Context

The Old City of Sana'a, the capital of the Republic of Yemen, is situated in a mountainous, semi-arid region at the centre of the country, at an elevation of approximately 2350 m above sea level. This elevation produces a climatic regime characterised by pronounced diurnal temperature fluctuation and, at times, sub-zero night-time temperatures—conditions directly relevant to the freeze–thaw mechanisms discussed in Section 4.3. Owing to its historic role as a major commercial and political centre along important regional trade routes, the Old City retains a dense, largely intact fabric of multi-storey traditional residential architecture, which led to its inscription on the UNESCO World Heritage List [46].

4.2. Principal Traditional Building Materials

Four material categories constitute the material-vulnerability taxonomy applied in Step 2 of the methodological framework (Section 3.2): stone, timber, fired clay brick (ajur/yajur), and lime plaster. The stones used in traditional Sana'ani construction include basalt, marble, limestone, sandstone, and granite, selected for their durability and

aesthetic qualities. Stone is typically used for the ground-floor load-bearing walls, providing the structural base for the upper storeys. Timber ranks third in frequency of traditional use after earth and stone. Commonly used species include oak, pine, acacia, sidr (jujube), red pine, and apricot wood, principally employed in ceiling and floor systems, structural columns, and roof and water-installation linings intended to prevent leakage. Fired clay brick (ajur/yajur) is traditionally used in the upper storeys and façades of Sana'ani buildings. It should be distinguished from unfired earth construction, such as sun-dried earth brick (libn) or rammed/monolithic earth techniques. In the present pilot building, the upper-storey masonry identified as yajur is therefore described as fired clay brick rather than earthen brick. Traditional brick dimensions measured approximately 20 cm in width by 8 cm in thickness in older construction, with a lighter 16.5 cm by 4 cm variant in more recent use (Table 5).

Traditional surface finishes require terminological distinction. In this study, qudad refers specifically to the traditional lime-based waterproof render used on exposed or moisture-prone surfaces, whereas gypsum plaster refers to gypsum-based finishes used for architectural surface treatment and ornamentation. Because no mineralogical or binder-composition analysis was undertaken during the pilot, the generic term "plaster finish" is retained where the precise binder could not be independently verified from the field evidence. Qudad and gypsum plaster are therefore not treated as interchangeable materials.

Table 5. Traditional brick specifications in Sana'ani construction.

Property	Description
Area of use	Exterior wall façades of the upper storeys
Dimensions (older type)	Width 20 cm, thickness 8 cm
Dimensions (newer type)	Width 16.5 cm, thickness 4 cm
Typical application	From the second storey upward

Lime plaster (al-qudad). Al-qudad is a traditional lime-based plaster applied to exterior surfaces, roofs, and wet areas to prevent water penetration and to repair surface cracking. It is additionally used to seal joints between construction materials and is commonly finished with an oil coating to enhance weather resistance.

4.3. Material-Specific Deterioration Mechanisms

Historic buildings undergo progressive deterioration as a result of the interaction between structural factors (foundation conditions, load-bearing system, material selection, workmanship quality), environmental exposure (climatic conditions and natural hazards), and anthropogenic factors (faulty repair practices, incompatible-material interventions, and physical damage from human use) [47,48]. For diagnostic coding within Step 2, the deterioration processes are subsequently grouped into three principal categories: physical, chemical, and biological deterioration. Physical deterioration refers to mechanical decay arising from the weakening of internal material bonds without accompanying mineralogical change, typically driven by freeze–thaw cycling, thermal expansion-contraction, and mechanical stress. It manifests as cracking, surface abrasion, honeycombing, joint-material loss, and fragment detachment [30]. Chemical deterioration refers to compositional change within a material's internal structure resulting from atmospheric and climatic agents, occurring through hydration, hydrolysis, oxidation, and dissolution reactions. Moisture and temperature fluctuation are principal triggers. Resulting damage includes black-crust formation, salt efflorescence, flaking, pitting, and surface scaling, as well as rust staining from the corrosion of embedded or adjacent metal elements [31]. Biological deterioration results from the colonisation of building surfaces by bacteria, algae,

lichen, fungi, moss, and vascular plants under favourable moisture and temperature conditions, producing both mechanical and chemical decay. Effects include surface staining, spalling, blistering, and pitting; root penetration into joints and wall surfaces additionally poses a structural risk to the load-bearing system.

4.4. General Conservation and Repair Approaches

Conservation interventions in historic buildings aim to extend the service life of building materials while preserving their original characteristics. A measured survey and condition assessment—consistent with Steps 1–3 of the framework proposed in Section 3.2—should precede any conservation or repair work, supplemented where feasible by laboratory material analysis [49]. The general categories of intervention outlined below constitute the intervention vocabulary from which the prioritisation matrix (Step 5, Section 3.2) subsequently derives specific, element-level recommendations. Material cleaning. Material cleaning methods include water washing, chemical cleaning, mechanical cleaning, controlled spraying, and heat- or laser-based techniques, selected according to soiling type and surface sensitivity; cleaning must proceed in a controlled, gradual manner to avoid permanent surface damage. Consolidation and protection. Consolidation treatments strengthen decayed surfaces and restore structural continuity between sound and weakened material, typically applied by brushing, spraying, or drip application, and requiring periodic reapplication. Repointing and completion of missing material. Repointing of lime- and pozzolana-based (horasan) mortars requires matching the properties of the original mortar; completion of missing stone or brick elements requires materials closely matched in colour, texture, hardness, and physical behaviour to the original fabric. Repair and selective replacement. Where an element has experienced localised loss or failure that cannot be addressed through consolidation alone, deteriorated components may be selectively repaired or replaced using compatible materials while retaining the maximum feasible amount of sound historic fabric. Moisture control and surface protection. Given the centrality of moisture to the deterioration mechanisms described in Section 4.3, drainage systems, waterproofing, and ventilation solutions to prevent rising damp constitute a critical and frequently prioritised category of intervention, with direct relevance to preventing the biological colonisation discussed above. Conserving fabric through repair, compatible materials and moisture control, rather than through replacement, is also the route by which these approaches contribute to sustainability (Section 3.5).

5. Pilot Application: The Ahmed El-Hattaf House

This section reports the framework's application to a single pilot building, following the five-step sequence of Section 3.2; each subsection corresponds to the output of one step.

5.1. Step 1 Output—Field Documentation of the Pilot Building

5.1.1. Urban Location

The pilot building is located in Yemen, City of Sana'a, Al-Qusali neighbourhood, House No. 7411, within the Old City of Sana'a, a UNESCO World Heritage Site. The approximate location of the pilot building is 15.3536° N, 44.2100° E in WGS 84. Its location within the Old City and the cadastral parcel are shown in Figure 3.

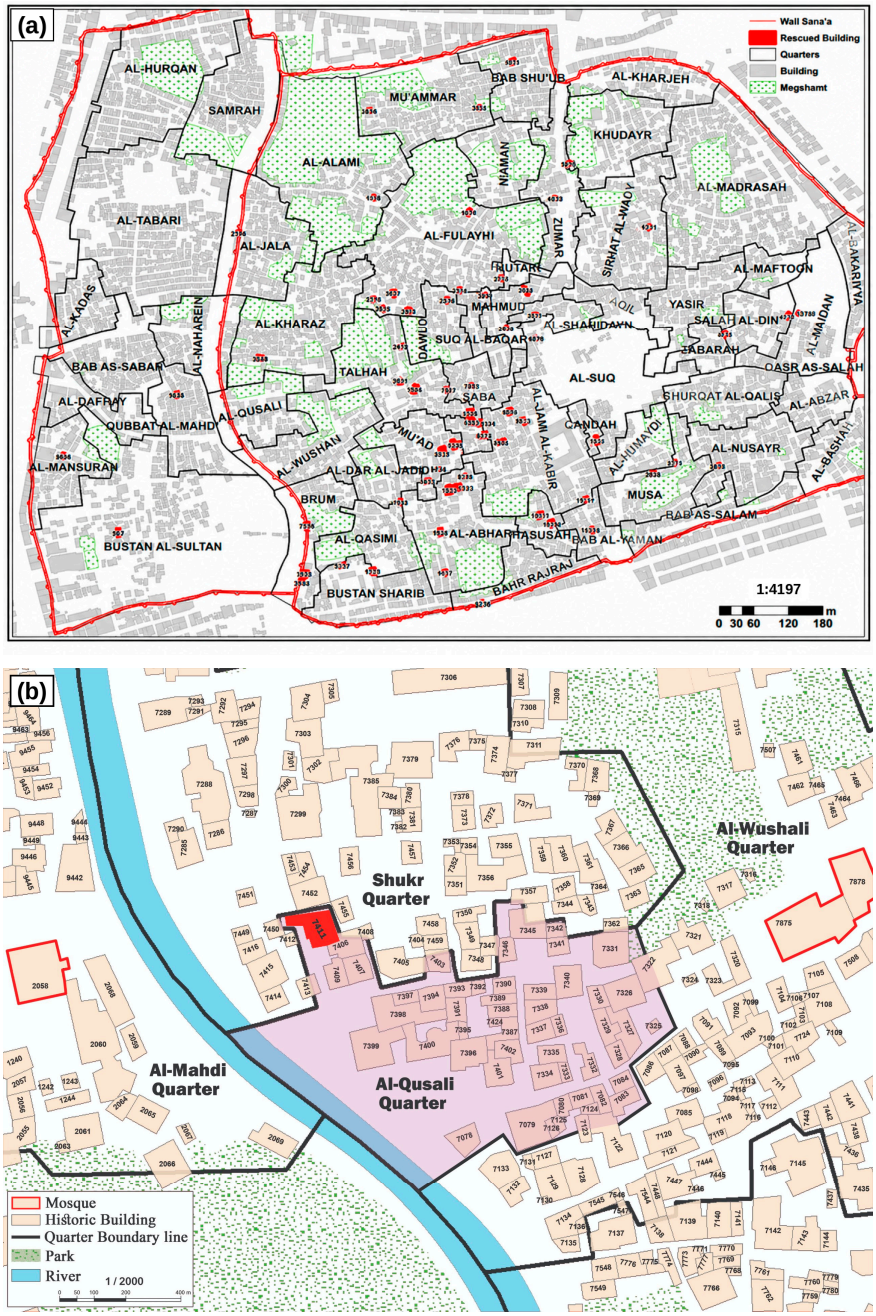

Figure 3. Location of the pilot building (WGS 84: 15.3536° N, 44.2100° E): (**a**) Al-Qusali neighbourhood within the Old City of Sana'a; (**b**) cadastral plan showing parcel No. 7411. In (**a**), Megshamt denotes the traditional urban gardens (maqashim) of the Old City; in (**b**), the pilot building (parcel No. 7411) is shown in solid red and the Al-Qusali quarter is shaded in purple.

5.1.2. Historical Background

The Ahmed El-Hattaf House carries significant architectural and historical value due to the original plan layout, building materials, and façade composition which reflect the traditional residential architecture of the Old City of Sana'a. The building is notable, aesthetically, for its dark-coloured, wide-glazed windows, arched openings, and simple yet elegant dome forms. The orientation of the main façade toward the Imam al-Mahdi Mosque in Sana'a reinforces the building's position within the urban context and its visual relationship with public space. Built as a three-storey structure, the building uses limestone on the ground floor and masonry brick on the upper storeys, presenting a typical example of traditional Sana'a construction techniques. The spatial organisation of the

building is arranged so that the ground floor contains the entrance hall, storage areas, and vertical circulation elements, while the upper floors contain rooms, kitchens, and wet spaces serving the residential function.

The construction date of the Ahmed El-Hattaf House has not been independently verified through archival, cadastral, waqf, or other documentary records. The broader historical context of Sana'a includes two principal periods of Ottoman rule, 1538–1635 and 1872–1918 [17]; however, this chronology is presented only as contextual background and is not used to assign a construction date to the pilot building. Accordingly, the present study does not attribute the building to a specific historical period, and archival verification remains a priority for future documentation.

5.1.3. Architectural Features

The pilot building reflects the fundamental characteristics of traditional residential architecture in the Old City of Sana'a. In terms of its façade organisation, spatial layout, and vertical distribution of functions, it clearly represents the architectural character distinctive to the city. The principal façade is shown in Figure 4.

The building's façade design is defined by horizontal bands (hizam) and vertical window arrangement widely used in the traditional architecture of Sana'a. The white gypsum ornamentation on the façade creates a strong contrast with the stone and brick surfaces, producing aesthetic unity. This ornamentation functions not merely as a decorative element but also as a climatic design feature that enhances the play of light and shadow. The windows are arranged in a larger and more regular rhythm on the upper storeys, meeting the natural lighting and ventilation requirements of the interior spaces. The building's load-bearing system and use of materials are organised in accordance with the material taxonomy established in Section 4.2: natural stone is used on the ground floor, while masonry brick is used on the upper storeys, providing strength and durability on the lower floors while creating a lighter perceived mass above. The gypsum ornamentation on the façade fulfils both an aesthetic and a protective function. The building follows the vertical functional organisation typical of traditional Sana'ani houses: service and storage spaces occupy the ground floor, while living, reception and more private residential spaces are distributed across the upper floors. This vertical hierarchy, together with the façade composition and material stratification, provides part of the typological evidence used in the Step 4 heritage-significance assessment.



Figure 4. Principal façade of the pilot building, showing the horizontal band (hizam) pattern and gypsum ornamentation.

5.1.4. Architectural Documentation

The measured architectural documentation of the pilot building, comprising floor plans, a roof plan and the north elevation, is presented in Figure 5; the drawings were prepared at a scale of 1:100.

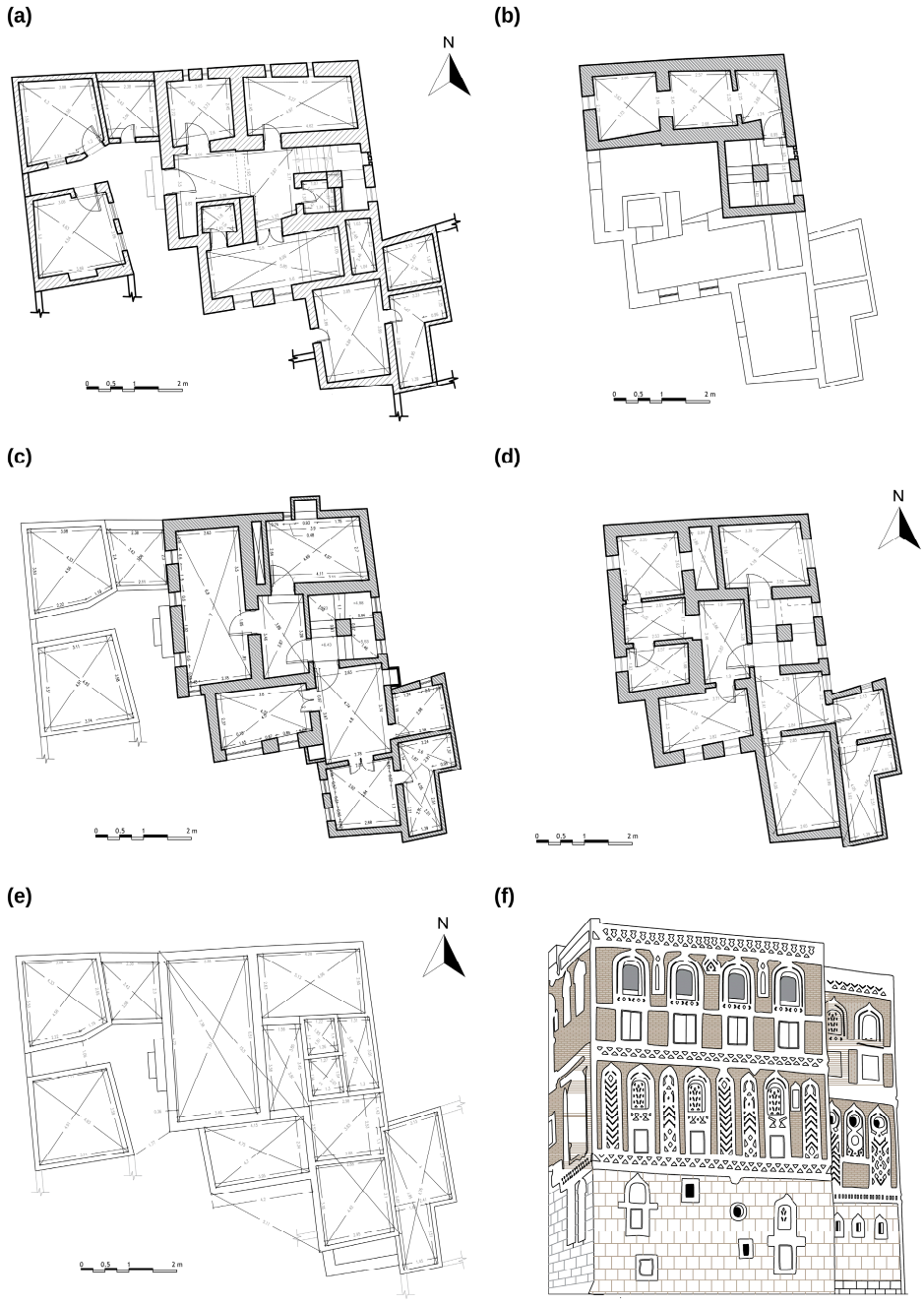

Figure 5. Architectural documentation of the study building: (**a**) ground floor plan; (**b**) mezzanine floor plan; (**c**) first floor plan; (**d**) second floor plan; (**e**) roof plan; (**f**) north elevation. Hatched areas indicate walls cut by the plan section, and grey figures are dimensions in metres.

5.1.5. Architectural and Historical Value: Baseline Observations

The documented architectural characteristics of the pilot building are consistent with the broader traditional residential typology of the Old City of Sana'a. Its multi-storey

configuration, material composition, spatial organisation, and façade treatment reflect locally established construction and climatic-adaptation practices. Because the construction date has not been independently verified, the heritage-significance assessment in Step 4 does not rely on a specific chronological attribution. Instead, it is based on the building's documented architectural, material, constructional, and typological characteristics and their contribution to the continuity of traditional Sana'ani residential architecture.

5.2. Step 2 Output—Material Vulnerability Findings

Applying the material-vulnerability taxonomy established in Section 4.2 and the tripartite deterioration classification established in Section 4.3, field observation of the pilot building identified vulnerability patterns in three of the four traditional material categories: stone, timber, and lime plaster. No material-specific deterioration attributable to the fired-clay-brick component was independently distinguishable from the plaster-related findings during field survey; this is noted as a limitation of the material-vulnerability classification for this pilot building (see Section 3.6) rather than an indication that the brick fabric is unaffected.

5.2.1. Stone

Deterioration of the black-stone and limestone elements is expressed primarily through cracking, mortar-joint loss, local surface decay, and material loss, particularly on the south façade and at corner areas. These manifestations are consistent with physical and moisture-related deterioration mechanisms discussed in Section 4.3. Field observations indicate that inadequate drainage and water leakage from adjacent wet areas are plausible contributing factors, particularly where water accumulation was evident on the south façade. Because no structural calculation or material testing was undertaken, the observed cracks are treated here as a potential concern for load-bearing continuity rather than as evidence of confirmed structural instability. Representative stone deterioration is shown in Figure 6.



Figure 6. Black-stone masonry showing surface blackening and mortar-joint loss consistent with the moisture-driven deterioration described for elements W-S and W-C (Section 5.2.1).

5.2.2. Timber

Deterioration of the timber ceiling system is expressed through deformation, localised decay, and partial collapse. Prolonged rainwater exposure associated with loss of gutter function is identified from field evidence as the principal apparent contributing factor. The observed deformation may also have been influenced by the dimensions, spacing, and spanning arrangement of the timber members; however, no structural calculation

or mechanical testing was undertaken to quantify load-bearing capacity. The findings are therefore interpreted as field-based evidence of moisture-related physical deterioration rather than as a definitive structural-capacity diagnosis. Representative timber deterioration is shown in Figure 7.



Figure 7. Exposed timber ceiling structure showing decay and partial exposure of the roof covering, consistent with the deformation mechanism described for element C-1 (Section 5.2.2).

5.2.3. Traditional Plaster Finishes: Qudad-Type Lime Render and Gypsum-Based Finishes

Deterioration affecting the building's traditional plaster finishes was expressed through cracking, spalling, moisture staining, and surface loss. Where the material could be identified from construction context and field appearance, the finishes were distinguished as qudad-type lime render or gypsum-based plaster; where such distinction could not be established reliably, the neutral term "plaster finish" was retained. Deterioration was observed at both ground- and first-floor levels; however, the ground-floor plaster exhibited more extensive moisture staining and active surface loss at the time of survey, whereas deterioration at the first-floor level was predominantly characterised by comparatively stable cracking and localised surface loss. This distinction in observed activity and short-term deterioration risk informed the different urgency classifications subsequently assigned to P-GF and P-1F in Step 3. Associated deterioration was also observed in adjacent architectural elements, including broken glazing, non-functional locking mechanisms, and deterioration of timber window and door components. Moisture staining on an interior lime-plaster surface is illustrated in Figure 8.



Figure 8. Vertical moisture staining on an interior lime-plaster surface, illustrating the cross-cutting moisture-vulnerability driver (Section 5.2.4) affecting elements P-GF and P-1F.

5.2.4. Cross-Cutting Vulnerability Driver: Moisture and Drainage

Deformation and breakage in the building's rainwater gutter systems constitute a cross-cutting vulnerability driver rather than a material-specific one: by preventing the effective removal of rainwater from the building, this failure accelerates the material-specific deterioration pathways identified independently in Sections 5.2.1–5.2.3 for stone, timber, and plaster alike. Consistent with Section 4.3's identification of moisture as a principal trigger of both physical and chemical deterioration, this driver is treated in Step 3 (Section 5.3) as a contributing factor logged against each affected element, rather than as a distinct material category in its own right. The material-specific findings and the cross-cutting driver are summarised in Table 6.

Table 6. Step 2 output: material vulnerability summary for the pilot building.

Material	Dominant Deterioration Type(s) (Section 4.3)	Principal Manifestation	Principal Contributing Factor
Stone (black stone, limestone)	Physical, chemical	Cracking, joint-gap formation, surface material loss	Moisture from inadequate drainage; south-façade water accumulation
Timber (ceiling systems)	Physical	Deformation, localised collapse	Sustained rainwater contact via non-functional gutters
Lime plaster/gypsum finishes	Physical, chemical	Cracking, spalling, surface loss	Moisture exposure; concentrated on ground and first floors
Fired clay brick	Not independently distinguished (see limitation, Section 3.6)	–	–
Cross-cutting driver	–	Gutter deformation and breakage	Structural/maintenance failure amplifying all material-specific pathways above

5.3. Step 3 Output—Element-Level Condition and Urgency Classification

Consistent with the element-level classification requirement specified in Step 3 of the framework (Section 3.2), and building on the material-vulnerability findings established in Step 2 (Section 5.2), each identified building element was independently assessed using the study-specific Condition Class (CC1–CC5) and Urgency Class (UC1–UC4) scheme presented in Table 2. This classification is informed by the condition-survey and urgency principles of EN 16096:2012 [11] but represents an author-defined element-level adaptation rather than a reproduction of the standard's original categories. Condition Class and Urgency Class are retained as separate assessment outputs and are subsequently interpreted hierarchically in Step 5 rather than combined mathematically into a composite priority score. The resulting element-level classifications are reported in Table 7.

Table 7. Step 3 output: element-level condition and urgency classification for the pilot building. Full damage descriptions and location detail for each element are given in Sections 5.2.1–5.2.4; only element identifiers and classification outputs are tabulated here for readability.

Element ID	Element Type/Material	CC	UC
W-S	Load-bearing wall, stone (south façade)	CC4	UC3
W-C	Load-bearing wall, stone (corner areas)	CC3	UC3
C-1	Ceiling bay, timber	CC4	UC4
R-1	Roof structure, timber/earthen covering	CC4	UC4
P-GF	Plaster finish, ground floor	CC3	UC3
P-1F	Plaster finish, first floor	CC3	UC2
WD-1	Windows and doors, timber/glazing	CC2	UC2

G-1	Rainwater gutters	CC4	UC4
BU-1	Upper-storey wall, fired clay brick	–	–

Two principal patterns emerge from the element-level classification. First, the highest urgency category (UC4) is assigned to the ceiling system (C-1), roof structure (R-1), and rainwater gutters (G-1), all of which are directly associated with the uncontrolled moisture pathway identified in Step 2 (Section 5.2.4). These elements therefore enter the earliest intervention phase. Second, nominally similar materials can receive different urgency classifications when their observed condition and intervention requirements differ. For example, P-GF is classified as UC3 whereas P-1F is classified as UC2, demonstrating the additional resolution provided by element-level assessment compared with a single whole-building classification [38]. The unresolved entry for the upper-storey fired-clay-brick walls (BU-1) is retained rather than omitted so that the identified data gap remains visible at the classification stage.

5.4. Step 4 Output—Heritage Significance Assessment

Consistent with Step 4 of the framework (Section 3.2), the heritage significance of each element was assigned by a single assessor using the three-level rubric and the evidence base described there: measured drawings, the element-referenced photographic records, field observations of materials and construction, and the architectural and typological baseline documented in Section 5.1. Table 8 reports each rating together with the dimension(s) evidenced in its recorded basis and the decision rule that this implies (A, architectural contribution; M, material and construction significance; H, historical and typological significance; rules H1, H2, M1 and L1 as defined in Section 3.2). Structural and functional criticality was not included in this assessment and was considered separately during Step 5 prioritisation. The ratings should be interpreted as a pilot application of the rubric and not as a formally validated multi-rater heritage-significance assessment.

Table 8. Step 4 output: element-level heritage-significance assessment for the pilot building.

Element ID	Element/Material	Heritage Significance	Basis for Significance
C-1	Ceiling bay, timber	High	[M; H2] Traditional timber ceiling construction representing significant historic material and construction character. Single-dimension case.
W-S	Load-bearing wall, stone (south façade)	High	[A, M; H1] Principal historic stone masonry forming part of the street-facing façade and traditional material character.
R-1	Roof structure	Medium	[M (secondary); M1] Traditional roof construction contributing to the building's historic material system but with limited direct visual expression.
W-C	Load-bearing wall, stone (corner)	High	[M; H2] Historic stone masonry integral to the building's traditional construction character. Single-dimension case.
P-GF	Plaster finish, ground floor	High	[A, M; H1] Principal carrier of the characteristic façade ornamentation and traditional surface treatment.
G-1	Rainwater gutters	Low	[L1] Functional and routinely replaceable element with limited intrinsic heritage significance.
P-1F	Plaster finish, first floor	Medium	[A, M (secondary); M1] Traditional façade finish contributing to a secondary elevation.
WD-1	Windows and doors	Low	[L1; borderline, alternative level Medium] Functional opening components with limited documented evidence of exceptional historical or material significance.

BU-1	Upper-storey wall, fired clay brick	High *	[M, H; H1] Principal traditional upper-storey material contributing substantially to the building's typological and material identity.

Note. A, architectural contribution; M, material and construction significance; H, historical and typological significance; H1, H2, M1, L1, decision rules defined in Section 3.2. The bracketed tags in the last column record the dimension(s) evidenced in the basis recorded at the time of the pilot assessment and the rule that this implies; dimension-level ratings were not recorded separately at that time, and the tags were derived afterwards from the recorded basis. * Heritage significance is assigned to BU-1 despite the absence of a complete condition assessment, allowing its cultural significance and the associated diagnostic data gap to remain visible in Step 5.

The heritage-significance assessment establishes a distinct cultural-value layer that is carried forward into Step 5 without mathematically overriding technical urgency. This separation allows technically urgent but low-significance elements, such as drainage components, to remain actionable where their failure threatens higher-significance fabric. This separation also allows cultural sustainability to be traced in the sequence: the significance of each element is recorded, carried forward and open to challenge instead of being absorbed into a composite priority score.

Consistency check and borderline cases. The ratings in Table 8 are those assigned in the pilot; none was altered when the protocol in Section 3.2 was formalised. Read against the protocol, the recorded basis of six ratings (W-S, P-GF and BU-1 as High; R-1 and P-1F as Medium; G-1 as Low) is consistent with the assigned level. Three entries are more open to alternative judgement: C-1 and W-C are High on a single documented dimension and depend on rule H2, and WD-1 is rated Low as an aggregated element of functional units although its windows are described in Section 5.1.2 as contributing to the building's aesthetic character (Medium is the alternative level; the entry is flagged as borderline). This check is documentary and is not an independent validation.

Sensitivity of the sequence. Because phase membership is fixed by Urgency Class alone, a change in any significance rating can alter only the order of elements within a phase. Re-rating C-1 would not change the implementation sequence in Table 9, because C-1 belongs to the Phase 1 group implemented as one dependent unit (Section 6.2). Re-rating W-C to Medium would leave it behind W-S and ahead of the non-structural P-GF, because structural dependency precedes significance within a phase. Re-rating WD-1 to Medium would leave it behind P-1F, which has the higher Condition Class (CC3 against CC2). These are checks of the design logic on the recorded values, not independent re-assessment.

Table 9. Step 5 output: sequenced intervention matrix for the pilot building.

Phase	Timeframe (Per UC, Table 2)	Element ID	Element/Material	Sequencing Rationale
Phase 1	UC4—within 3 months	C-1	Ceiling bay, timber	UC4 element with major deterioration, partial collapse, and direct safety and fabric-stability implications; prioritised as an immediate conservation concern.
Phase 1	UC4—within 3 months	R-1	Roof structure	UC4 element and direct protective dependency for C-1; roof failure permits continued moisture ingress into the ceiling system.
Phase 1	UC4—within 3 months	G-1	Rainwater gutters	UC4 preventive dependency; although of low intrinsic heritage significance, drainage repair is required to prevent recurrence of deterioration in C-1 and R-1.

Phase 2	UC3—within 1 year	W-S	Load-bearing wall, stone (south façade)	UC3 load-bearing masonry affecting the principal façade; sequenced ahead because of its structural role and high heritage significance.
Phase 2	UC3—within 1 year	W-C	Load-bearing wall, stone (corner)	UC3 load-bearing masonry; prioritised ahead of non-structural P-GF because of structural dependency.
Phase 2	UC3—within 1 year	P-GF	Plaster finish, ground floor	UC3 high-significance façade finish; sequenced after load-bearing masonry within the same urgency phase.
Phase 3	UC2—within 1–3 years	P-1F	Plaster finish, first floor	UC2 element with moderate heritage significance and no immediate structural dependency.
Phase 3	UC2—within 1–3 years	WD-1	Windows and doors	UC2 functional element with comparatively low heritage significance and no immediate structural dependency.
Pending investigation	Not classifiable (data gap)	BU-1	Upper-storey wall, fired clay brick	High heritage significance, but the data gap prevents condition classification; flagged for priority diagnostic survey.

5.5. Step 5 Output—Prioritisation and Decision Matrix

Consistent with Step 5 of the framework (Section 3.2), conservation sequencing begins with the Urgency Class established in Step 3. Within each urgency band, sequencing is refined by examining causal and structural dependency, followed by heritage significance and condition severity. This hierarchy allows technically necessary preventive actions to remain highly prioritised even where the affected component has limited intrinsic heritage significance. The resulting sequenced intervention matrix is presented in Table 9.

Interpretation. The matrix converts the independently derived technical assessment from Step 3 and heritage-significance assessment from Step 4 into an actionable intervention sequence while preserving Urgency Class as the primary determinant of intervention timeframe. Causal and structural dependency, heritage significance, condition severity, and preventive need are subsequently used to sequence elements within each urgency phase. BU-1 illustrates the framework's explicit treatment of incomplete evidence. Because sufficient condition data were unavailable, the element remains classified as "pending investigation" rather than being omitted or assigned an unsupported Condition Class, Urgency Class, or repair timeframe. Its high heritage significance justifies prioritising additional diagnostic investigation, but no substantive intervention category is assigned until adequate Step 2 and Step 3 evidence has been obtained. Within Phase 1, the three elements were treated as a single dependent unit (Section 6.2); the row order in Table 9 therefore records the reasoning for each element and does not prescribe a temporal order.

5.6. Operability Evaluation

This subsection assesses, against the operability criterion of Section 3.1, whether the five-step framework was executed end to end on the pilot building, independently of whether the classifications generalise (deferred to replication, Section 3.6).

Operability was demonstrated within the limits of Section 3.6. Each step produced its specified output: a documentation baseline (Section 5.1), a material-vulnerability table (Table 6), an element-level condition and urgency classification (Table 7), a heritage-significance assessment (Table 8) and a sequenced intervention matrix (Table 9). No step failed to produce output or required deviation from its specification to accommodate this building.

Two design features were particularly evident in the pilot application. First, element-level classification distinguished between nominally similar components rather than

forcing them into a single building-level category. The plaster elements P-GF and P-1F, for example, were assessed independently and could therefore receive different urgency classifications where supported by different field evidence. Second, the framework retained a genuine data gap, the absence of field-verified condition information for the fired-clay-brick component BU-1, as a visible "pending investigation" output through Steps 2–5 rather than silently omitting the element or assigning it an unsupported low-priority classification. These outcomes illustrate the principal operational value of maintaining element identity, evidence provenance, and uncertainty throughout the workflow.

The pilot also identified the need for greater formalisation of the heritage-significance stage. The protocol set out in Section 3.2 (Table 3) responds to that need by making criteria, evidence rules and borderline provisions explicit, but it has not yet been applied by independent assessors; consistency between assessors therefore remains untested.

Overall, the pilot supports the limited claim that the framework is executable under field conditions and yields coherent, internally consistent outputs from a building-independent specification (Section 3.1). It does not evidence generalisability across typologies, materials or damage profiles, nor the sustainability benefits discussed in Section 7.2, whose status is graded in Section 5.7.

5.7. Sustainability Reading of the Pilot Prioritisation

This subsection reads the pilot record against the six dimensions of Section 2.6, applying the evidence grading of Section 3.5. It draws on Table 9 and Section 6 and makes no statement on magnitude. Because the framework was applied before and during the works (Section 3.3), the readings describe the relationship between the prioritisation and what was subsequently done, not a comparison with what would have been done without it (Table 10).

Table 10. Sustainability reading of the pilot prioritisation, by dimension and evidence status (interpretive; no quantitative data).

Dimension	Observed in the Pilot Record	Plausible but Not Verified	Not Examined
Environmental	Interventions were scaled to element condition: sections of W-S and W-C were dismantled and rebuilt; damaged plaster was removed and renewed (P-GF, P-1F); WD-1 was repaired where components remained sound. Failed elements (C-1, R-1) were replaced or reconstructed.	Element-level targeting limited the volume of new material introduced compared with a whole-building or whole-system approach.	Embodied carbon, waste, transport and energy; environmental effect of the introduced asphalt and galvanised-metal components.
Resource	Work was organised into three phases by Urgency Class, and one element (BU-1) was left without intervention pending diagnosis. The survey required only a laser distance meter, a smartphone camera and CAD software (AutoCAD 2024) (Section 3.2).	Phasing concentrated limited funds, materials and labour on the most urgent elements and on the causes of deterioration; deferring BU-1 avoided intervention without evidence.	Cost, time, staffing and material quantities; comparison with an unprioritised programme.

Cultural	Replacement material for high-significance elements was matched to the original (timber and jointing for C-1; black stone and limestone for W-S and W-C; lime-based, qudad-consistent material for plaster), and the traditional layered roof finish was retained externally. The departure from authenticity (galvanised gutter sections) was confined to a low-significance element.	Matching materials and techniques helps transmit traditional craft knowledge and the visual and material identity of the Old City.	Actual transmission of craft knowledge; values held by owners, residents and craftspeople; independent specialist rating.
Social	The building is a traditional residential house, and the ceiling, roof, drainage, walls, plaster and openings serving its residential function were addressed. The sequence and its rationale are recorded and open to scrutiny.	A transparent, evidence-linked rationale can support communication with owners and authorities and help keep vernacular dwellings maintained and in use.	Occupancy; owner and community outcomes; stakeholder participation in significance rating.
Preventive conservation	Drainage (G-1) and roof (R-1) were sequenced with the ceiling (C-1) in Phase 1 as one dependent unit although G-1 has low significance; gutters were renewed and resloped; replacement timber was oil-treated; a waterproofing layer was introduced in the roof.	Removing the moisture pathway reduces the likelihood that the rebuilt ceiling and roof will deteriorate by the same mechanism.	Post-intervention performance of gutters, roof membrane and wall ties; long-term compatibility of the asphalt layer with the earth covering.
Resilience	Moisture and drainage failure was identified as the cross-cutting driver; the matrix records the reasons for each priority so that it can be revised.	Improved rainwater management lowers exposure to a climate-sensitive deterioration pathway [32]; a revisable, field-based matrix is adaptable where resources and access are limited.	Behaviour under extreme rainfall or other hazards; monitoring over several seasons; performance in conflict or post-conflict conditions.

Two features of the record qualify any favourable reading. First, C-1 and R-1 were already at CC4 when surveyed and the roof structure had collapsed under sustained rainfall (Section 6.2); reconstruction and replacement were unavoidable, and the framework could not prevent a loss that had already occurred. Its preventive potential is prospective, lying in placing moisture control and routine maintenance (UC1–UC2) ahead of failure when it is applied earlier. Second, the asphalt waterproofing layer and galvanised-metal gutter sections reflect a trade-off between authenticity and performance (Section 6.2). The framework makes this trade-off explicit by linking it to significance and functional role, but it does not establish whether the introduced materials are advantageous in the long term, which remains a question for monitoring.

6. Conservation Interventions: Implementation Against the Step 5 Matrix

This section reports the conservation interventions carried out on the pilot building and examines them against the sequenced matrix produced by Step 5 of the framework (Section 5.5, Table 9), rather than presenting them, as in earlier documentation of this building, as an undifferentiated list of planned works. The five-step framework (Section 3.2) was applied prospectively: field documentation and the resulting Step 3–Step 5 classification and sequencing (Sections 5.3–5.5) were completed before and during the conservation works reported below and were used to guide the sequencing and prioritisation of the interventions actually carried out, rather than being constructed afterwards to rationalise work already completed. Framing intervention this way distinguishes clearly

between the framework's analytical outputs (Sections 5.1–5.6, which classify and prioritise deterioration) and the intervention decisions that follow from them—consistent with the separation between observation, classification, and intervention established in Section 3 (cf. [38]).

6.1. Correspondence Between Recommended Intervention Types and the Prioritisation Matrix

Table 11 maps the general intervention vocabulary established in Section 4.4 (cleaning, consolidation, repointing/completion, moisture control) onto the specific elements and phases identified in Table 9, making explicit which category of general conservation approach was applied to each prioritised element and why.

Table 11. Intervention type by element and phase.

Element ID	Phase (Table 9)	Intervention Type (Section 4.4)	Specific Action	Governing Principle
C-1	Phase 1	Repair and selective replacement	Decayed timber ceiling elements dismantled and replaced with matched traditional timber; ceiling slopes corrected and a waterproofing layer introduced	Material compatibility: replacement material matched to original species and jointing method rather than substituted with modern alternatives.
R-1	Phase 1	Moisture control and surface protection	Roof structure reconstructed following collapse; asphalt waterproofing layer introduced beneath a traditional earth-and-plaster finish	Moisture control with minimum visual intervention: the waterproofing layer was introduced beneath the traditional earth-and-plaster finish to improve rainwater resistance while retaining the roof's external traditional material character. The long-term compatibility of the introduced layer should be monitored as part of future maintenance.
G-1	Phase 1	Moisture control and surface protection	Rainwater gutters renewed and re-sloped; galvanised metal sections introduced where traditional materials could not reliably restore function	Pragmatic departure from strict material authenticity, justified by G-1's low intrinsic heritage significance and its critical moisture-control function as a preventive dependency for higher-significance elements C-1 and R-1.
W-S, W-C	Phase 2	Consolidation and protection/repointing	Damaged wall sections dismantled and rebuilt using matched black stone and limestone; timber ties introduced at cracked sections to restore bonding	Material compatibility and structural minimum intervention: original stone type retained; timber ties address the specific joint-gap mechanism identified in Step 2 (Section 5.2.1).
P-GF, P-1F	Phase 2/Phase 3	Material cleaning/repointing	Façades cleaned; damaged plaster removed and renewed using lime-based (qudad-consistent) material	Material compatibility: renewal material selected to match the lime-plaster vulnerability profile established

				in Section 4.2, rather than a modern substitute.
WD-1	Phase 3	Consolidation and protection	Broken glazing replaced; timber components sanded, treated, and refinished; locking mechanisms restored	Minimum intervention: repair prioritised over wholesale replacement where components remained structurally sound.

6.2. Phase 1 Interventions: Roof, Ceiling, and Drainage System

Consistent with the Phase 1 designation established in Table 9, intervention on the roof structure (R-1), ceiling system (C-1), and gutters (G-1) addressed the cross-cutting moisture-vulnerability driver identified in Step 2 (Section 5.2.4) as a single, sequentially dependent unit, rather than as three independent repairs. Following collapse of the roof structure under sustained rainfall exposure, suitable timber was sourced for the main and secondary beam members; main timbers were positioned along the short span direction, with secondary timbers placed horizontally to close inter-beam gaps. An asphalt waterproofing layer was then introduced above the timber structure, covered with a traditional earth layer and a final plaster coat—a sequence intended to restore the roof's rainwater resistance without departing from its traditional layered construction logic. The asphalt layer was positioned above the structural timber and beneath the traditional earth and plaster finish specifically so that the roof's external appearance and layered material logic were preserved and the intervention remained visually and materially reversible from the exterior; because no hygrothermal (moisture–vapour transmission) testing was undertaken, the long-term compatibility of the asphalt membrane with the vapour-permeable traditional earth covering above it, specifically, whether trapped moisture migration could affect the earth layer over time, remains an open question identified here as a priority for post-intervention monitoring rather than one that can be resolved from the available field evidence. The on-site application of the traditional earth and mortar layers during roof reconstruction is shown in Figure 9.



Figure 9. On-site application of traditional earth and mortar layers during roof reconstruction, corresponding to the Phase 1 intervention described for R-1 and C-1 (Section 6.2).

Decayed timber ceiling elements (C-1) were replaced following the same material-matching principle, addressing directly the deformation and localised collapse mechanism identified in Section 5.2.2. To mitigate the biological and moisture-related vulnerability of timber established in Section 4.3, replacement timber components were treated with an oil-based coating prior to being covered with a clay layer and a gypsum-plaster

finish, consistent with traditional practice documented for the building's material category (Section 4.2). The restored ceiling is shown in Figure 10.

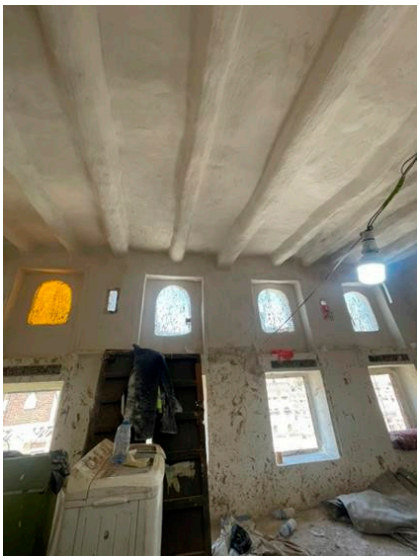

Figure 10. Restored timber ceiling and traditional glazed openings following completion of the Phase 1 intervention on element C-1 (Section 6.2). Compare with Figure 7 (pre-intervention condition).

Gutters (G-1) were renewed and re-sloped to restore effective rainwater drainage, addressing the specific failure mechanism identified as the principal contributing factor behind both C-1 and R-1 deterioration (Section 5.2.4). Although G-1 has low intrinsic heritage significance, its critical drainage function and direct causal relationship with the deterioration of C-1 and R-1 justified its inclusion in the first intervention phase. Galvanised metal sections were introduced where they offered more reliable long-term performance than the strict traditional-material replacement. This illustrates the framework's capacity to support differentiated material decisions according to an element's heritage significance and functional role rather than applying a uniform authenticity standard across all components.

6.3. Phase 2 Interventions: Load-Bearing Walls and Ground-Floor Plaster

Addressing the stone-wall deterioration identified in Section 5.2.1, damaged sections of W-S and W-C were repaired using matched black stone consistent with the existing masonry fabric. Timber ties were introduced at selected cracked sections with the intention of improving inter-block bonding and limiting further crack development. These actions responded to the inadequate bonding, joint deterioration, and moisture-related mechanisms identified through field assessment. Because no post-intervention structural monitoring was undertaken within the scope of this study, the effectiveness of these measures in arresting future movement remains to be verified through subsequent inspection. The reconstruction of a corner wall section is shown in Figure 11.

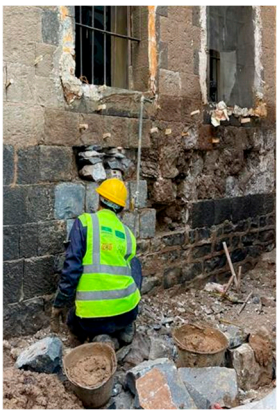

Figure 11. Reconstruction of a corner wall section using matched black stone, corresponding to the Phase 2 intervention described for element W-C (Section 6.3).

Ground-floor plaster (P-GF) was addressed through façade cleaning followed by the removal and renewal of damaged lime-plaster sections, consistent with the cracking and spalling pattern documented in Section 5.2.3.

6.4. Phase 3 Interventions: First-Floor Plaster, Windows, and Doors

Consistent with the later UC2 timeframe assigned to P-1F and WD-1 (Table 9), intervention on these elements followed the same material-matching logic applied in Phase 2 but at lower urgency. Window and door maintenance addressed broken glazing, non-functional locking mechanisms, and timber decay identified in Section 5.2.3: glazing was replaced, timber shutters were sanded and refinished, and a transparent protective coating was applied to mitigate future moisture-related decay. The on-site repair of a window opening and timber frame is shown in Figure 12.



Figure 12. On-site repair of a window opening and timber frame, corresponding to the Phase 3 intervention described for element WD-1 (Section 6.4).

6.5. BU-1: Status of the Pending-Investigation Element

Consistent with its designation in Table 9, no intervention was undertaken on the upper-storey fired-clay-brick walls (BU-1) during the phases reported above; the diagnostic survey flagged as a prerequisite in Section 5.5 had not yet been conducted at the time of this study. This is reported here explicitly, rather than omitted, so that the intervention record in Sections 6.2–6.4 is read as a partial, phase-consistent implementation of Table 9 rather than as a complete resolution of every deterioration finding reported in Section 5.

7. Discussion

This discussion returns to the research questions of Section 1. It examines the framework's contribution relative to existing instruments given that none of its components are new (Section 7.1), including its relationship to sustainability (Section 7.2), the boundary of technical classification in conflict-affected settings (Section 7.3), consistency with the wider literature (Section 7.4) and the limitations that define the next research phase (Section 7.5).

7.1. Novelty and Contribution Relative to Existing Instruments

The pilot shows how an element-level workflow can give greater diagnostic resolution than building-level classification when sequencing is required. The most comparable Sana'a study [38] applied standardised condition and urgency assessment across many buildings, whereas the present study differentiates components within one. Recent HBIM-based approaches already integrate condition records, element-level information and intervention priorities [18,19]; the present framework is therefore complementary, not technologically superior.

Because no component is claimed as new, the contribution lies in what their integration makes possible. Component-level coding and spatially referenced damage recording are already established in EN 16096-based guidance. The pilot illustrates four capabilities: (i) traceability, a single element identifier linking each priority in Table 9 to its significance rating (Table 8), classification (Table 7), vulnerability finding (Table 6) and documentary record; (ii) separation of variables, so that the reason for each position in the sequence can be read from the matrix (G-1 enters Phase 1 because of its urgency and preventive dependency despite low significance); (iii) an ordered sequencing rule that justifies a preventive dependency explicitly instead of treating it as an exception to a ranking; and (iv) persistent uncertainty, with BU-1 remaining visible as a pending diagnostic requirement from Step 2 to Step 5. None is produced by any one component alone. They are demonstrated for one building and one assessor team, and their value elsewhere remains to be tested. The workflow demands fewer resources than a full HBIM environment but is not a substitute for one where such an environment is available.

In practical terms, the pilot was carried out by a small field team with a handheld laser distance meter, a smartphone camera and CAD software (AutoCAD 2024), without BIM software, point-cloud capture or laboratory testing. The workflow can be seen as three tiers of increasing data intensity: an essential tier (Steps 1–3) sufficient for an auditable, EN 16096-informed condition record; an intermediate tier adding Step 4 for institutions able to involve a conservation specialist; and an extended tier adding systematic photographic indexing. Staffing, time and cost were not systematically recorded and are not reported, so the tiers indicate scalability qualitatively and not a budgeted plan.

7.2. Contribution to Sustainable Conservation

The pilot and the reviewed literature support a bounded argument for the framework's sustainability relevance. It rests on the decision structure of the workflow, not on measured outcomes, and uses the grading of Tables 4 and 10. The framework is relevant to SDG Target 11.4 [2,3] to the extent that it supports decisions that safeguard heritage fabric under resource constraints, not as a tool for monitoring progress towards it.

Environmental and resource sustainability. Element-level assessment lets intervention follow the distribution of damage: the most severe conditions were concentrated in the roof, ceiling, drainage and south-façade wall (CC4), with plaster finishes and corner masonry assessed as moderately affected (CC3) and openings least affected (CC2) (Table 7), and treatments ranged from reconstruction and replacement to sectional rebuilding, plaster renewal and repair (Section 6). This graduation is the mechanism by which

prioritisation can reduce replacement of sound material, in line with minimum-intervention and compatibility principles [37,47]. Ordering work by urgency and dependency likewise directs scarce funds and skilled labour first to the interventions whose omission would cause most further loss, and recording BU-1 as pending avoids treatment without evidence. These are plausible contributions, not measured savings.

Cultural and social sustainability. A separately recorded significance rating allows strict material compatibility for high-significance fabric and documented pragmatic solutions for low-significance functional components to be applied consistently and audited, as the contrast between the timber and stone repairs and the galvanised gutters illustrates (Section 6). Repairs in traditional materials may also support the transmission of craft knowledge, although this was not assessed. The social dimension is addressed only indirectly: the sequence is transparent and the equipment simple, but the ratings reflect one assessor's judgement, and the framework does not elicit the values of residents or craftspeople. Participatory valuation is the main extension needed (Section 7.3).

Preventive conservation and resilience. The sequencing rule is the framework's most direct expression of preventive conservation: by letting a low-significance drainage element (G-1) take precedence in Phase 1 because it protects the roof and ceiling (R-1, C-1), it operationalises the view that moisture management and preventive maintenance underpin the durability of earthen and composite construction [29,40]. Because climate-related changes in rainfall and moisture availability can alter deterioration rates [32], improving rainwater management also reduces exposure to one pathway through which such changes act; this resilience argument was not tested. The pilot also shows the limits of the preventive claim, since C-1 and R-1 had reached CC4 and the roof had collapsed before intervention; preventive potential is greater when the framework is applied earlier, with UC1–UC2 elements receiving routine maintenance.

Trade-offs. The framework does not remove tensions between sustainability aims. The asphalt waterproofing layer and galvanised gutters were intended to improve moisture performance but depart from authenticity, and their long-term compatibility and environmental implications were not assessed (Section 6.2). The framework's contribution is to make such trade-offs visible and attributable to stated criteria, not to resolve them; the implications remain potential benefits, not demonstrated outcomes (Section 7.5).

7.3. Post-Conflict Intervention: Technical Classification and Its Limits

The intervention record in Section 6 shows that the framework's outputs (Tables 7–9) translated into a coherent phased sequence (Table 11) under real field conditions, addressing the operability question central to the design-science framing of Section 3.1 [50]. The comparison with the post-conflict Ottoman heritage reconstruction suggests, however, a boundary to what technical classification can resolve. Grodach's analysis of the reconstruction of Mostar's Stari Most, a sixteenth-century Ottoman bridge destroyed during the Bosnian War [51], shows that post-conflict restoration decisions are rarely purely technical: they are shaped by contested identity politics and competing historical narratives that an instrument such as EN 16096 is not designed to capture. Step 4 gestures toward this wider dimension by incorporating architectural-historical value, but through a single analyst's typological judgement rather than multi-stakeholder deliberation. This is a scope boundary, not a deficiency: the framework is a technical decision-support instrument intended to inform, not replace, the processes through which priorities are negotiated, and integrating such deliberation would also strengthen its social dimension (Section 7.2).

7.4. Consistency with the Wider Literature on Sana'ani Building Deterioration

The Step 2 findings (moisture-induced stone decay, timber ceiling deformation and plaster failure concentrated at lower storeys) are consistent with the general mechanisms in the traditional-materials literature and their climate sensitivity [30,32]. Conservation-oriented documentation studies in AlUla and Historic Jeddah similarly show that moisture-related deterioration is interpreted more effectively when field observations are linked to spatially explicit architectural documentation [12,13]. This supports integrating material-level observations with element-referenced documentation.

7.5. Limitations and Validation Agenda

The limitations in Sections 3.6 and 5.6 are drawn together as a validation agenda. First, there were no independent evaluators: Condition Class, Urgency Class and significance ratings were assigned by the research team without cross-checking, unlike the verification protocols reported by [39] for conflict-zone damage surveys, so inter-rater reliability for Steps 3 and 4 is unknown. Second, no laboratory analysis supported the Step 2 classifications. Third, documentation used low-cost equipment without survey control or independently quantified accuracy (Section 3.2). Fourth, the framework was evaluated through a single pilot, so generalisability across typologies, materials and damage severities remains to be demonstrated.

These limitations are treated as the specification for the next research phase. The sustainability implications should be read as potential conservation benefits, not verified outcomes. A validation agenda would comprise:

- multi-building replication across typologies, material combinations, deterioration levels and conservation contexts, including buildings assessed before failure has occurred;
- documentation with independent survey control and stated tolerances (for example total-station control, calibrated photogrammetry or laser scanning), so that the accuracy of measured drawings can be reported;
- independent multi-assessor trials in which at least two trained assessors classify the same elements without consultation, with agreement reported using a statistic suited to ordinal data (for example weighted kappa or Krippendorff's alpha) and disagreements reconciled through a recorded procedure;
- targeted laboratory diagnoses, such as moisture-content and soluble-salt profiling, binder and mineralogical analysis of plasters, and assessment of timber decay;
- participatory elicitation of heritage values from owners, residents, local authorities and craftspeople to test and, where necessary, revise the Step 4 rubric; and
- sustainability verification through comparative life-cycle or embodied-carbon assessment of repair and replacement scenarios, cost and labour records by phase, and post-intervention monitoring over several seasons.

8. Conclusions and Future Directions

This study addressed a methodological gap in the assessment and conservation of traditional historic buildings by developing an integrated element-level framework linking field documentation, material-specific vulnerability assessment, standardised condition and urgency classification, heritage-significance integration and conservation prioritisation. None of these components is claimed as new. The contribution lies in their transparent integration through a shared element identifier, separate recording of condition, urgency, significance, causal dependency and evidential status, an ordered sequencing rule without a composite score, and the persistence of unresolved evidence as a pending-investigation status. Step 4 was specified through dimension-level criteria, evidence rules

and decision rules, including provisions for borderline cases, so that it can be reproduced and challenged.

The framework was applied to a traditional multi-storey residential building in the UNESCO-listed Old City of Sana'a as a pilot demonstration of operability under real field conditions. It generated a coherent, traceable sequence of outputs from field observation to intervention planning, and element-level assessment distinguished deterioration conditions that building-level classification would have obscured. Moisture emerged as the principal cross-cutting driver affecting stone masonry, timber roof and ceiling systems, traditional plaster and drainage-related elements, so that preventive actions such as roof maintenance, drainage improvement and moisture control may need to precede direct repair of individual elements; this has wider relevance for earthen, stone and timber heritage where deterioration is driven by interconnected rather than isolated failures. Documenting uncertainty was also important: the upper-storey fired-clay-brick component, whose condition could not be assessed reliably, remained visible as a pending diagnostic requirement and was not omitted or treated as low risk.

The decision structure of the framework relates to sustainability by directing intervention to failing elements, protecting high-significance fabric through a separately recorded rating, placing causes of deterioration ahead of or alongside repair, ordering scarce resources by urgency and recording evidential gaps. These relationships are conceptual. The pilot included no life-cycle, cost or monitoring analysis, and it showed the limits of a preventive argument when a framework is applied after failure has occurred; sustainability benefits should be regarded as potential and requiring verification.

The pilot supports a bounded conclusion: the framework is operational and internally coherent when applied by a single assessor team to one traditional building, using low-cost documentation without independently quantified accuracy, but its reproducibility, robustness and transferability have not been established. Future research should follow the validation agenda of Section 7.5: multi-building replication; metrically controlled documentation; independent multi-assessor comparison for Condition Class, Urgency Class and significance; targeted laboratory analysis; participatory elicitation of heritage values; and quantitative sustainability verification.

For practice, the findings support element-level rather than solely whole-building surveys when intervention planning is required, and suggest that drainage and moisture-control systems be treated as foundational measures whose failure affects multiple high-value elements. Authenticity should be considered in relation to the significance and function of each component: high-value fabric may require strict material compatibility, whereas low-significance functional elements may justify carefully documented contemporary solutions where these better protect the asset, provided their long-term compatibility is monitored. Overall, the study shows the potential value of moving from descriptive condition recording towards a transparent decision-support process in which vulnerability, urgency, significance, causal dependency and uncertainty are documented explicitly, and it establishes an agenda for broader validation and refinement.

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