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ORIGINAL ARTICLE

Najdi architecture in HBIM for sustainable conservation

Ahmad Baik[1]

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Abstract
The combination of cultural heritage elements with modern architectural practices leads to sustainable urban development while protecting social and cultural identities. The Najdi region in Saudi Arabia showcases its distinctive architectural elements including doorways Tarma Alfuraj and Shuraf which provide essential knowledge about sustainable design and cultural heritage protection. This research investigates the possibility of adding Traditional Najdi Architectural Elements to Heritage Building Information Modelling (HBIM) library which will create a standardized system for preserving these elements and their application in modern urban development projects. The Salmani Architectural Style receives special attention because it unites traditional Najdi design elements with contemporary architectural principles which prioritize sustainability alongside cultural preservation. This research uses laser scanning and photogrammetry and augmented reality tools to develop a dynamic system which documents and reinterprets these elements while maintaining their authentic value for the changing urban landscape of Saudi Arabia. This paper presents an extensive approach to digitize and catalog Najdi elements while resolving difficulties of implementing their complex designs and cultural elements into HBIM frameworks. The HBIM library functions as both a heritage conservation repository and an architectural and urban planning resource.

Keywords HBIM · Traditional najdi architecture · Laser scanning · Salmani style

1 Introduction

1.1 The background of Najdi architecture

The traditional built environment in Najd shows an inward orientation but particular architectural features developed to serve urban life throughout these settlements across many centuries. The current state of Najdi settlements provides valuable insights about how architecture relates to urban existence despite their current vacancy. Five Najdi settlements located in the Saudi Arabian region became the focus of extensive research in recent times for studies [1, 2]. Traditional settlements outside built spaces featured solid architectural elements that formed compact urban arrangements. The external environment featured only necessary gateways along with narrow windows which only appeared at higher elevations. The built environment's spatial order received its primary support from architectural elements which created a harmonious setting. These elements adjusted to local demands to establish the built environment's visual framework and its distinctive character. The hierarchical spatial arrangement in traditional settlements organized different elements according to their functions which created equilibrium between public and private areas. The study [1] documented unique elements that appeared in different sections of the built environment showing how people maintained spatial order through communal actions spanning centuries. The hierarchical organization allowed people to make daily decisions with flexibility which became a fundamental dynamic quality of spatial order [1]. According to Rapoport macro and micro level collective decision-making processes shape built environments while embedding shared socio-cultural values into their structures [3]. The explanation of cultural influences on physical form development requires understanding how social principles merge with physical objects to transmit meanings. Culture functions as both a main adaptive mechanism and controlling mechanism that guides human behavior and distinguishes

✉ Ahmad Baik
abaik@kau.edu.sa

[1] Geomatics Department, Architecture and Planning Faculty, King Abdulaziz University, Jeddah 21589, Saudi Arabia

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individuals according to Geertz and Damen [4]. The traditional urban and building forms of Najdi communities require understanding of their cultural background to grasp their development. A cultural analysis of a precultural environment requires the interpretation of meaning and use as essential elements [5]. Traditional built environments utilize symbols which contain powerful collective social and cultural meanings for non-verbal communication. Duncan and Moore examine how collectivistic social structures and gender roles affect the meaning of houses according to their research on social structures and house meanings [6].

1.2 The Salmani architectural style

The Salmani Architectural Style derived its name from King Salman bin Abdulaziz while uniting traditional elements with modern architectural features in Saudi buildings (see Fig. 1). The architectural style of Saudi Arabia draws its roots from the Najdi style but incorporates contemporary elements to represent the fast-paced urban development of the Kingdom. The King Salman Charter for Architecture and Urbanism established six fundamental principles which include sustainability, liability, continuity, human-centricity, authenticity and innovation [2]. The principles function as architectural guidance for designers who wish to create buildings which honor local traditions while fulfilling contemporary requirements. Salmani architecture combines traditional architectural elements with contemporary functionality to safeguard Saudi heritage aesthetics and symbolism and address modern environmental requirements and social needs and technological advancements. The architectural style functions as a development framework which outlines methods to merge heritage elements with innovative solutions throughout the Kingdom [7]. The implementation of traditional Najdi architectural elements within the Salmani style demands a deep comprehension of their cultural and symbolic significance. The method maintains Najdi architectural essence through reinterpretation to create a more vibrant cultural story for modern Saudi architecture. The HBIM library integration of these elements will help the Salmani style advance toward innovative design solutions that preserve historical elements for future development.

1.3 Importance of preserving cultural heritage in contemporary architectural practices

The preservation of cultural heritage in Saudi Arabian architectural practices today functions beyond nostalgic or historical respect because it establishes the foundation for sustainable development and cultural identity and national heritage preservation [8]. The preservation of cultural heritage through architectural designs represents a deep recognition of Saudi Arabia's ancestral traditions and societal values. Saudi Arabia possesses an abundant cultural heritage which contains remarkable architectural achievements and traditional craftsmanship that both document the nation's past and showcase its multicultural heritage. Architects who incorporate heritage elements into modern designs honor Saudi Arabia's history while creating feelings of national pride among its residents [9].

The preservation of cultural heritage through architectural practices drives sustainable development because traditional design approaches teach valuable lessons about climate adaptation and resource conservation and environmental harmony. Saudi Arabia protects its historical story through preservation efforts while developing a sustainable architectural approach that honors its cultural heritage to create a resilient built environment for upcoming generations [10].

1.4 Role of BIM in architectural design and heritage conservation

Building Information Modelling (BIM) functions as a fundamental link between technological innovation and

Fig. 1 Exemplars of the Salmani Architectural Style at the King Abdulaziz Foundation: (**a**) juxtaposition of traditional and contemporary materials, (**b**) architectural grandeur of the main hall, (**c**) intricate window design reflecting heritage motifs

cultural heritage maintenance within architectural practice throughout Saudi Arabia. BIM as an advanced digital system enables precise architectural design documentation and restoration of historical architectural components [11, 12]. BIM's three-dimensional modelling capability helps architects and conservationists document heritage structures accurately so they can make restoration decisions through precise detail documentation [11, 13–15].

The team-based approach of BIM facilitates architects to collaborate with engineers and historians and stakeholders for achieving comprehensive heritage conservation through various stakeholder perspectives. BIM-based digital documentation of traditional architectural components enables Saudi Arabia to protect its cultural heritage while developing modern designs that blend traditional elements with contemporary innovations [16].

Heritage Building Information Modelling (HBIM) has developed through recent technological advances to expand its heritage preservation applications. HBIM digital twin functionality enhances preservation efforts by creating sustainable management systems for cultural assets [17]. The integration of laser scanning with finite element analysis (FEA) in HBIM systems according to research in [11, 14, 17] provides essential data for evaluating building structural integrity and planning preservation activities. Conservationists initiate the process by using 3D laser scanning to generate point clouds that develop into detailed digital models which simulate building reactions during environmental stress such as seismic activity. The method enables restoration teams to make data-driven interventions that protect heritage structures from damage [14]. The implementation of HBIM technology in Saudi Arabia protects the historic Najdi buildings while preserving their structural integrity and cultural significance.

Extended reality technologies including augmented reality (AR) and virtual reality (VR) have been integrated into HBIM to enhance accessibility and user interaction with cultural heritage [18–20]. The deployment of XR platforms together with HBIM according to [18–21] produces virtual heritage site interactions that attract users. Users obtain educational value through this approach which benefits both stakeholders and architects and general public members who participate in virtual site tours [19]. XR technology implementation at Najdi heritage sites will create opportunities for digital heritage management as well as educational initiatives and tourist growth.

The implementation of HBIM now includes processes that rely on artificial intelligence. The analysis of historical building decay patterns through large 3D scan datasets becomes automated using AI and machine learning techniques that process this information for identification purposes. The combination of automated inspections with high precision maintains conservation quality while shortening the duration of manual inspections [22, 23]. The application of AI-driven methods in Saudi Arabian heritage conservation will enhance efficiency when managing large-scale heritage projects at Diriyah, AlUla and Historic Jeddah [24].

Research now emphasizes that HBIM needs complete data exchange functionality to manage complex historical sites which need stakeholder cooperation. The authors of Oreni et al. (2013) show how problems occur when combining HBIM systems with FEA tools since heritage conservation requires continuous model exchange for structural assessments [25]. According to Dore and Murphy (2017) HBIM models need interoperable systems to link with additional analytical tools for complete documentation and analysis [26]. Saudi Arabian architects can achieve unified work with engineering professionals and heritage specialists through the resolution of interoperability problems [13].

A breakthrough heritage management system emerges through the development of HBIM models which combine multiple functions for conservation efforts and educational programs alongside urban development projects. The Balbanera Church HBIM model demonstrated dual functionality by performing structural analysis alongside providing digital documentation for future researchers and conservationists as described by López et al. (2018) [27]. HBIM functions as an adaptable heritage management system because of these practical applications.

A sustainable and comprehensive approach to heritage conservation would be achieved through the HBIM framework dedicated to traditional Najdi architectural elements in Saudi Arabia. The digital cataloguing process will enable Saudi Arabia to defend its cultural heritage while guiding modern architectural development. Fadli and AlSaeed (2019) emphasize the need to integrate cultural heritage into modern design practices for protecting regional identity as urbanization speeds up [28].

1.5 The research contribution

The research provides substantial value to architectural conservation and digital documentation through its innovative method of adding Traditional Najdi Architectural Elements to Heritage Building Information Modelling (HBIM) libraries. The research tackles the critical need to protect cultural heritage while creating new opportunities for sustainable architectural development. The HBIM framework enables systematic documentation of these elements which allows their easy integration into modern designs especially when working with Salmani architectural style designs.

Traditional Najdi elements demonstrate their ability to adapt to contemporary architecture through this method which shows their potential for reinterpretation and

preservation that meets modern design requirements. The study demonstrates that Traditional Najdi Architectural Elements possess deep socio-cultural importance because they represent both physical structures and symbolic expressions of local heritage and identity. The research investigates the historical development and visual characteristics, and environmental functions of Traditional Najdi built elements to demonstrate their essential role in protecting regional cultural heritage.

These architectural elements play an essential role in developing the Salmani style's distinctive architectural identity because they unite traditional Najdi design elements with contemporary design principles. This research demonstrates how HBIM and 3D laser scanning technologies can protect cultural heritage while creating sustainable architectural practices throughout Saudi Arabia and additional regions. The digital BIM library that integrates Traditional Najdi Architectural Elements into the Salmani architectural style protects cultural heritage while maintaining their ongoing relevance in modern architectural developments.

1.6 Scope and justification

The selection of doorways and Tarma (wooden ceiling panels) and Alfuraj (window grills) and Shuraf (cornice moldings) for the initial HBIM library is based on their architectural importance and practicality. In Najdi vernacular construction, these four elements collectively embody the formal, structural, and ornamental vocabulary of the Salmani style:

- The doorways function as the main connection between interior and exterior areas and their carved frames and proportions demonstrate both climatic adaptation (ventilation, shade) and social symbolism (status, hospitality).
- The Tarma panels are among the most richly decorated elements, showcasing the region's timber-craft traditions and lending themselves to parametric modelling due to their repetitive geometric patterns.
- The Alfuraj grills function as light and privacy mediators through their intricate mashrabiya inspired perforations that represent both cultural significance and structural consistency.
- The Shuraf cornices serve as visual markers that indicate the transition from solid mass to sky and their profiles contain both local proportion rules and water-shedding strategies.

The study focuses on these four elements to achieve a workable scope for detailed documentation which strikes a balance between representation and detail level and parametric complexity to establish a base for future expansion of other Najdi architectural components.

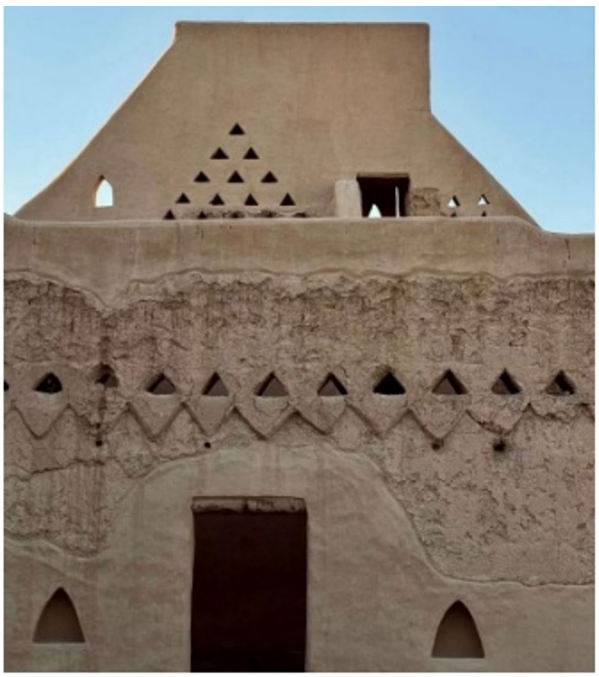

Fig. 2 Architectural documentation of Alfuraj elements in Diriyah's historic sites, showcasing their functional and aesthetic roles in traditional Najdi settlements

2 Background and literature review

The research examines architectural elements because they exist as continuous components which build urban areas and buildings and shape the constructed environment. The research investigated four architectural features Doorway, Tarma, Alfuraj, and Shuraf through case studies of traditional Najdi settlements including Ad-Diriya, Sudus, Alkhabra, Ushaiqer, and old Riyadh.

The research investigated how cultural practices together with environmental issues and construction methods and religious beliefs and additional factors influenced both architectural elements and their use in urban and building development. The two pictures show traditional buildings with Alfuraj examples from Diriyah (Fig. 2) and the Traditional Najdi Architectural Elements known as Shuraf (Fig. 3). An evaluation of each architectural component explored their cultural significance and environmental suitability along with their original functional intent. The evaluation of these architectural elements within Najdi social traditions revealed that social principles together with spatial dynamics significantly shaped the built environment by linking space and place elements that defined its character and embedded meanings. The evaluation examined whether the meaning and usage of an element transforms when observed

Fig. 3 Shuraf elements adorning a heritage building in Najd, illustrating their dual role in structural reinforcement and cultural symbolism

from a user's perspective who interacts with either the urban environment or the building itself. The built environment follows inherent principles which cause architectural elements to respond to their context thereby shaping the characteristics of constructed spaces. The elements which derive their meaning from religious beliefs along with social-cultural aspects tend to remain consistent throughout time. The inhabitants can modify mostly technical and environmental elements which adapt to social meanings to become integral parts of the built environment during its evolution.

2.1 Heritage building information modelling (HBIM)

Heritage Building Information Modelling (HBIM) represents a specific BIM application which focuses exclusively on historic and heritage structures. The preservation and documentation and management of historical buildings' unique characteristics use multiple digital technologies and methodologies [13].

The heritage BIM system extends traditional BIM functionality by supporting heritage conservation needs through material documentation and construction technique recording and historical significance preservation. Advanced scanning methods including LiDAR and photogrammetry and laser scanning enable the precise acquisition of detailed information about structures [12]. The collected data gets converted into intelligent 3D models which create complete digital duplicates of heritage sites. Through Heritage BIM stakeholders can make educated preservation decisions about restoration and maintenance strategies because the system allows them to analyze and visualize historical structure evolution while maintaining authenticity and cultural value for future generations [16].

2.2 Advantages of heritage BIM for heritage conservation and restoration

Heritage Building Information Modelling (HBIM) provides multiple advantages for heritage conservation and restoration activities. The main advantage of HBIM consists in its power to generate detailed digital models of historical buildings which preserve complex elements that would otherwise disappear through aging or deterioration. The detailed digital documentation provides valuable information to conservationists and architects and preservationists who use it to analyze structural conditions and detect deterioration areas and develop exact restoration plans.

Through simulation HBIM allows users to predict restoration outcomes which helps them choose strategies that preserve both authenticity and integrity of heritage sites. The implementation of HBIM enables different experts to work together through information sharing and workflow optimization which results in better preservation of cultural heritage. The digital archives created through HBIM enable increased accessibility and educational opportunities because they support research activities and educational programs and virtual tours which promote public engagement with heritage sites [29].

2.3 Challenges and opportunities in integrating traditional elements into BIM libraries

The research method of the study was descriptive and included four phases. The research began by gathering available documents including maps and visual aids that presented information about different aspects and spatial arrangements of elements such as site plans, road layouts

and public and private building layouts within traditional settlements. During the following stage historical data became organized into primary and secondary sources to achieve a proper understanding. The third stage involved verifying the data through focus group interviews as well as individual interviews document sorting and review of literature on traditional Najdi architectural elements. The fourth stage involved direct observation of the operational relationships between urban and architectural elements. Graphical resources together with historical settlement documents and archival materials served to understand the spatial and physical features of each settlement better. The research focused on determining element positions and their functional significance according to usage and meaning contexts. The integration of Traditional Najdi Architectural elements into heritage conservation practices for Building Information Modelling (BIM) operations faces numerous challenges. The main challenge lies in appropriate digital modeling of these elements because they possess detailed characteristics alongside significant cultural value and historical elements which BIM standard procedures struggle to incorporate. Traditional architectural elements present challenges during modeling because they are handmade with distinctive anomalies which make them harder to model than standard architectural components [30–32].

The development of HBIM technology enables better heritage element digitization but the modeling of intricate ornamental details along with BIM platform interoperability remains challenging [33]. Research demonstrates that heritage element integration into BIM libraries becomes difficult because software constraints prevent it and there are no pre-defined parametric families for non-standardized architectural components. These architectural components fail to integrate seamlessly with modern buildings because they would compromise both historical integrity and structural and environmental sustainability characteristics [25].

The authors of [16, 25, 29, 32, 34] have identified multiple drawbacks in their current research because they do not explain effectively how traditional architectural components can be adapted into parametric BIM objects. The HBIM methodologies excel at documenting historical sites but they do not resolve the problem of integrating these models into current urban planning and construction processes. The problem requires developing an HBIM library dedicated to Traditional Najdi elements which would contain parametric models together with metadata about historical significance and material composition and construction techniques.

HBIM provides multiple beneficial aspects that help protect and restore cultural heritage sites. The primary advantage of HBIM lies in its ability to produce highly precise digital models of historical structures that preserve both current and future deteriorated elements. Digital documentation at this level serves conservationists and architects and preservationists as a valuable resource to analyze structure conditions and identify deteriorated areas and create precise restoration plans [16]. HBIM enables restoration strategy simulations which help professionals make decisions before actual implementation to preserve the authenticity and integrity of heritage sites [22]. The system supports multidisciplinary professional coordination because it enables information sharing and workflow organization and cultural heritage conservation teamwork. The system promotes public engagement and educational opportunities through digital archive creation which serves research and educational purposes and virtual tours thus enhancing public heritage interaction [35].

The research develops an HBIM framework for Traditional Najdi architecture which focuses on interoperability alongside cultural authenticity while providing real-world application solutions. This library will document heritage elements through high-fidelity digital models along with contextual data and historical references to facilitate their use in contemporary projects. The system will enable architects' researchers and conservationists to include traditional Najdi elements in current designs while maintaining cultural element integrity.

The challenge of representing historical architecture accurately through HBIM libraries exists in both the opportunity to integrate traditional elements and the difficulties of precise representation. The process of identifying traditional details through digital modelling software remains challenging because carved moldings handmade materials and special architectural elements do not integrate seamlessly. The process of maintaining digital accuracy for these elements through scanning methods or manual modelling techniques proves to be very challenging [22]. The obstacles present opportunities to enhance the content of HBIM libraries. The development of new digital methodologies alongside tools for traditional element representation enables heritage digital repositories to expand their scope and precision [31]. Through traditional element integration into HBIM libraries users can study cultural heritage documentation in greater detail which leads to better understanding of historical craftsmanship and architectural techniques. The collaboration of historians with preservationists and technology experts results in developing extensive digital libraries that show traditional architectural elements in detail which promotes better heritage conservation and restoration practices [22, 25].

2.4 Doorway

A doorway known as Al-Bab serves as the principal entryway to residential and building spaces throughout traditional

Najdi settlements. This architectural element functions as a vital access point which reveals important aspects of residents' social interactions and economic circumstances through non-verbal means. Different doorways with their wide range of styles and shapes and decorative elements help reveal the economic position and lifestyle of the building's owner to the community members [36]. The owner's social position together with their priorities becomes visible through elaborate craftsmanship and intricate woodwork and floral motifs and geometrical designs and religious inscriptions. The decorative elements serve as indicators of financial prosperity together with elevated living standards (see Fig. 4). Simple doors that lack decorations could indicate a lower economic status but some religious individuals choose plain doors because of their faith beliefs [6]. Traditional settlements display door placement in two ways based on the intended use and target audience between male visitors and family members. Door elements receive specific social meanings from local craftsmen which members of the community understand. The doorway serves to define both the house structure and functions as an important visual landmark which helps residents and visitors navigate the settlement to find the house. The uniqueness of doorways leads residents to describe their visual features so visitors can identify houses in the settlement. The two types of doorways show distinct characteristics because guest doors display wider dimensions with decorative elements and colorful finishes, yet family doors remain smaller with minimal decoration. The prominent location of guest doors along public or semi-public streets helps guests find their way and displays the social position of the owner. The system functions as part of traditional Najdi settlements' core concepts which regulate social contact between residents. The doorway functions as an entryway to provide both physical access and non-verbal communication opportunities between residents and their visitors and the public. Door ornamentation varies to convey distinct meanings within the community where it represents social rankings of residents. People with higher financial means typically decorate their main guest door extensively but maintain their family door with minimal embellishments to show both their social position and their relationships with visitors. The local community used basic architectural components to create a visual language which represented social dimensions while preserving essential spatial organization in the traditional Najdi built environment.

2.5 Tarma

The exterior wall structure known as Tarma exists as mud or wood constructions that usually appear near house doors to let women observe outside visitors through small openings at the base [36]. The Arabic word Tarma refers to "the person who cannot speak" which directly relates to this architectural element because it functions to observe visitors at the door from an unseen position outside. The traditional Tarma exists in four different forms which include half-circle, square, triangle and rectangle shapes (see Fig. 5). Different building positions and private space arrangements within settlements determine the varied forms of this element despite maintaining its fundamental operational purpose. The built environment-maintained unity through different visual representations which local preferences shaped for personalized structures. The Tarma element appears predominantly in two-storey buildings because it provides better street and doorway observation capabilities from elevated positions which single-floor structures do not typically have [6].

The Tarma element increases privacy in built structures through street monitoring from inside spaces while restricting outside views. The element's diverse forms could stem from space hierarchy because street dimensions and placement determine its development [37]. Street width determines how far the Tarma extends from the wall because it may block daylight while creating conflicts on tight streets. The spatial limitations have driven adaptations in the element's forms which maintain its core functionality.

The Tarma functions as a visual indicator to locate building doorways when viewed from a distance [37]. The presence of Tarma marks the exterior wall section near doorways to help people navigate urban areas and distinguish between adjacent entrances through its unique designs. The Tarma design serves two functional purposes that support urban areas as well as indoor spaces without compromising its traditional Najdi architectural role.

2.6 Alfuraj

The architectural feature known as Alfuraj (plural: Furjat) consists of a small window or aperture which takes the form of a triangle or rectangle located on exterior building walls within traditional Najdi settlements (see Figs. 6 and 7). The name "Furjah" comes from Arabic which means "an opening" because of its functional and meaningful purpose. The Alfuraj serves two essential functions by allowing light and air to enter buildings (Fig. 8). The observation towers connected to settlement walls use this feature for defensive purposes. The strategic placement of these openings in wall upper sections near the roof Line protects interior spaces from outside visibility especially when looking from neighboring walls. Traditional rooms including guest spaces and kitchens and washrooms contain two rows of Furjat which measure between 20 and 35 cm in height according to Mohammed Othman. The two rows of openings near the

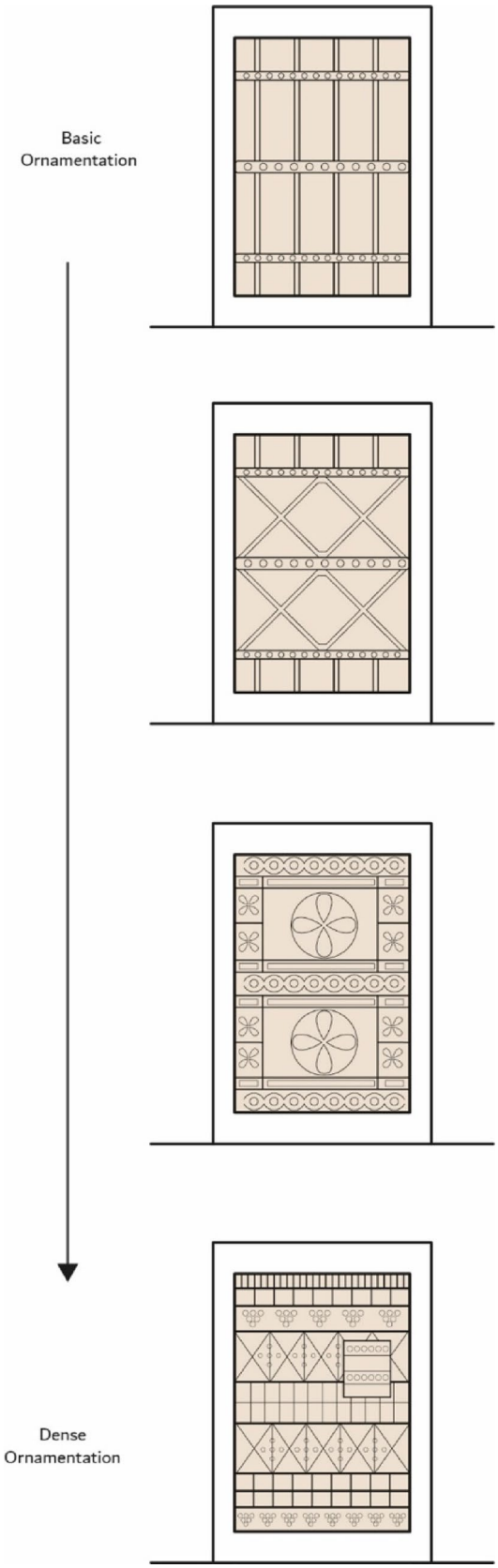

Fig. 4 Typological classification of Najdi doorways (Al-Bab), highlighting socio-economic symbolism through design variations. (adapted from Alnaim, 2021).

ceiling and floor level work together to allow air to enter the space. The small dimensions of Alfuraj enable residents to seal them with mud or stone during winter months without affecting the building structure [36]. The local residents created multiple wall arrangements of Alfuraj which demonstrated both functional and aesthetic purposes while meeting their particular spatial requirements (see Fig. 9).

The main purpose of Alfuraj was to enable airflow and lighting access for rooms that did not have direct exposure to the central courtyard. The compact nature of traditional Najdi settlements together with privacy expectations led to external opening restrictions especially in deep areas that needed street-facing openings to have neighbourly agreement. Alfuraj developed into an indoor and outdoor element which addressed particular requirements without violating neighbourly privacy [1, 6].

The physical manifestation of Furjat in Najdi settlements appears in two forms which direct themselves either towards the interior for functional needs or towards the exterior for aesthetic purposes (see Fig. 10). The way buildings are situated, and their dimensions determine these physical expressions. The limited exterior wall usage in deep areas leads to indoor Alfuraj installations which provide daylight and air circulation to inner spaces without compromising privacy. The placement of Alfuraj on exterior walls occurs above eye level when streets are wide. The density of Alfuraj on exterior walls depends on street width and open spaces which enables a method to decrease solid wall intensity in dense areas just like doorways do in broad streets. The inhabitants used these concepts to control elements according to particular spatial arrangements. Alfuraj serves a dual purpose by improving ventilation and lighting in traditional buildings, yet it appears differently in public and private spaces which results in personalized façade designs. The element functions across all social classes and spatial areas to maintain operational functionality while adding exterior wall visual appeal through various placement methods and density levels. The patterns of Furjat openings which depend on building size and settlement location help identify the social standing and importance of the property owner. The Najdi people demonstrate their preference for element optimization by adjusting them to fulfill various social-cultural requirements while maintaining environmental and technical requirements [6].

2.7 Shuraf

The architectural feature known as Shuraf (plural: Shurfat) receives its name from Arabic “Sharaf” or “Ashraf” which means “to observe” or “to look.” At building termini and along their edges Shurfat serves as an architectural component which functions both inside and outside.

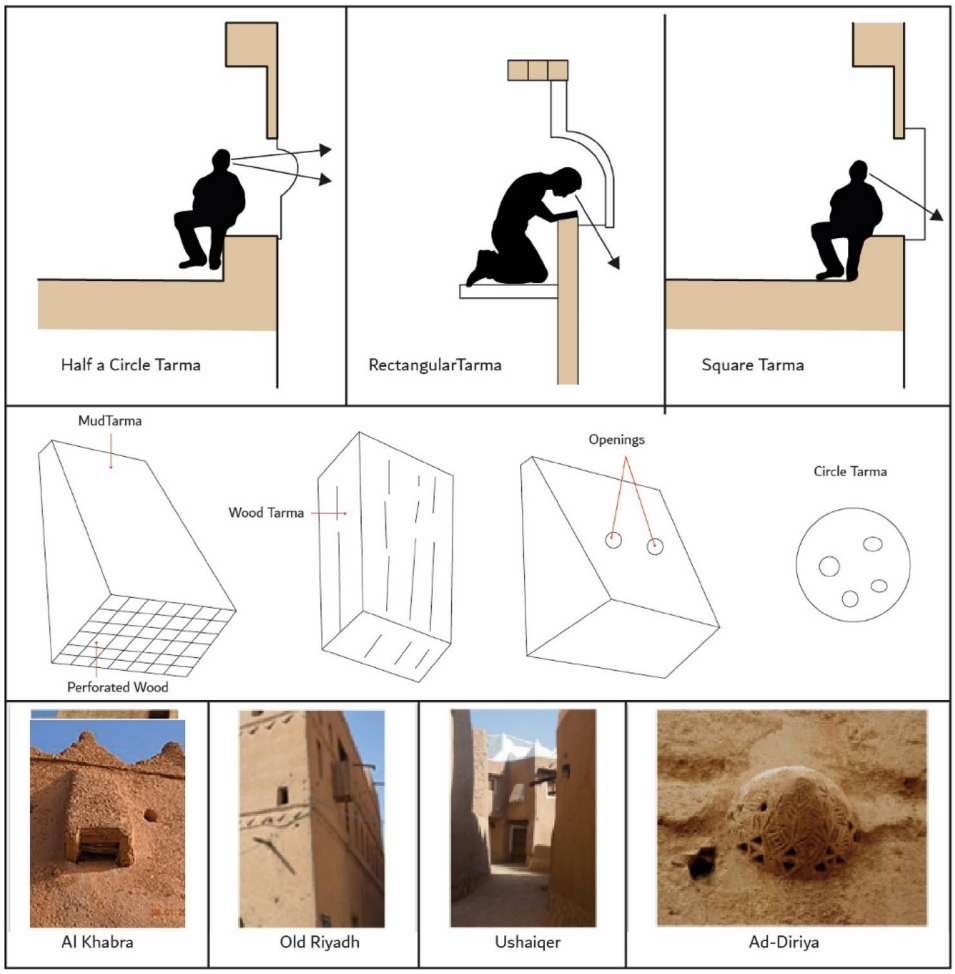

Fig. 5 Morphological diversity of Tarma elements in Najdi architecture, demonstrating their adaptive forms for privacy and spatial observation.
(adapted from Alnaim, 2021).

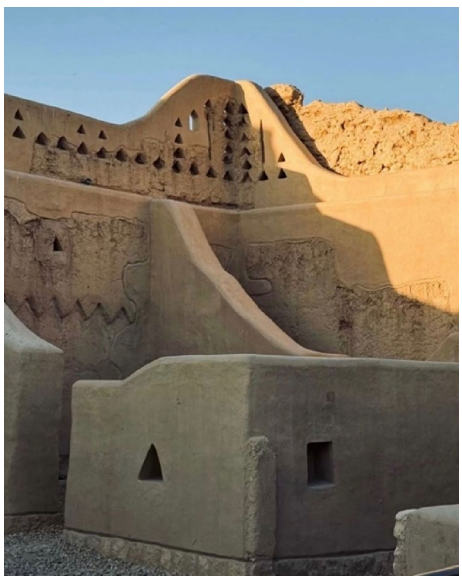

Fig. 6 Alfuraj configurations in Diriyah's traditional structures, emphasizing their role in environmental modulation and spatial identity

Fig. 7 Strategic placement of Alfuraj in Diriyah's transitional spaces, balancing light penetration and privacy

The decorative Shurfat structures combine mud bricks with local gypsum plaster called "Nora" which receives white

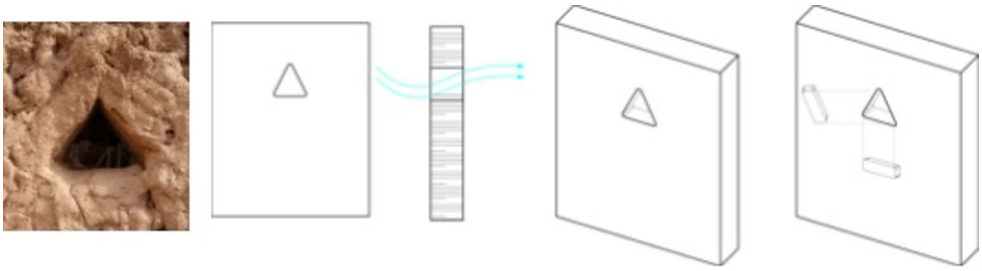

Fig. 8 How Alfuraj use and how it built

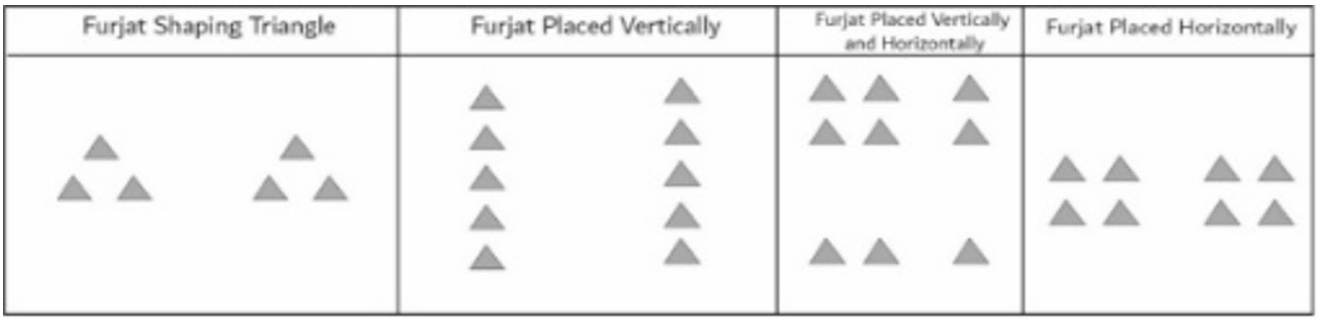

Fig. 9 Taxonomy of Alfuraj designs in Najdi architecture, categorizing geometric patterns and functional alignments. (adapted from Alnaim, 2021).

Fig. 10 Façade-integrated Alfuraj designs, illustrating their dual function as environmental regulators and ornamental features. (adapted from Alnaim, 2021).

Location	Furjat Pattern Example	Furjat Image Example
Small/ Medium Building		
Large Building		
Palace		

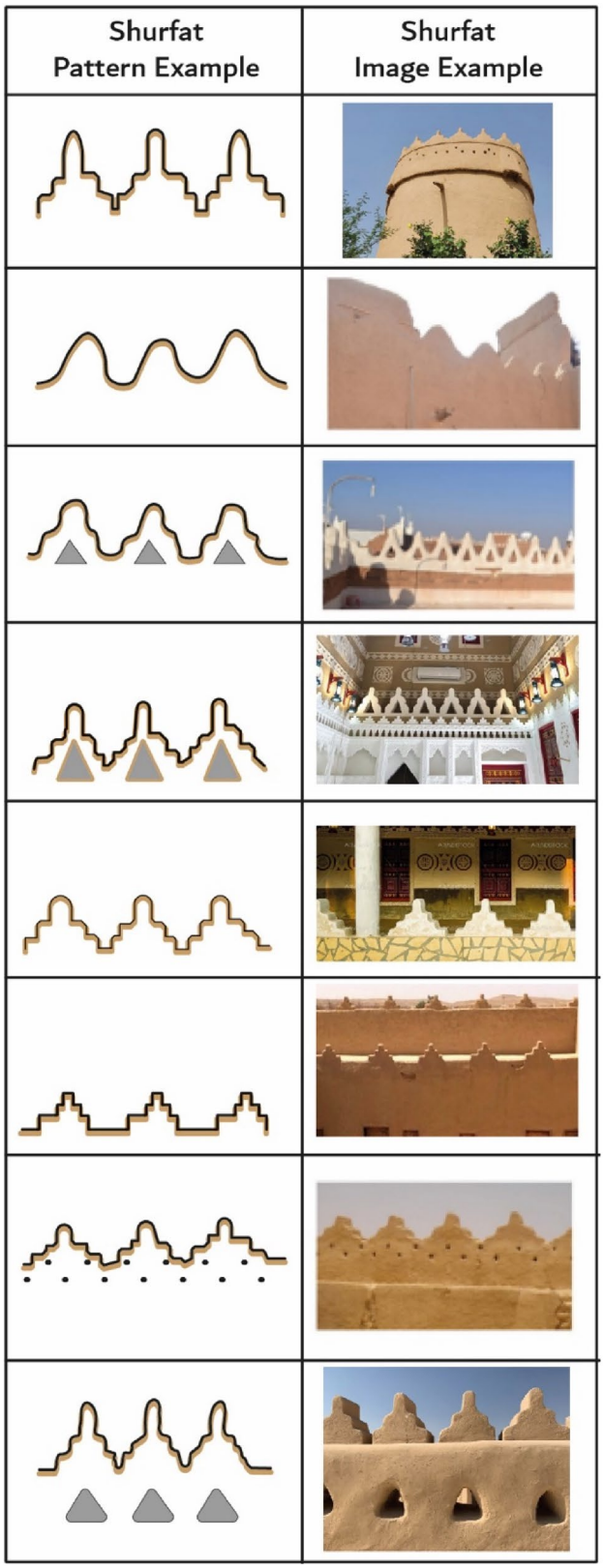

Fig. 11 Parametric variations of Shuraf elements, reflecting regional craftsmanship and their symbolic connection to celestial motifs

painting to protect mud parapet walls from rain. Shurfat presents itself through different physical designs which include curved lines and plant leaf forms as well as arrows and straight lines and angled structures and pyramid shapes and always directs its head towards the sky hence the local term "A'arayis Alsama" (brides of heaven). Various designs of the Shurfat component are shown in Fig. 11.The height extension through Shurfat provides privacy for roof spaces which people use for nighttime rest during summer months. The building roof's termination benefits from its design which unites solid and void elements while creating a distinctive skyline for the settlement. The decorative Shurfat element appears both inside and outside buildings with particular prominence in the majlis (guest) space [36, 38, 39].

Shurfat functions as an architectural wall extension that blocks courtyard views from neighbors while enabling rooftop family interactions between residents. Through its placement between adjacent houses Shurfat helps families maintain close relationships by providing women with an alternative to walking through public streets for socializing. Shurfat installations extend their reach beyond building edges and parapets because they are also found in settlement walls and fortified towers. The visual appearance of Shurfat resembles one another yet they convey different meanings because settlement walls use them for security observation while buildings use them to promote neighborly interaction and enhance visual appeal [6]. The study revealed an essential finding regarding how Shurfat density changes according to both location and functional requirements. The settlement walls contain larger dense Shurfat forms which focus on protection and defense but building Shurfat numbers depend on owner social standing and building site location. Shurfat around rooftop parapets and courtyards appear more frequently in wealthier households and these structures vary in their placement between walls and corners. Both internal and external Shurfat placements share identical characteristics because internal elements appear decorative and spaced out while external elements present themselves as robust and solid.

The physical manifestation of Shurfat depends on building location which produces unique patterns according to site position. The deep connection between residents and their environment led to the creation of building elements which matched their cultural traditions. The controlled interaction and integration of architectural components along with place-making practices sustained the Najdi architectural identity throughout centuries. The generative process maintained the built form's unified appearance alongside its lasting features. The Shurfat element showed adaptability in dense private areas while buildings near open spaces and wide streets-maintained flexibility in their use. Through this integration process the built environment maintained its

structural unity and preserved its fundamental characteristics throughout time.

3 Development of a traditional Najdi architectural HBIM library (methodology)

A Traditional Najdi Architectural Heritage Building Information Modelling (HBIM) Library requires a methodical application of digital technology alongside cultural knowledge for properly documenting traditional Najdi architecture elements that can be added to current BIM systems. The research methodology follows four major stages: Fieldwork and Data Acquisition, Data Processing and Annotation, Integration and Utilization and Continuous Improvement and Expansion. The initial step of data collection involves obtaining high-resolution TLS data through scanning work plans and RAW scans.

The data needs proper alignment and noise filtering to reach both high precision and uniformity levels. The data co-registration and integration stage merges historical data while properly retaining cultural information with geometric measurements. The "Scan to HBIM Processing" phase requires the simplification of Najdi objects and specifies the level of detail needed for accurate representation. The enhanced HBIM models serve to enhance documentation and preservation of Najdi traditional projects. Figure 12 shows the Implementation Method of HBIM to Enhance Najdi Traditional Projects.

The process starts with TLS data acquisition before data alignment and noise filtering procedures take place. The co-registration and data integration phases merge historical information while maintaining cultural context preservation. During the "Scan to HBIM Processing" phase researchers concentrate on both the simplification of complex shapes and the determination of suitable detail levels for correct representation. The collected models receive standard organization in the Traditional Najdi Architectural HBIM Library to function as an effective storage system for Najdi architectural heritage that can be used in modern practice. High-resolution data acquisition through Terrestrial Laser Scanning (TLS) and photogrammetry and historical

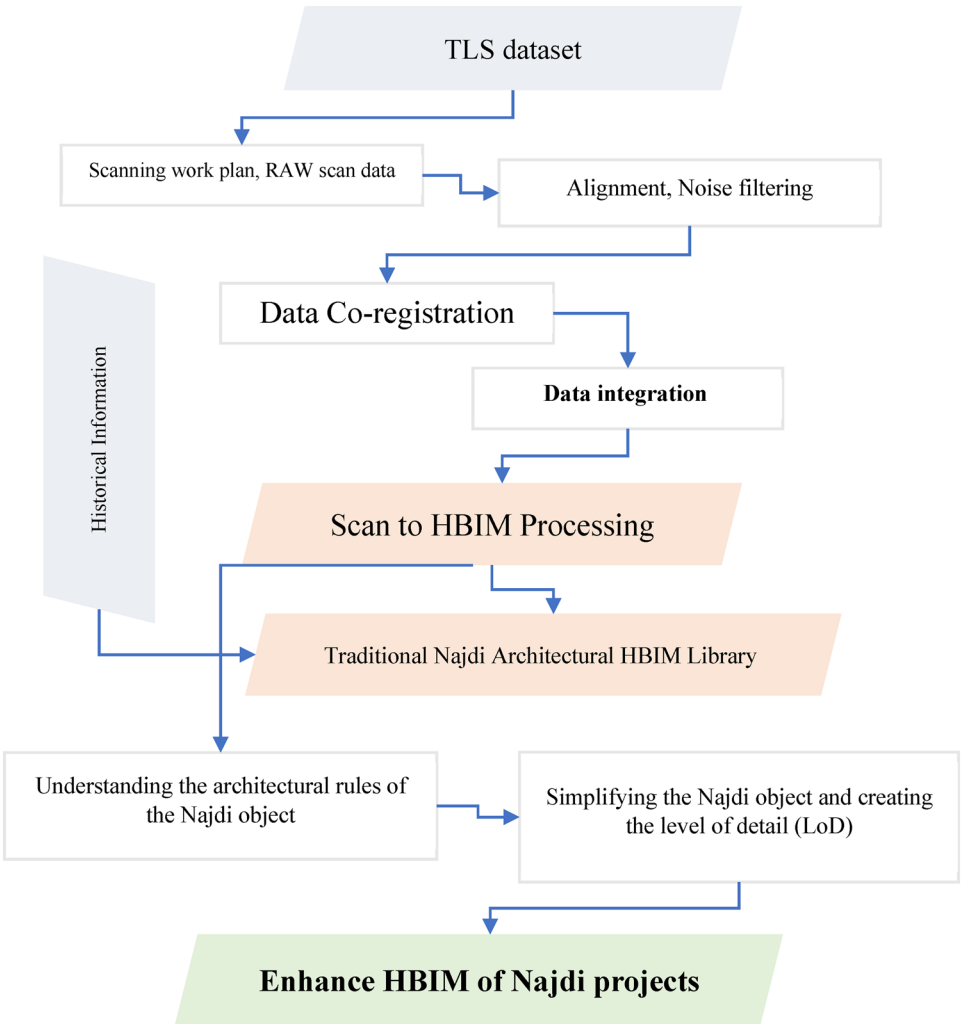

Fig. 12 Methodological framework for HBIM implementation in Najdi heritage projects, integrating TLS data acquisition, cultural annotation, and digital modelling

record evaluation along with expert advice forms the foundation of the initial phase (Fieldwork and Data Acquisition) [40, 41]. The integration of historical documents with archival photographs and oral histories enhances the dataset by adding cultural and contextual details and expert consultations validate both the accuracy and relevance of collected data. The second phase of data processing focuses on making raw data accurate by registering and annotating it to generate 3D models with enhanced metadata. The data achieves higher precision through the implementation of Iterative Closest Point (ICP) and machine learning-based noise reduction algorithms [42]. The integration of cultural and contextual elements into the 3D models happens during this phase through metadata annotations which document material usage and construction approaches and historical value [43]. The "Scan to HBIM Processing" phase includes two main steps: the reduction of complicated forms into simpler structures and the determination of suitable detail levels to maintain both model accuracy and computational performance [44]. During the third phase of integration and utilization validated 3D models receive organized structure through an HBIM library which groups architectural components into doors, windows, decorative motifs and structural components. IFC standard formats are implemented to make data compatible with current BIM platforms which allows architects and engineers and cultural heritage specialists to access the data easily [31, 45, 46]. The library enables multiple uses such as restoration projects, virtual reconstructions and educational initiatives which contribute to cultural continuity and sustainable development [47].

Fig. 13 High-fidelity 3D laser scanning of traditional Najdi architectural components, capturing geometric and material fidelity for HBIM integration

The HBIM library receives continuous improvement and expansion through the fourth phase that includes new element additions and emerging technologies like AI-driven pattern recognition and augmented reality. User feedback from architects and cultural heritage experts is processed systematically to enhance library quality and fix existing gaps or limitations in the system [42]. The platform operates dynamically to become a powerful tool for preserving and promoting Najdi architectural heritage and supporting urban planning and tourism applications as well as digital humanities research [48]. Through this methodology digital technologies are combined with cultural expertise to produce an adaptable comprehensive resource that supports both cultural continuity and sustainable development.

3.1 The comprehensive process is structured into the following phases

The Traditional Najdi Architectural HBIM Library development methodology combines modern technology with cultural competencies through a structured process. The four main stages make up the complete workflow:

Phase 1: Fieldwork and Data Acquisition

The process starts with precise geometric data acquisition of traditional Najdi architectural elements through advanced laser scanning equipment which produces accurate 3D representations (see Figs. 13 and 14). The data acquisition process includes photogrammetry methods which generate detailed photographs of architectural features. The collected data receives additional validation through the extraction of information from architectural plans together with photographs and written descriptions. The documentation process requires essential collaboration between local communities and historians and architects to obtain oral histories and contextual information which ensures effective cultural and traditional knowledge integration.

Phase 2: Data Processing and Annotation

The data processing and annotation phase combines laser scanning geometric and visual data with historical and contextual information to create complete datasets for each architectural element (see Figs. 15, 16 and 17). The BIM framework contains systematically organized data which includes elements sorted by type and function and historical period and detailed metadata about material properties and construction techniques and cultural significance. The development of precise 3D models for each element follows this step by exactly duplicating complex designs and materials and construction approaches while accounting for regional differences and cultural elements.

Phase 3: Integration and Utilization

The integration and utilization phase requires the organization of validated elements into a well-structured

Fig. 14 Onsite 3D laser scanning workflow: (**a**) initial scan setup with spherical targets for registration, (**b**) pre-registration using Cyclone Field 360 software

searchable BIM library which creates a complete Traditional Najdi architectural components repository (see Figs. 18 and 19, and Fig. 20). The library exists to provide simple access to researchers and architects and conservationists who need it for heritage conservation and restoration projects (see Fig. 21). The BIM library exists to support educational and research applications while promoting its use in academic and professional settings to study and preserve Najdi architectural heritage.

Phase 4: Continuous Improvement and Expansion

The continuous improvement and expansion phase establishes data collection protocols for ongoing updates which enable newly discovered or reconstructed elements

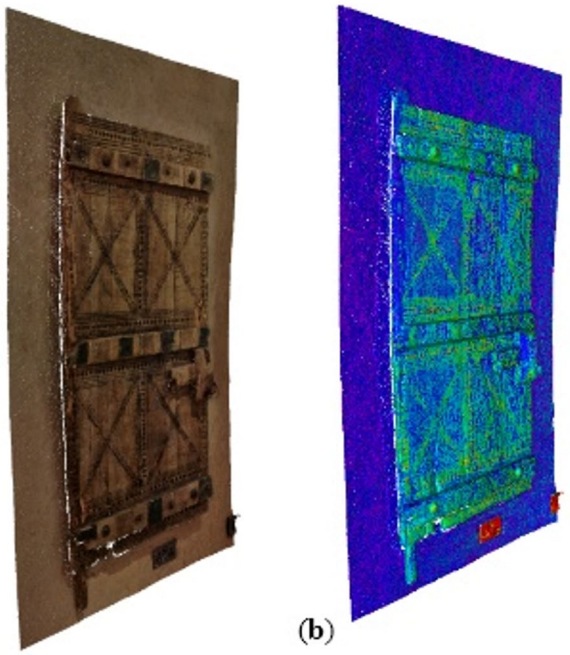

Fig. 17 3D laser scanning of Najdi doorways: (**a**) RGB-captured intricate carvings, (**b**) intensity data revealing construction techniques

to integrate directly into the BIM library. The phase focuses on integrating new technologies like augmented reality (AR) and virtual reality (VR) to improve visualization and interaction with digitized elements (see Figs. 22 and 23). A feedback system allows BIM library users to propose enhancements and identify errors which drives library

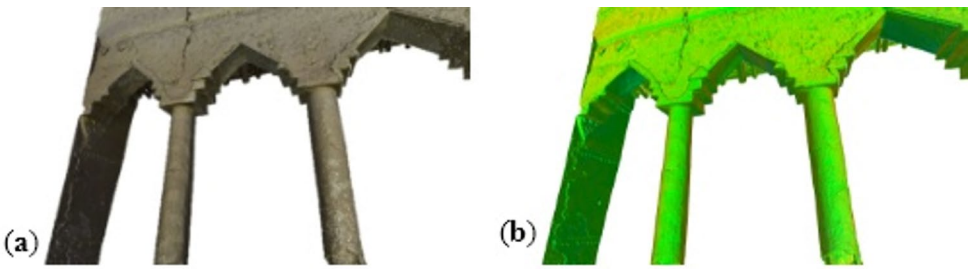

Fig. 15 3D laser scanning outputs of traditional Najdi arches: (**a**) RGB-rendered point cloud, (**b**) intensity-based visualization highlighting structural details

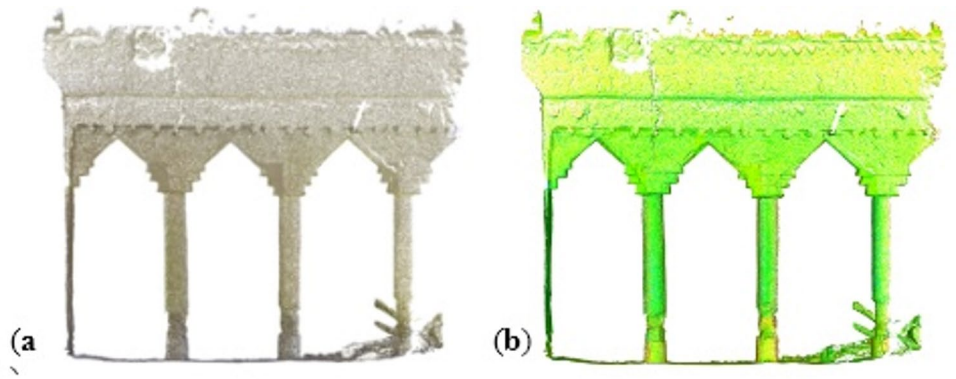

Fig. 16 Digital documentation of Najdi arches via 3D laser scanning: (**a**) photorealistic RGB representation, (**b**) intensity mapping for material analysis

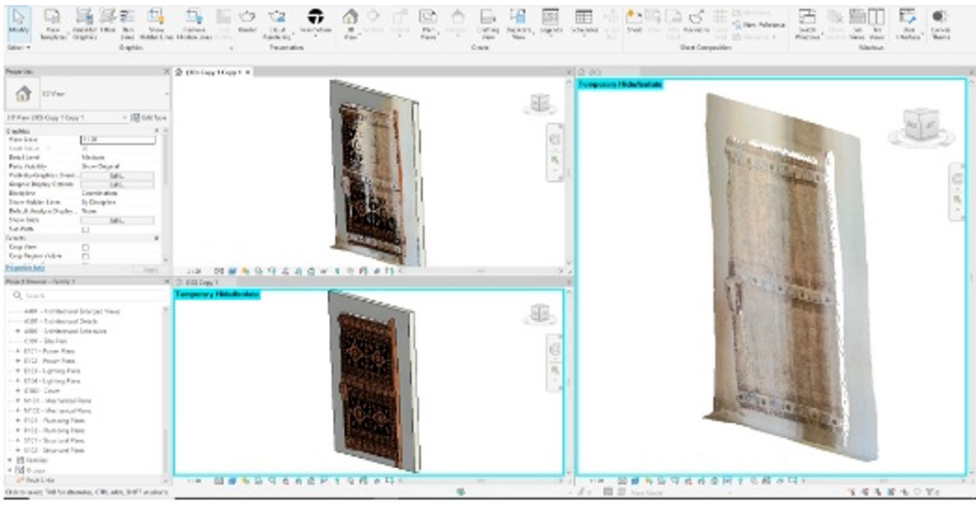

Fig. 18 HBIM Library development for Najdi doorways in Autodesk Revit 2024, showcasing parametric modelling of heritage elements

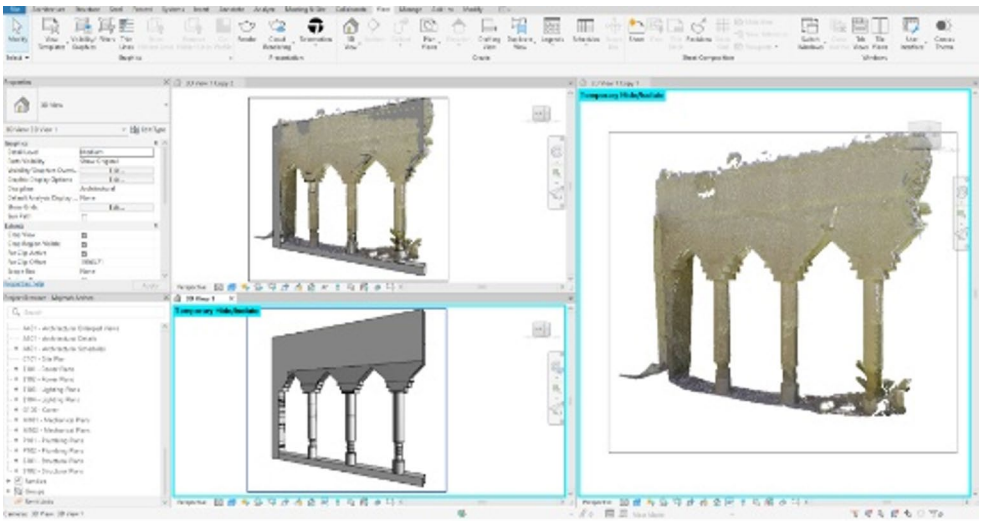

Fig. 19 Parametric modelling of Najdi arches in Autodesk Revit 2024, integrating geometric accuracy with cultural metadata

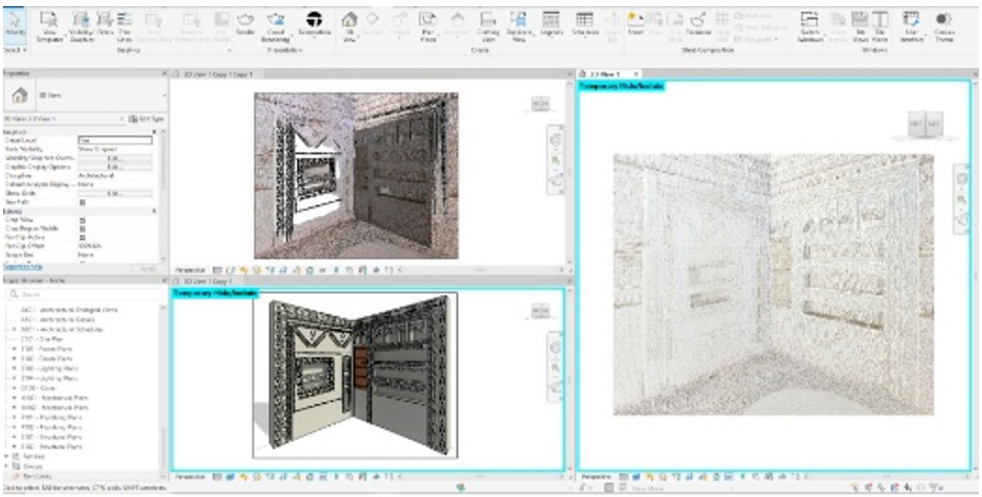

Fig. 20 HBIM Library creation for Najdi niches in Autodesk Revit 2024, emphasizing detail-oriented digital preservation

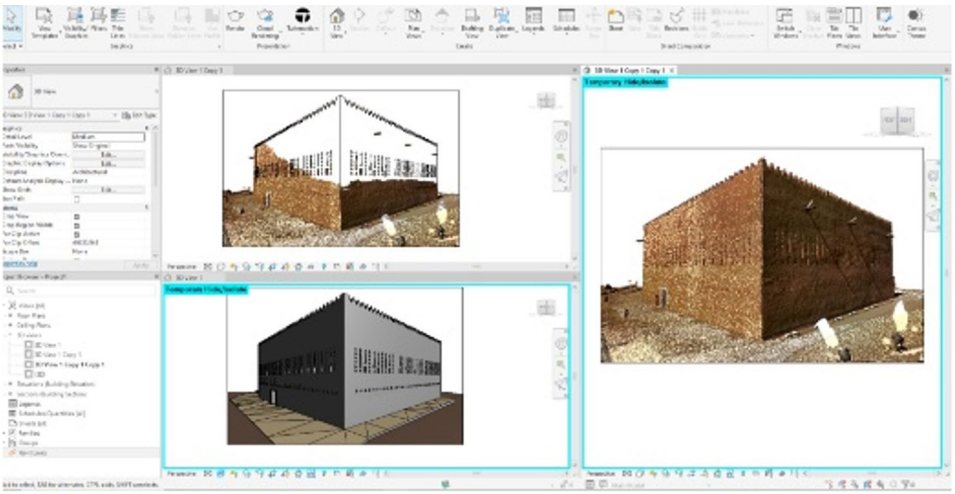

Fig. 21 HBIM model integration of Najdi architectural objects in Autodesk Revit 2024, demonstrating interoperability for heritage conservation

Fig. 22 Augmented reality visualization of HBIM-modeled Najdi arches, enabling interactive heritage exploration

development through user feedback and technological progress.

4 Results

The Traditional Najdi Architectural Heritage Building Information Modelling (HBIM) Library developed systematically into a complete and evolving database which documents the complex details of traditional Najdi architectural components including doorways, Tarma, Alfuraj, and Shuraf. The combination of Terrestrial Laser Scanning (TLS) and photogrammetry and augmented reality (AR) digital technologies enables the creation of precise 3D models that incorporate extensive metadata. The current technological progress has not resolved all issues that prevent complete accuracy and authenticity.

The main issue arises from the fact that laser scanning and photogrammetry work as surface-based technologies. The external geometry capture capabilities of these tools remain strong yet their ability to interpret internal structural elements weakens when the Level of Detail (LoD) is low. The current technology restrictions necessitate the implementation of X-ray imaging and Ground Penetrating Radar (GPR) to detect hidden features in heritage structures [42].

The cultural and aesthetic identity of Najdi architecture suffers because decorative elements and ornaments have disappeared either partially or completely [43]. The HBIM models experience reduced credibility and precision because of missing components which results in estimated accuracy levels between 90 and 95%.

The current situation demonstrates the necessity for AI-based reconstruction methods to restore missing data points while preserving cultural integrity. The development of

Fig. 23 AR-enabled interaction with HBIM-catalogued Najdi niches, bridging digital and physical heritage experiences

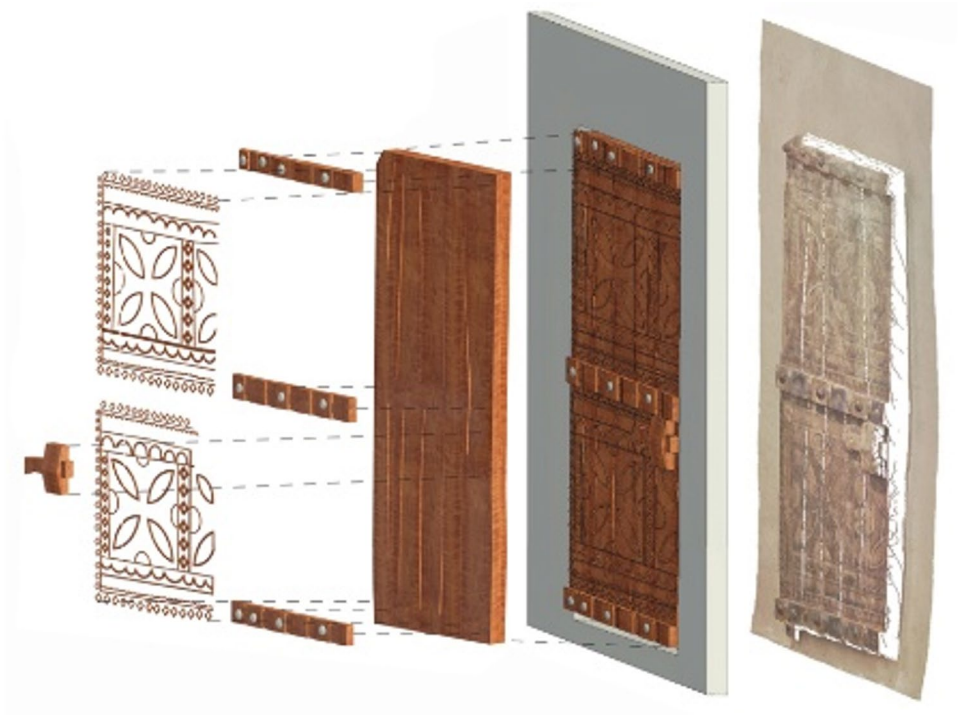

Fig. 24 Digital reconstruction of a traditional Najdi doorway in Revit, illustrating the transition from point cloud to parametric HBIM family

Revit families for traditional doors appears in Figs. 24 and 25 which demonstrates the digital library functionality of the HBIM framework. The models demonstrate high accuracy, yet they expose ongoing difficulties between technological constraints and cultural preservation requirements.

5 Discussion

This study shows digital technologies play a fundamental part in the protection and combination of traditional Najdi architectural features for modern usage.

The HBIM library faces substantial barriers which require immediate resolution for its long-term success. The main problem in current scanning technology operation exists. TLS and photogrammetry methods succeed at

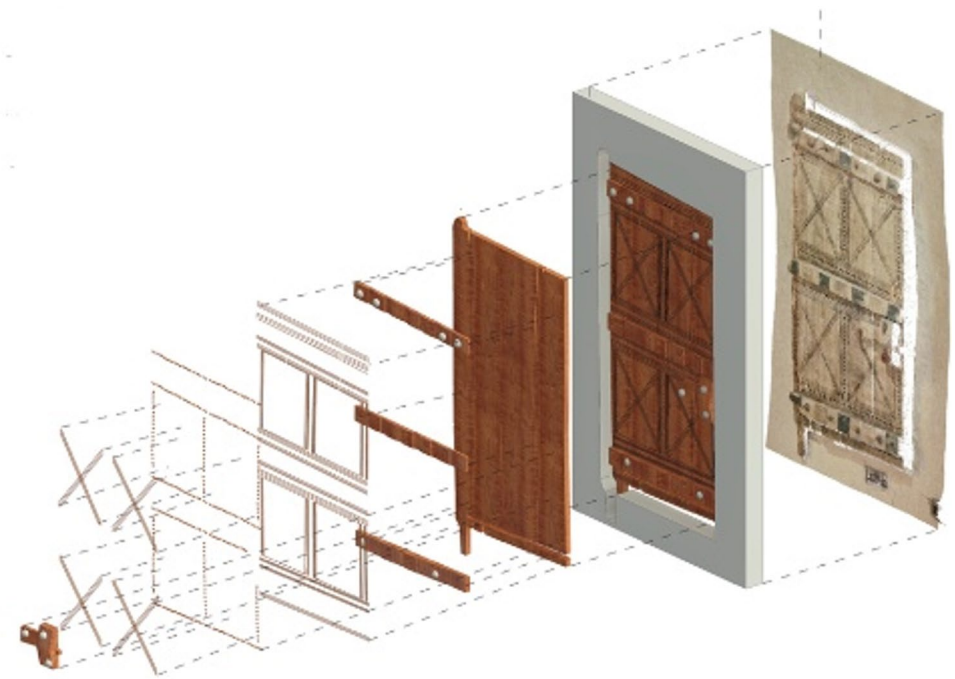

Fig. 25 Advanced Revit family development for Najdi doorways, highlighting metadata enrichment for cultural heritage preservation

capturing surface geometry but they fail to understand internal structural components when the Level of Detail (LoD) is inadequate. X-ray imaging and GPR technology needs implementation to create a complete understanding of heritage structures [15]. The lack of advanced documentation tools increases the danger of incomplete model creation that could damage the accuracy of the HBIM models.

The main challenge in this research involves the disappearance or deterioration of essential architectural features which include decorative patterns and intricate carvings. The cultural and aesthetic value of Najdi architecture heavily depends on these essential architectural elements. The absence of these essential elements results in incomplete HBIM models which negatively affects their accuracy and reliability. Researchers should implement AI-driven reconstruction techniques which use available datasets to generate predictions of missing features while maintaining cultural authenticity standards [24]. The HBIM library becomes a stronger resource for architects and urban planners and conservationists when these approaches are implemented to improve its completeness and credibility.

The integration of traditional Najdi architectural elements into modern designs needs thorough evaluation of both technological aspects and cultural aspects. A major obstacle arises from the need to protect historical integrity while performing functional modifications to these elements. The Salmani Architectural Style demonstrates an effective method for uniting traditional design elements with modern building principles through sustainable and innovative solutions that maintain cultural heritage [2]. Through the HBIM library architects gain access to reinterpret these architectural elements while preserving their socio-cultural value and fulfilling present-day needs.

AR and VR technologies along with other emerging technologies improve the accessibility and usability of heritage data. These digital tools allow users to interact with digital elements through virtual spaces. These applications succeed only when the underlying HBIM models provide precise and complete information. The implementation of these technologies for heritage preservation and urban planning requires solving the challenges that have been previously discussed [19].

This research adds substantial value to smart cities discussions because it shows how digital heritage preservation supports sustainable development along with cultural enhancement and architectural innovation. The proposed HBIM library provides a foundation that will enable upcoming architectural conservation work both in Saudi Arabia and across the world. The preservation process protects vital heritage components which become resources to create contemporary architectural solutions that express cultural heritage [20]. Future applications of this library are envisioned in large-scale heritage projects and modern developments, enabling Saudi Arabia to position itself as a global leader in the innovative fusion of heritage and urban planning. Although the HBIM library makes substantial progress in documenting and preserving Najdi architectural heritage it requires continuous work to overcome technical and methodological challenges. Saudi Arabia can establish itself as a global leader in heritage and urban planning innovation by

resolving these obstacles which will support cultural preservation and sustainable growth. The authors propose to work together with architects and urban planners and government representatives for large-scale urban and heritage projects to establish Saudi Arabia as a global leader in heritage and urban planning innovation.

6 Conclusion

This study investigates the integration of traditional Najdi architectural elements into a Heritage Building Information Modelling (HBIM) library, focusing on the Salmani Architectural Style. The systematic documentation and digitization of key elements such as doorways, Tarma, Alfuraj, and Shuraf into a comprehensive HBIM framework preserve their cultural significance while ensuring their seamless integration into contemporary architectural practices. The results demonstrate that HBIM serves as a transformative tool for bridging past and present, capturing intricate details of traditional elements while fostering collaboration among architects, preservationists, and technologists. The Salmani Architectural Style exemplifies the value of harmonizing traditional aesthetics with modern design principles, emphasizing sustainability, innovation, and cultural continuity. By leveraging advanced digital tools such as laser scanning, photogrammetry, and augmented reality (AR), this research establishes a dynamic platform for documenting and reinterpreting these elements in a manner that ensures their authenticity and relevance in the evolving urban fabric of Saudi Arabia. Future applications of this HBIM library are envisioned in large-scale heritage projects and modern developments, enabling Saudi Arabia to position itself as a global leader in the innovative fusion of heritage and urban planning. The proposed library offers a digital repository of Traditional Najdi Architectural Elements, facilitating systematic documentation and futureproofing of Saudi Arabia's architectural heritage. By integrating these elements into contemporary practices through the HBIM framework, this study highlights how modern technologies can safeguard cultural legacies while advancing sustainable design practices. The long-term impact of this work lies in its capacity to reshape how heritage sites are preserved and maintained. This digital documentation methodology serves as a foundation for future architectural conservation efforts, both within Saudi Arabia and internationally. It ensures that critical heritage elements are not only preserved but also used to inspire contemporary architectural solutions that reflect cultural identity. Collaborative efforts with architects, urban planners, and government bodies will be essential to implement these elements in large-scale urban and heritage projects, both domestically and globally. The potential for international collaboration extends further, where Saudi Arabia can lead efforts to integrate traditional architectural elements into modern urban development through HBIM frameworks. The use of advanced technologies such as AR and virtual reality (VR) will play a critical role in visualizing and interacting with these digitized elements, offering immersive experiences for both conservation professionals and the public.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Competing interests The author declares that there are no competing interests of a financial or personal nature related to this submission.

Ethical approval This study did not involve experimentation on human participants or vertebrate animals. Therefore, no formal ethical approval was required.

Informed consent No human participants were involved; hence, no informed consent was required.

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