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Sustainable Preservation of Malay Traditional Houses through Digital Technology Integration: An Adaptive Framework for East Sumatra, Indonesia

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Abstract Traditional Malay houses represent the cultural identity, social values, and ecological adaptation of coastal communities in eastern Sumatra. However, preservation efforts face significant challenges due to modernization, material degradation, and declining engagement among younger generations. Previous studies have tended to be fragmented, focusing separately on technological, material, or social aspects. This study formulates three main hypotheses: (1) Building Information Modeling (BIM) and AR/VR technologies can accelerate documentation processes and provide more immersive tools for education and public engagement; (2) the use of adaptive materials, such as engineered wood and laminated bamboo, can enhance structural resilience without compromising architectural character; and (3) community participation strengthens the acceptance of conservation strategies grounded in cultural values. The research adopts a mixed-method approach, incorporating physical observations, interviews, BIM modeling, AR/VR integration, and community surveys analyzed using the Analytical Hierarchy Process (AHP). The results indicate that immersive technologies (VR and immersive visualization) hold the highest priority weight in conservation efforts (91%), while general digital technologies and the adaptation of spatial patterns and materials serve as supporting factors, based on a high level of expert consensus (87%). In contrast, the authenticity of traditional materials ranks as a lower priority due to material scarcity and high maintenance costs. BIM and AR/VR technologies are proven to enhance documentation accuracy, restoration visualization, and youth engagement, while innovative materials offer more durable alternatives for structural reinforcement. The findings also confirm that conservation success is strongly influenced by community participation and local wisdom. This study concludes that the synergy between digital technologies, material adaptation, and community engagement forms a strategic adaptive framework for the sustainable preservation of Traditional Malay Houses in the digital era. This framework has the potential to serve as a foundation for conservation policy development, heritage digitalization, and the application of adaptive materials in other cultural heritage areas.

Keywords Malay Traditional House, Sustainable Conservation, BIM, Augmented Reality, Innovative Materials, Community Participation

1. Introduction

Architectural heritage, particularly Traditional Malay Houses, represents the cultural identity, social values, and local wisdom of coastal communities in Sumatra. As stilt houses, these buildings function not only as dwellings but also as symbols of life philosophy that reflect harmony with nature [1]. However, their existence is increasingly threatened by modernization, urbanization, climate change, and shifting values within contemporary society.

Modernization affects not only the physical aspects of buildings but also public perceptions of the meaning and identity of traditional houses. Interview findings indicate that some community members accept the use of modern materials such as concrete, ceramic tiles, and metal roofing for practical reasons, while others reject these materials because they are perceived to diminish the symbolic values of the houses. This phenomenon aligns with Value-Based Conservation Theory, which emphasizes the need to balance cultural authenticity with adaptive requirements.

The conservation of Traditional Malay Houses in eastern Sumatra faces interconnected physical, social, and policy-related challenges. Physically, structural degradation is often caused by the deterioration of wooden materials due to humid climatic conditions, termite infestation, and inadequate maintenance. Functional transformations and architectural modifications that are inconsistent with the original characteristics further accelerate the degradation process. From a social perspective, interest among younger generations in preserving Traditional Malay Houses is declining, hindering the intergenerational transmission of traditions and knowledge related to house maintenance [2]. These challenges are compounded by limited resources, financial support, technical expertise, and conservation policies that have yet to fully support sustainable preservation.

In the urban area of Stabat, Langkat Regency, the number of Traditional Malay Houses has decreased as a result of lifestyle changes and insufficient policy protection. Many buildings have been inappropriately modified, replaced with incompatible materials, or demolished, threatening the collective memory of the community [2]. Although several previous studies have addressed the preservation of traditional architecture, most have focused on a single aspect, such as technology, materials, or social dimensions [3], without integrating these aspects into a comprehensive framework. This gap underlines the urgency of the present study.

Based on this research gap, the study formulates the main research question: *How can the integration of digital technologies (BIM, AR/VR, IoT), innovative material adaptation, and community participation enhance the sustainable conservation of Traditional Malay Houses in eastern Sumatra?*".

The research hypotheses propose that:

(1) BIM and AR/VR technologies will accelerate documentation processes and increase public participation in education and conservation,
(2) The adaptation of innovative materials such as engineered wood and laminated bamboo can enhance structural resilience without compromising cultural character, and
(3) Community participation strengthens the transmission of cultural values and increases acceptance of conservation strategies.

To establish a strong conceptual foundation, this study is grounded in three main theoretical frameworks:

(4) Value-Based Conservation Theory, which emphasizes the protection of identity, symbolic meaning, and community values as the basis of preservation,
(5) Digital Heritage Framework, which views BIM, AR/VR, photogrammetry, and IoT as strategic tools for sustainable documentation, visualization, and management of cultural assets, and,
(6) Adaptive Architecture and Material Theory, which asserts that spatial flexibility and material innovation enable preservation efforts to remain relevant without sacrificing architectural essence.

The integration of these three theoretical frameworks enables the development of an adaptive conservation model that is socially, culturally, technically, and ecologically relevant for the preservation of Traditional Malay Houses in the modern era.

2. Research Methods

2.1. Research Design

This study employs a mixed-method approach using an exploratory sequential design. In the initial phase, a qualitative approach is applied to identify cultural values, the impacts of modernization, building techniques, and conservation practices emerging within the community. The qualitative findings are subsequently elaborated and validated through a quantitative approach to ensure consistency and strengthen the empirical foundation of the study [4]. The integration of these two approaches ensures both depth of interpretation and analytical rigor in formulating an adaptive conservation model.

Primary data were obtained through field observations, in-depth interviews with key informants, visual–digital documentation, and community questionnaires. Secondary data were derived from academic literature, government regulations, and credible online sources. Data analysis was conducted using both inductive and deductive reasoning, involving processes of categorization, synthesis, and verification to achieve stable and accountable interpretations.

The study consists of three interrelated and complementary stages:

1. Qualitative stage, including physical observation, in-depth interviews, and visual documentation to identify architectural characteristics, cultural values, changes resulting from modernization, and conservation constraints. This stage serves as the

foundation for understanding the socio-cultural context.
2. Digital stage, encompassing BIM modeling, photogrammetry, and AR/VR simulations to produce standardized documentation and more accurate technical analyses. At this stage, an initial evaluation of the potential use of innovative materials—such as engineered wood and laminated bamboo—is conducted to assess their structural effectiveness.
3. Quantitative stage, involving a respondent survey (n = 100) and priority analysis using the Analytical Hierarchy Process (AHP). This stage numerically validates the qualitative findings, determines the relative importance of technological, material, and community participation factors, and identifies the most relevant conservation priorities.

To enhance validity, AHP is employed not only as a prioritization tool but also as a means of triangulating the qualitative findings. Internal validity is ensured through source triangulation (observations, interviews, questionnaires), methodological triangulation (BIM, AR/VR, AHP), and technical triangulation (photogrammetry, sketches, and field measurements).

The integration of these three stages enables the development of a conservation framework that incorporates digital technologies, material innovation, and cultural values, thereby addressing the requirements of sustainable preservation for Traditional Malay Houses.

2.2. Location and Samples

The research objects comprise three Traditional Malay Houses located in the urban area of Stabat, Langkat Regency, North Sumatra, Indonesia. The samples were selected purposively based on three main criteria:
1. The buildings are more than 50 years old, in accordance with the requirements for cultural heritage designation under Law Number 11 of 2010.
2. The houses exhibit distinctive Malay architectural characteristics, including stilt-house construction, gable or hipped roofs, and wooden carvings consistent with studies of Traditional Malay architecture.
3. The houses are located in urban areas designated as cultural heritage conservation priorities under the Regional Tourism Development Master Plan (RIPPDA) of Langkat Regency (Regional Regulation No. 5 of 2020).

In addition to the three primary samples, supplementary observations were conducted on three other Traditional Malay Houses along the eastern coast of Sumatra. These additional observations were used to strengthen the comparative context and to ensure that a diversity of Malay architectural characteristics was adequately represented in the analysis.

2.3. Data Collection Techniques

Data collection was conducted using four complementary methods to ensure analytical depth and verification accuracy:
1. Field observation and measurement, carried out on the three primary samples and three comparative houses. This method involved accurately recording existing conditions, dimensions, and construction details [5]. Observations covered structural conditions, levels of deterioration, material types, construction details, and modifications resulting from modernization. These data serve as the technical foundation for BIM modeling and material analysis.
2. Interviews, involving 16 key informants consisting of Traditional Malay house owners, traditional leaders, architects, and local government officials [6]. The interviews explored qualitative information regarding historical backgrounds, cultural values, community perceptions of modernization, local conservation practices, and expectations for preservation. These data provide a basis for understanding the socio-cultural values that influence conservation sustainability.
3. Visual and digital documentation, including photography, architectural sketches, and 3D scanning, to produce accurate visual representations. This documentation forms the basis for BIM modeling and AR/VR simulations, while also enabling technical analysis and material evaluation to support structural innovation.
4. Questionnaires, distributed to 100 community respondents to assess perceptions, levels of awareness, and degrees of participation in conservation efforts. These data are required for AHP analysis to validate qualitative findings and to determine conservation priorities.

This multi-method approach strengthens analytical accuracy while testing the hypothesis that effective conservation emerges through the integration of technology, material innovation, and community participation.

2.4. Data Analysis

Data analysis was conducted through five structured stages integrating qualitative, digital, and quantitative approaches:
1. Reduction and categorization of qualitative data (observations and interviews) were organized thematically into cultural values, physical conditions and deterioration, impacts of modernization, community participation, and conservation challenges. This stage resulted in the initial construction of a thematic framework for data interpretation.

2. BIM modeling (Autodesk Revit) was developed based on field measurement data, encompassing both structural elements (columns, beams, floors) and non-structural elements (ornaments and roof patterns) [7]. BIM analysis was used to identify structural damage, simulate restoration requirements, and evaluate the compatibility of innovative materials with traditional structural systems.
3. AR/VR integration (Unity Engine) was integrated for restoration visualization and public education purposes [8]. This stage assessed the accuracy of digital documentation while also examining the relevance of AR/VR as participatory tools for education and conservation.
4. An evaluation of two adaptive materials—engineered wood and laminated bamboo—for structural reinforcement was conducted through analytical and simulation-based methods (based on technical data from relevant literature and BIM modeling) [9]. The evaluation included analyses of compressive strength potential, termite resistance, theoretical deformation levels, and visual and architectural compatibility with Traditional Malay Houses. This assessment determined the feasibility of these materials as structural reinforcement alternatives that preserve the visual identity of Malay houses.
5. Priority analysis using the Analytical Hierarchy Process (AHP) was applied to determine the relative importance of technological, material, and community participation factors. This process quantitatively validated the qualitative findings, although the scope of external validity remains limited to the context of the study area.

Data validation was conducted through source, method, and technical triangulation by:

(1) comparing interview, observation, and questionnaire data
(2) verifying findings using digital data (photographs, 3D scans, and BIM models)
(3) testing the consistency of social perceptions through qualitative analysis and AHP.

This triangulative approach strengthens internal validity and ensures that the integration of technology, materials, and socio-cultural aspects accurately reflects actual field conditions.

3. Results and Discussion

3.1. Integrated AHP Findings and Adaptive Conservation Implications

The results of the Analytical Hierarchy Process (AHP) calculations indicate a significant paradigm shift in conservation practices. Criteria related to immersive technologies obtained the highest priority weights. This finding reflects a transition from approaches centered on material authenticity toward strategies that emphasize the effectiveness of digital technologies in documentation, visualization, and cultural education.

Conservation priorities derived from the AHP analysis are presented in four tables. Table 1 summarizes expert consensus on the main criteria, Table 2 presents the priority weights and rankings of the top-level criteria, Table 3 validates the consistency of the pairwise comparison matrices, and Table 4 illustrates the complete priority hierarchy (global weights) down to the parameter level.

3.1.1. Priority Structure of AHP Criteria

Table 2 shows that two main criteria—Virtual Reality (VR) technology and quality of immersiveness and social media—have the highest and equal priority weights, each at 0.273, thereby ranking first in the AHP hierarchical structure. Meanwhile, the criteria of technology, adaptation of spatial patterns and material reuse, as well as material aspects (including meaning and structural strength, material historicity, and material authenticity) each have a weight of 0.091 and are positioned at the second rank.

This distribution indicates that the conservation of Traditional Malay Houses is perceived as a dynamic process oriented toward the sustainability of meaning, spatial experience, and public engagement, rather than being solely focused on the preservation of original materials.

3.1.1.1. Theoretical Validation of the AHP Priority Structure and Comparison with the Literature

The AHP results, which indicate the highest weight for the criterion of AR/VR integration for public engagement and education, suggest that experiential dimensions and value transmission are considered more critical than material authenticity, which received a relatively low weight (0.091; see Table 2). These findings explicitly validate and reinforce the three theoretical frameworks underlying the adaptive conservation model, namely:

a) Strengthening Value-Based Conservation (VBC). In the context of eastern Sumatra, the AHP results demonstrate that social values (engagement) and functional values (structural resilience) are now perceived as more important than aesthetic or material values. This shift represents a pragmatic response to modernization pressures and material scarcity, whereby communities recognize that preserving the essence and meaning of traditional houses through immersive experiences (VR/AR) is more sustainable than enforcing the use of original materials that are increasingly difficult to obtain.
b) Validation of the Digital Heritage Framework (DHF). The findings position the Digital Heritage Framework not merely as a documentation tool, but as a strategic medium for value transmission and long-term

relevance. By prioritizing AR/VR as the highest-ranked criterion, respondents emphasize the role of digital technologies in bridging generational gaps and enhancing cultural continuity.

c) Support for Adaptive Architecture and Material Theory (AAMT). The lower AHP priority assigned to material authenticity, combined with the high valuation of structural durability and building longevity, provides strong support for Adaptive Architecture and Material Theory. This framework legitimizes the use of substitute or innovative materials, provided that they maintain cultural meaning and architectural integrity.

The dominance of VR-related criteria aligns with global trends in heritage conservation, yet distinguishes this study from much of the existing literature, which typically emphasizes BIM primarily as a structural documentation tool. In contrast, this research demonstrates that stakeholders prioritize VR for its socio-cultural and educational functions, rather than as a purely technical instrument. The prioritization of VR's educational role over material authenticity further strengthens the argument for Digital Heritage as a catalyst for public engagement and participatory conservation.

3.1.2. Digital Technology as the Technical Foundation of Conservation

Based on Table 1, the technology variable achieved an expert consensus level of 88.60%, indicating strong acceptance of digital technologies in conservation practices. However, within the AHP priority structure (Table 2), general digital technology received a relatively low weight of 0.091, lower than that of immersive technologies. This finding suggests that while digital technology is considered essential, its role is perceived primarily as a supporting technical foundation rather than a dominant decision-making criterion in conservation strategies.

Table 1. Expert Consensus (%) on Key Criteria Variables within the Adaptive Conservation Framework

No.	Variable	Level of Expert Consensus (%)
1.	Technology	88,60
2.	Adaptation of spatial patterns and reuse of materials	89,80
3.	Virtual reality (VR) technology	94,80
4.	Meaning and strength of material structures	88,60
5.	History of building materials	86,80
6.	Authenticity of architectural materials	88,60
7.	Quality of immersiveness and social media	92,60

Table 2. Hierarchical Structure of AHP Main Criteria Priorities (Priority Weights and Rankings)

No.	Criteria	Average Row (Priority Weight)	Rank
1.	Technology	0,091	2
2.	Adaptation of spatial patterns and reuse of materials	0,091	2
3.	Virtual reality (VR) technology	0,273	1
4.	Meaning and strength of material structures	0,091	2
5.	History of building materials	0,091	2
6.	Authenticity of architectural materials	0,091	2
7.	Quality of immersiveness and social media	0,273	1

Table 3. AHP Hierarchy Consistency Test (Consistency Ratio/CR) for the Criteria Matrix

Calculation Steps	Formula	Result	Description
Priority Weight (Eigen Vector)	Average of the normalized matrix	Varied (0,273 and 0,091).	The average value of each row of the normalized matrix
λmax Value	∑(Initial Matrix×Priority Weight)	7,000	The average value of the product of the initial matrix and the priority vector
Consistency Index (CI)	(λmax −n)/(n−1)	0,000	Measures the level of inconsistency in the matrix
Random Index (RI)	RI value for n=7	1,32	Random index value str.
Consistency Ratio (CR)	CI/RI	0,000	CR < 0.10, Matrix Consistent

Table 4. Priority Hierarchy of Variables, Indicators, and Parameters Related to Architecture, Technology, and Preservation

No.	Criteria	Priority Weight	Indicators	Indicator Weight	Parameters	Parameter Weight	Global Weight	Rank
1.	Technology	0,091	Data acquisition	0,30	Use of laser scanning and photogrammetry	1,00	0,02730	6
			3D modeling	0,25	Converting scan data into 3D models (wood type, construction date, history, and philosophical meaning)	1,00	0,02275	9
			Digital archiving	0,20	Preservation of form, structure, and cultural value data	1,00	0,01820	11
			Multi-stakeholder collaboration	0,15	Centralized platform for collaboration	1,00	0,01365	14
			Local capacity development	0,10	Specialized skills training	1,00	0,00910	17
2.	Adaptation of Spatial Patterns and Material Reuse	0,091	Spatial pattern modification	0,40	Partial removal or cutting of spaces within the house	1,00	0,03640	4
			Substitute materials	0,35	Roof replaced with tiles or metal sheets	0,50	0,01593	12
					Walls replaced with wood, brick, or concrete blocks	0,25	0,00796	18
					Floors replaced with ceramic tiles	0,25	0,00796	18
			Impact of material changes	0,25	Material changes reduce thermal comfort	1,00	0,02275	9
3.	VR Technology	0,273	Immersiveness concept	0,60	High-level artificial environment (telepresence)	0,50	0,08190	1
					Users can experience spatial qualities	0,50	0,08190	1
			User impact	0,40	User impact (as a parameter)	1,00	0,10920	0
4.	Meaning and Structural Strength of Materials	0,091	Structural strength	0,40	Structural strength and construction durability	0,50	0,01820	11
					Harmony between humans, nature, and spirituality	0,50	0,01820	11
			Symbolic meaning	0,35	Symbolic meaning (as a parameter)	1,00	0,03185	5
			Life philosophy	0,25	Life philosophy (as a parameter)	1,00	0,02275	9
5.	Historicity of Building Materials	0,091	Original material sources	0,60	Materials sourced from surrounding forests	0,60	0,03185	5
					Ritual practices	0,40	0,02184	10
			Material treatment	0,40	Material treatment (as a parameter)	1,00	0,03640	4
6.	Authenticity of Architectural Materials	0,091	Original materials	0,40	Roof (nipa palm leaves), walls (wood), floor (wood)	0,50	0,01820	11
					Materials as primary determinants of architectural identity	0,50	0,01820	11
			Association with identity	0,35	Association with identity (as a parameter)	1,00	0,03185	5
			Availability challenges	0,25	Natural materials are scarce and costly	1,00	0,02275	9
7.	Quality of Immersiveness and Social Media	0,273	Digital conservation	1,00	Reconstruction of damaged Traditional Malay Houses	0,50	0,04550	3
					More interactive documentation	0,50	0,04550	3

At the parameter level (Table 4), the use of laser scanning and photogrammetry achieved a global weight of 0.02730 (ranked 6th), making it the most important technical parameter within this category. This result confirms that high-precision documentation constitutes the initial and indispensable stage of digital conservation. Furthermore, BIM-based 3D modeling recorded a global weight of 0.02275, followed by digital archiving (0.01820), multi-stakeholder collaboration platforms (0.01365), and local capacity development (0.00910). Collectively, these technologies enable accurate documentation, damage mapping, structural assessment, and the development of measurable restoration scenarios, consistent with previous studies highlighting the role of digital and immersive technologies in strengthening documentation accuracy and mitigating risks to traditional buildings [10] [11].

3.1.3. Spatial Adaptation and Material Reuse as Strategies for Functional Sustainability

Spatial adaptation and material reuse achieved a high expert consensus level of 89.80% (Table 1), reflecting broad acceptance of adaptive practices in the context of modernization. Nevertheless, the AHP priority weight for this criterion is 0.091 (Table 2), indicating that adaptation is perceived as a supporting strategy aimed at sustaining building functionality rather than as a primary conservation objective.

At the parameter level, changes in spatial configuration recorded a global weight of 0.03640 (Table 4), underscoring spatial flexibility as a key strategy for maintaining the functional relevance of traditional houses under evolving socio-economic conditions.

In contrast, parameters related to material substitution, such as replacing traditional roofs with tiles or metal sheets, walls with brick or concrete blocks, and floors with ceramic tiles, exhibit lower global weights (0.01593, 0.00796, and 0.00796, respectively). This distribution suggests that material substitution is regarded as a pragmatic solution but not a central conservation priority. Additionally, the impact of material changes on thermal comfort, with a global weight of 0.02275, highlights awareness of the environmental consequences associated with adaptive material interventions.

3.1.4. VR Technology as an Instrument for Education and Public Participation

Virtual Reality (VR) technology achieved the highest expert consensus level of 94.80% (Table 1) and the highest priority weight of 0.273 (Table 2), establishing it as the most dominant criterion in the AHP hierarchy. At the parameter level, aspects of immersiveness, including telepresence and spatial experience, each recorded a global weight of 0.08190, while the impact on users reached 0.10920 (Table 4).

These results confirm that VR functions not merely as a visualization tool, but as a strategic instrument for cultural education, heritage literacy enhancement, and intergenerational public engagement. This finding aligns with existing literature emphasizing the effectiveness of immersive technologies in improving cultural understanding and supporting community-based conservation initiatives [10]. Moreover, the prioritization of VR strongly supports Hypothesis 3 and is consistent with Value-Based Conservation Theory, which emphasizes the importance of communicating cultural values to the public as a foundation for sustainable heritage conservation.

3.1.5. Consistency of AHP Matrix and Robustness of Priority Structure

The AHP consistency test (Table 3) for architectural, technological, and conservation criteria indicates that the pairwise comparison matrix achieved a maximum eigenvalue (λmax) of 7.000, equal to the number of criteria ($n = 7$). This result yields a Consistency Index (CI) of 0.000, demonstrating that the derived weights and priority structure are mathematically consistent, stable, and methodologically valid. Consequently, the reliability of the AHP results as a decision-support tool for conservation planning is fully justifiable.

This level of consistency confirms that the dominance of immersive technology within the priority hierarchy is not the result of subjective bias, but rather a coherent and expert-driven evaluation process. Overall, the findings reinforce the notion that sustainable conservation no longer relies on a single approach, but instead emerges from the synergy of digital precision, architectural adaptability, and socio-cultural engagement, integrating accurate documentation, functional sustainability, and public education as key mechanisms for the transmission of cultural values in contemporary society.

3.2. Synthesis of Findings and Conservation Implications

The synthesis of the AHP priority structure confirms that the conservation implications for traditional Malay houses are inherently multidimensional, encompassing technological, conceptual, and strategic dimensions. The dominance of immersive technologies within the priority hierarchy—where VR and immersiveness achieved the highest weight (0.273)—indicates that sustainable conservation should be understood through the lens of value transmission and public participation. This integration forms an adaptive conservation framework that is highly relevant to the urban context of East Sumatra, where the preservation of cultural values must be balanced with the pressures of modernization.

These findings lead to three principal strategic implications that should be incorporated into conservation policy and practice:

1. Strengthening the technical foundation through precision technologies, general digital technologies (priority weight 0.091, supporting Hypothesis 1)

function as an essential technical foundation. Technologies such as laser scanning and BIM ensure high levels of documentation accuracy and damage assessment, guaranteeing that restoration and adaptive interventions are conducted in a measurable, evidence-based, and informed manner.

2. Legitimizing functional adaptive solutions, the prioritization of spatial adaptation and material reuse (priority weight 0.091, supporting Hypothesis 2) demonstrates that functional sustainability must be maintained to ensure the continued relevance of traditional houses. Adaptive strategies enable buildings to remain functional within dynamic urban environments while mitigating challenges related to high restoration costs, material scarcity, and changes in thermal comfort associated with traditional construction materials.
3. Enhancing cultural education and public engagement, the use of VR technology as a medium for education and public participation emerged as the highest-priority criterion (supporting Hypothesis 3). This finding highlights the potential of immersive technologies to expand cultural awareness and facilitate intergenerational transmission of heritage values, effectively overcoming physical accessibility constraints and the limited availability of original traditional materials.

Overall, these findings underscore the necessity of strengthening conservation policies that balance digital effectiveness (Digital Heritage Framework), material and spatial adaptability (Adaptive Architecture and Material Theory), and value-centered decision-making (Value-Based Conservation).

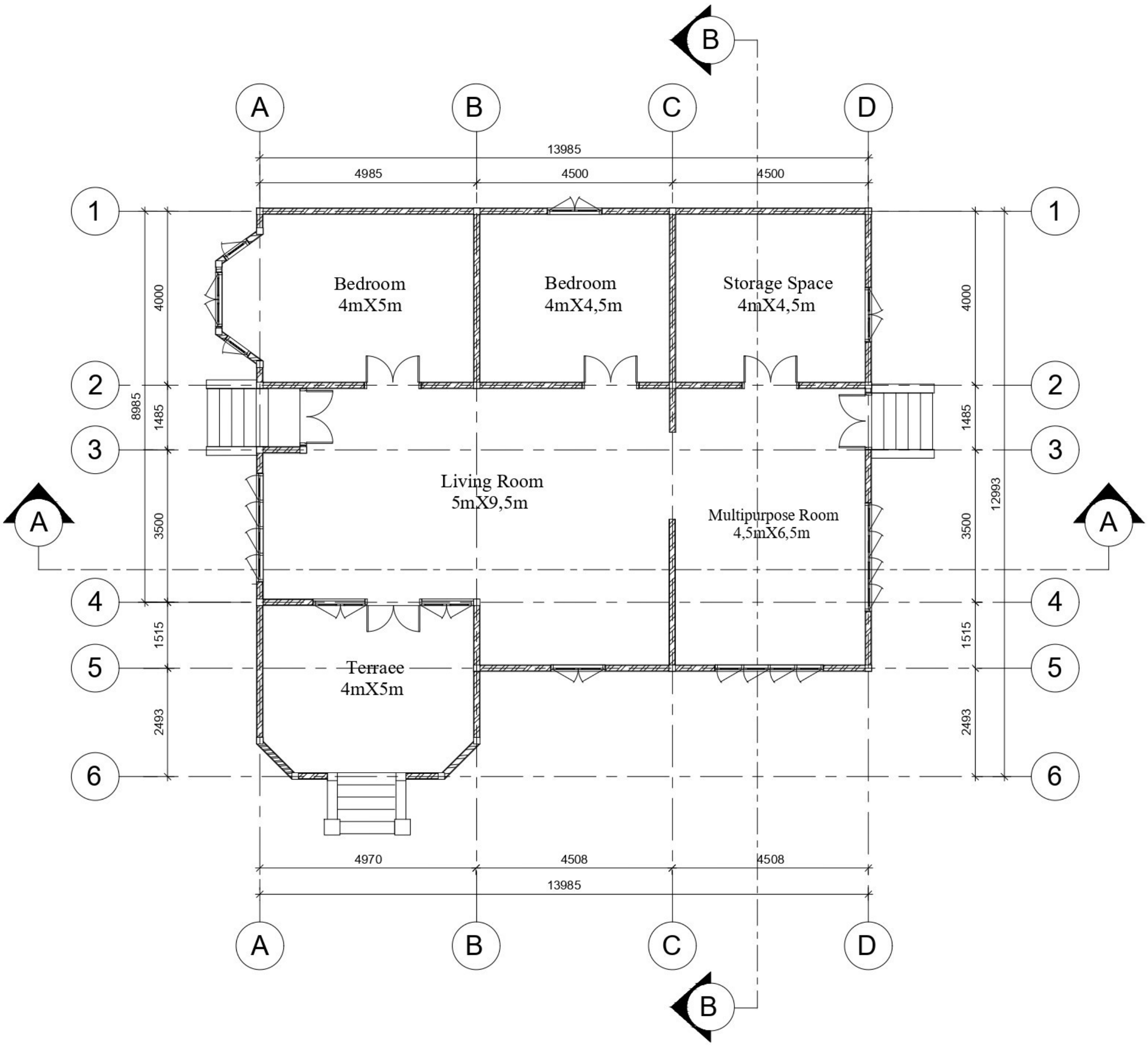
Although the AHP priority structure demonstrates exceptionally high internal consistency (CR = 0.000), the quantitative validation of this study remains constrained by the sample size (n = 100) and the localized focus on the urban area of Stabat. Consequently, the results should be interpreted as context-specific insights rather than generalized conclusions applicable to all Malay regions in East Sumatra. Future research is therefore recommended to expand the geographical scope and respondent pool to enhance external validity and generalizability, as well as to conduct empirical laboratory testing of the proposed adaptive materials to further substantiate their structural and environmental performance.

3.3. Digital Documentation and 3D Modeling

3D modeling using BIM has proven effective in accurately recording the architectural details of traditional Malay houses. The resulting digital models function as long-term archives, restoration references, and educational media [12]. The integration of 3D modeling, photogrammetry, and BIM enables comprehensive documentation of every structural element, including intricate wooden carvings, with a high level of precision. Recent technological advancements have thus opened new pathways for the in-depth documentation and understanding of traditional Malay architecture [11].

This form of digital documentation extends beyond two-dimensional representation, as it can be directly applied to restoration planning, maintenance strategies, and conservation simulations [11]. Reconstruction using Autodesk Revit demonstrates the diversity of traditional Malay house designs, which are digitally re-created with careful adherence to original forms, spatial layouts, and structural characteristics. These 3D visualizations facilitate early identification of structural deterioration, such as wood decay and deformation of building components. Furthermore, BIM-based simulations enable the evaluation of various conservation scenarios, including comparative performance analysis between traditional and innovative materials, as well as assessments of how spatial and material modifications affect thermal conditions and structural integrity.

The outputs in the form of two-dimensional construction plans and elevations generated through Revit are presented in Figure 1, illustrating the fundamental spatial configuration and structural system of the traditional Malay house, which serve as the basis for subsequent digital analyses.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Bedroom
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Storage Space
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Living Room
5mX9,5m
Multipurpose Room
4,5mX6,5m
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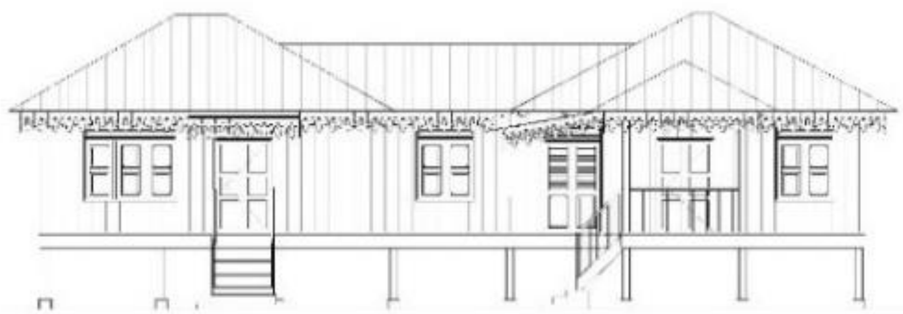
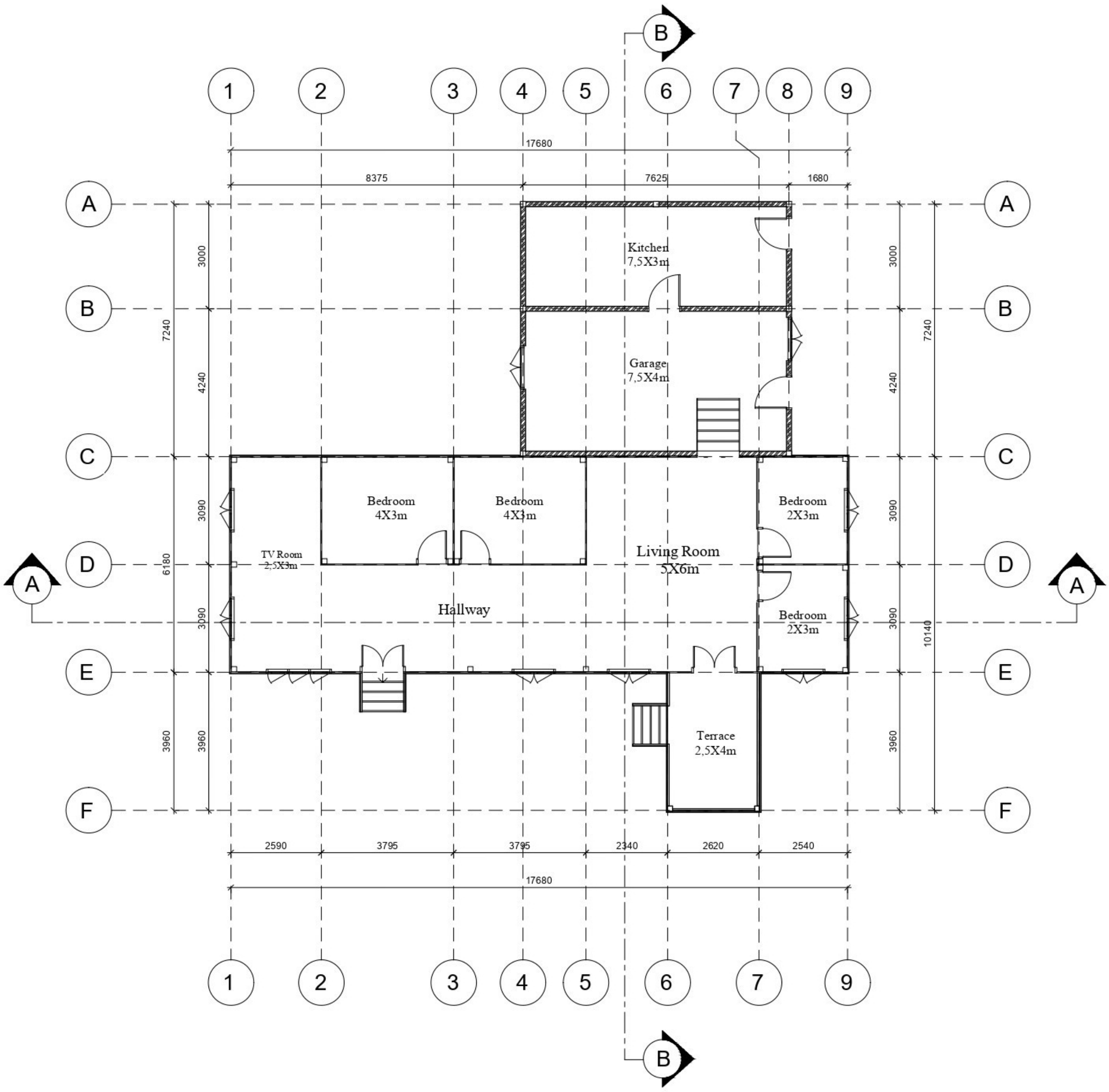
ST1




Kitchen
7,5X3m
Garage
7,5X4m
Bedroom
4X3m
Bedroom
4X3m
Bedroom
2X3m
TV Room
2,5X3m
Living Room
5X6m
Bedroom
2X3m
Hallway
Terrace
2,5X4m
17680
8375
7625
1680
3000
4240
7240
3090
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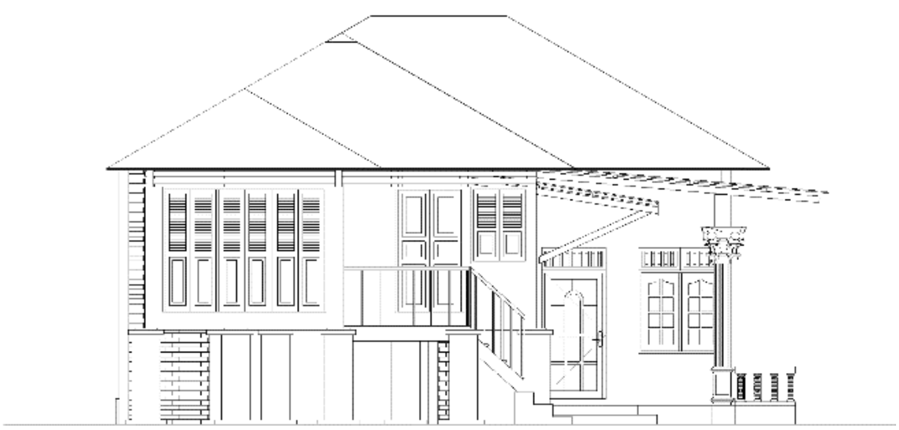
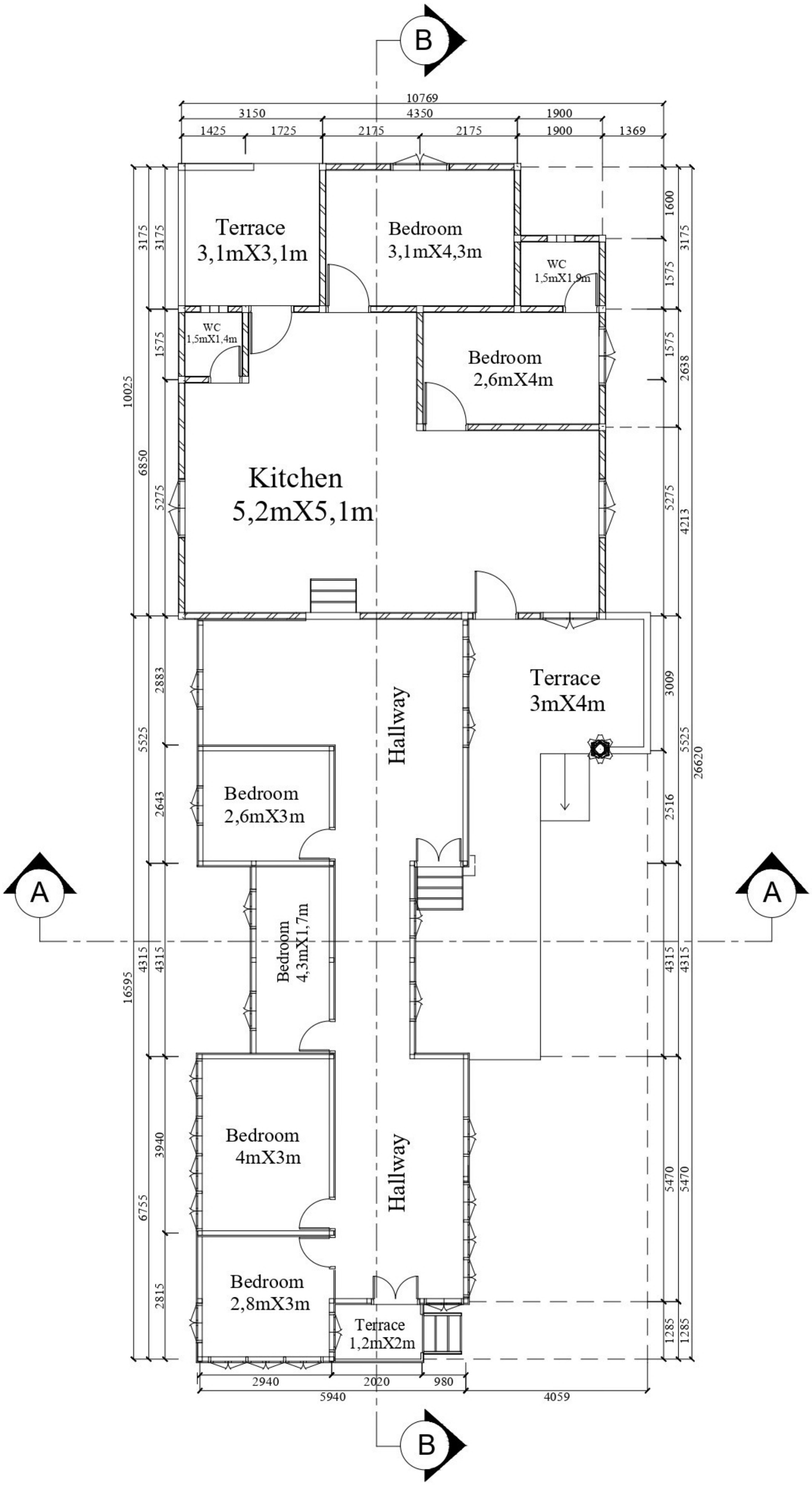
ST2





ST3

Figure 1. 2D Plan and Section of a Malay Traditional House generated through Revit. Source: Personal documentation

(ST2)

(ST3)

Figure 3. Reimagined 3D model of a Malay Traditional House using Revit. Source: Personal documentation

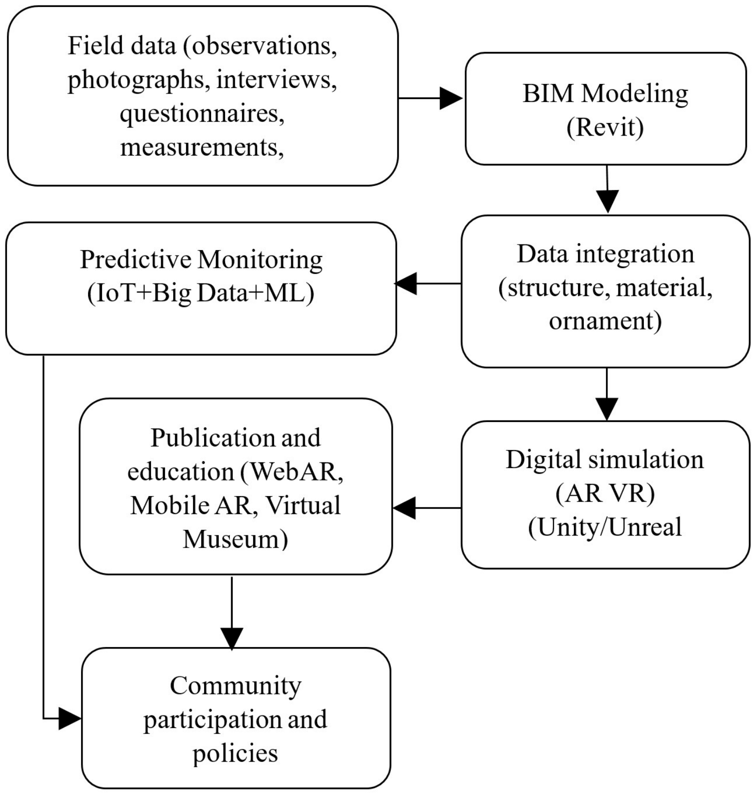


Figure 4. Digital Technology Utilization Scheme for the preservation and education of Malay Traditional Houses. Source: Personal documentation

The digital technology utilization framework for the preservation and education of traditional Malay houses is illustrated in Figure 4, depicting the interrelationship between BIM, AR/VR technologies, learning processes, and public engagement.

Within the framework of Digital Participation and Immersive Heritage Theory, AR/VR enables conservation to function not merely as a technical activity, but as an educational and experiential process that stimulates cultural memory, enhances public engagement, and supports intergenerational value transmission. In this context, AR/VR serves not only as an architectural visualization tool but also as a strategic instrument for cultural heritage revitalization.

3.5. Big Data and Predictive Monitoring

The application of Big Data and the Internet of Things (IoT) is increasingly transforming heritage conservation by shifting approaches from reactive to predictive management. IoT sensors installed in traditional Malay houses to monitor temperature, humidity, and vibration in real time enable early detection of potential structural damage or material degradation. The resulting data can be analyzed using machine learning algorithms to identify latent risks that may not be detectable through visual inspection alone. This approach aligns with previous studies [17].

By integrating IoT sensor data with 3D models generated through laser scanning or photogrammetry, conservation experts can conduct more accurate and detailed structural analyses, leading to more effective conservation planning [18]. This predictive approach not only supports technical preservation but also adds strategic value to cultural heritage conservation by minimizing the loss of architecturally and symbolically significant elements before damage becomes irreversible.

The application of AR/VR technologies further implies a paradigm shift in conservation, from physical preservation alone toward interactive, participatory educational experiences. These technologies strengthen the transmission of cultural values by presenting spatial simulations and visual narratives that are more accessible to younger generations—groups that are often most vulnerable to cultural disconnection from ancestral heritage.

Nevertheless, practical challenges remain, including high hardware costs, limited internet access, and low digital literacy within local communities. Addressing these barriers requires strategic partnerships among educational institutions, local governments, and communities. Shared facilities, digital literacy training programs, and the integration of AR/VR into cultural education curricula are essential to improving community readiness and participation in Malay architectural heritage conservation.

3.6. Technology, Material, and Cultural Synergy

The conservation of traditional Malay houses requires a synergistic approach that integrates digital technologies, material innovation, and living cultural values within the community. The application of BIM, photogrammetry, and VR has been shown to improve documentation accuracy, damage mapping, and public understanding of traditional architecture. Three-dimensional digital models enable comprehensive visualization and support restoration simulations and intervention planning. VR technology, in particular, provides immersive experiences that are highly effective for education and cultural value transmission. These findings are consistent with previous studies emphasizing the importance of immersive technologies in cultural conservation in the digital era.

From a material perspective, the use of innovative materials such as engineered wood and laminated bamboo, offers more durable and environmentally sustainable structural solutions without eliminating the architectural character of Malay houses. This finding supports the literature [16] on the efficiency of renewable materials in traditional building conservation, particularly in response to natural material scarcity and environmental sustainability demands. However, the adoption of modern materials is not always widely accepted by local communities.

Cultural resistance to modern materials indicates that conservation strategies cannot disregard local values [9]. Community opposition demonstrates that conservation addresses not only technical concerns but is deeply intertwined with cultural identity and inherited traditional values.

Therefore, sustainable conservation must adopt a hybrid approach, integrating technological and material innovation while preserving embedded cultural meanings. Without community involvement and responsive government policies, even advanced technologies may fail to achieve meaningful impact. Strengthening the role of local wisdom ensures that architectural heritage remains relevant and meaningful for future generations.

3.7. Community Participation and Local Wisdom

The conservation of traditional Malay houses is inseparable from community participation, as these houses function not only as physical structures but also as symbols of cultural identity and collective pride. Resistance to modern materials demonstrates that conservation is not merely a technical issue, but one closely linked to cultural identity [19]. The sustainability of traditional houses depends heavily on a sense of ownership, active engagement, and community acceptance of conservation strategies.

The integration of digital technologies such as BIM and AR/VR introduces new opportunities to strengthen cultural preservation through structured documentation, accurate restoration visualization, and accessible educational media for younger generations. These findings are consistent with previous research [10] indicating that VR enhances spatial understanding and public education. In line with this, studies such as [13] highlight how BIM and AR technologies have transformed cultural heritage conservation strategies. Furthermore, the application of Big Data and predictive systems introduces a new paradigm for evidence-based and efficient maintenance management.

However, technology alone cannot succeed without social and cultural support. Cultural resistance remains a tangible challenge, as some communities reject modern interventions such as concrete or non-traditional materials, reflecting concerns over the loss of symbolic meaning and architectural authenticity. This phenomenon reinforces the understanding that conservation is not solely a technical endeavor but is fundamentally tied to identity and cultural pride.

Consequently, conservation strategies must be participatory, prioritizing open dialogue among stakeholders—including local communities, academics, and government authorities—to balance modern technological applications with the preservation of local wisdom. In this context, local wisdom is not merely a complement to technology, but a foundational element that ensures social legitimacy, conservation sustainability, and the continued relevance of Malay architectural heritage in contemporary society.

3.8. Innovative Materials for Structural Durability

Manual conservation of traditional Malay houses that relies on original materials and traditional construction techniques is often time-consuming, labor-intensive, and costly. Field observations indicate that most homeowners have undertaken material adaptations, such as replacing decayed wooden foundations with concrete or substituting thatched roofs made of rumbia and nipa leaves with metal sheets to improve durability under humid climatic conditions. This phenomenon is consistent with tropical environmental conditions that accelerate wood deterioration and the increasing scarcity of local material.

Such adaptive practices align with the recommendations stated in Article 23 of the Joint Decree of the Minister of Home Affairs, the Minister of Public Works, and the Minister of Public Housing, which emphasize the importance of using economical and structurally durable local building materials. In this context, conservation is not interpreted as the absolute preservation of original materials, but rather as a strategy to maintain the functional and structural sustainability of buildings without disregarding their architectural and cultural value.

The analysis of innovative materials indicates that engineered wood and laminated bamboo lumber (LBL) are feasible adaptive materials for the conservation of traditional Malay houses. Both materials exhibit technical characteristics suitable for tropical environments. Engineered wood demonstrates high dimensional stability, resistance to moisture and termite attacks, and a modulus of elasticity ranging from 6,000–10,000 MPa, making it an effective alternative to replace original timber structural elements. Meanwhile, laminated bamboo lumber (LBL) exhibits compressive strength of approximately 70–90 MPa, low shrinkage rates, and high durability under humid conditions, rendering it a viable structural substitute for natural wood.

These technical evaluations reinforce the relevance of innovative materials as part of an adaptive conservation strategy. Such materials can be applied without altering the primary architectural form, thereby preserving the visual identity of Malay houses. Nevertheless, their application must consider community cultural perceptions to avoid resistance or the loss of perceived authenticity. This approach underscores the importance of conservation strategies that are responsive to cultural values while addressing structural requirements.

A concrete example of material adaptation can be observed in the house owned by Mrs. Asnah in Langkat, where a deteriorated wooden foundation was replaced with concrete to enhance structural durability (Figure 5).

Conversely, in other locations, homeowners have rejected material substitutions, considering them detrimental to the identity and symbolic value of the house (Figure 6). These contrasting cases illustrate the inherent tension between the need for adaptation and the desire to preserve authenticity. The use of environmentally friendly local materials, as emphasized by [20], remains relevant, although material scarcity poses significant challenges.

Beyond concrete, innovative materials such as engineered wood and laminated bamboo boards may also be applied. These materials offer a balance between modern practicality and traditional aesthetics (Figure 7 and Figure 8). Some homeowners have even adopted reuse and recycling principles by reusing salvaged materials that remain structurally viable. This practice not only supports environmental sustainability but also preserves the historical value of the building. Such an approach is consistent with the principles of sustainable adaptive reuse and contributes to more ecologically responsible architectural conservation.

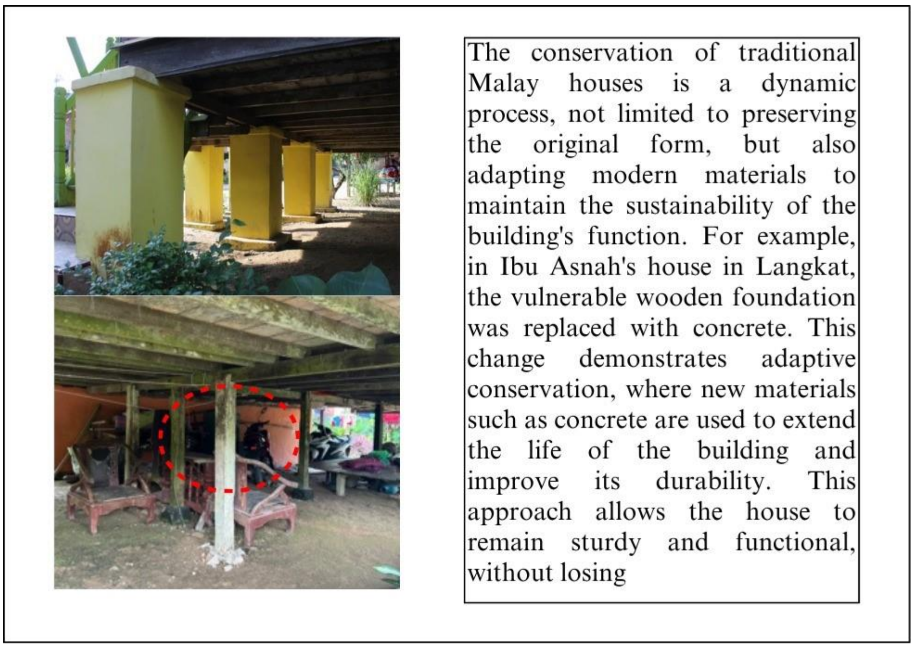


Figure 5. Concrete foundation of traditional Malay houses (ST3). Source: Personal documentation

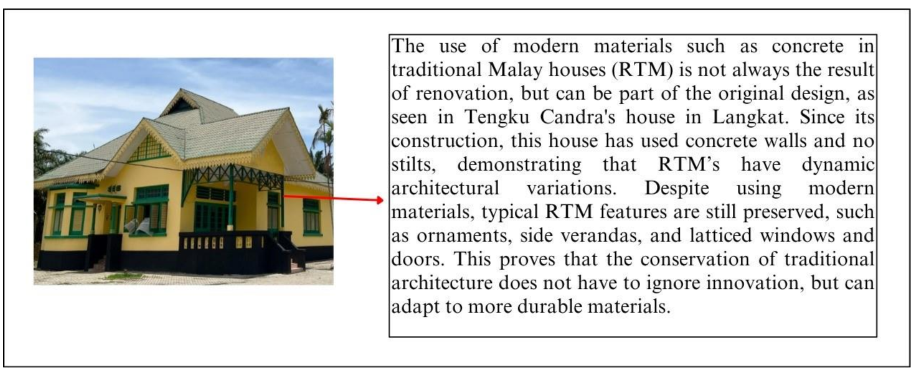


Figure 6. Traditional Malay house (ST1) with concrete wall modifications. Source: Personal documentation

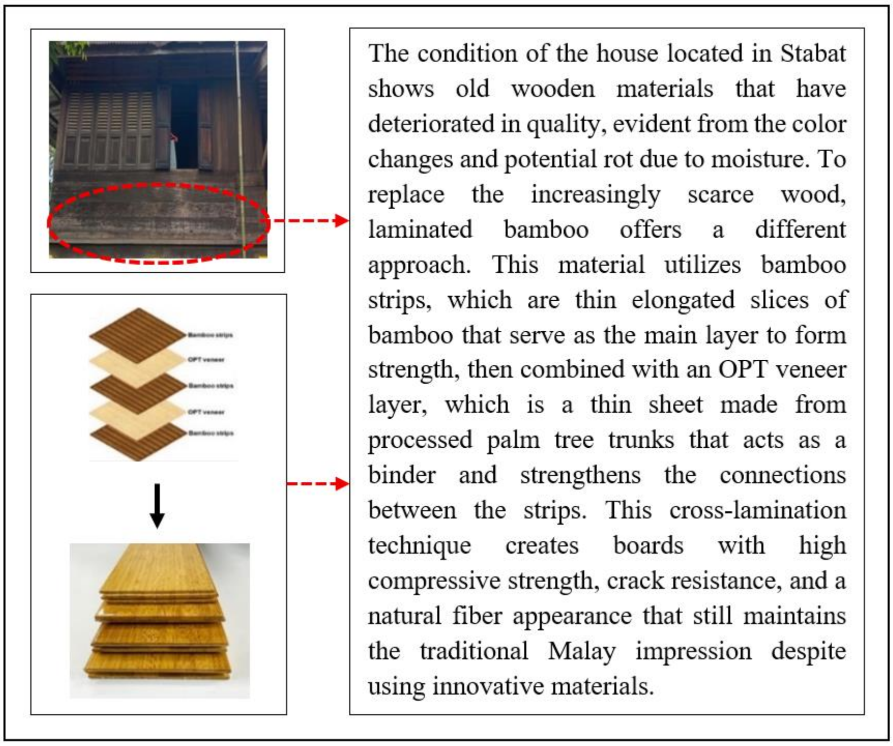


Figure 7. Laminated Bamboo Lumber (LBL). Source: Personal documentation

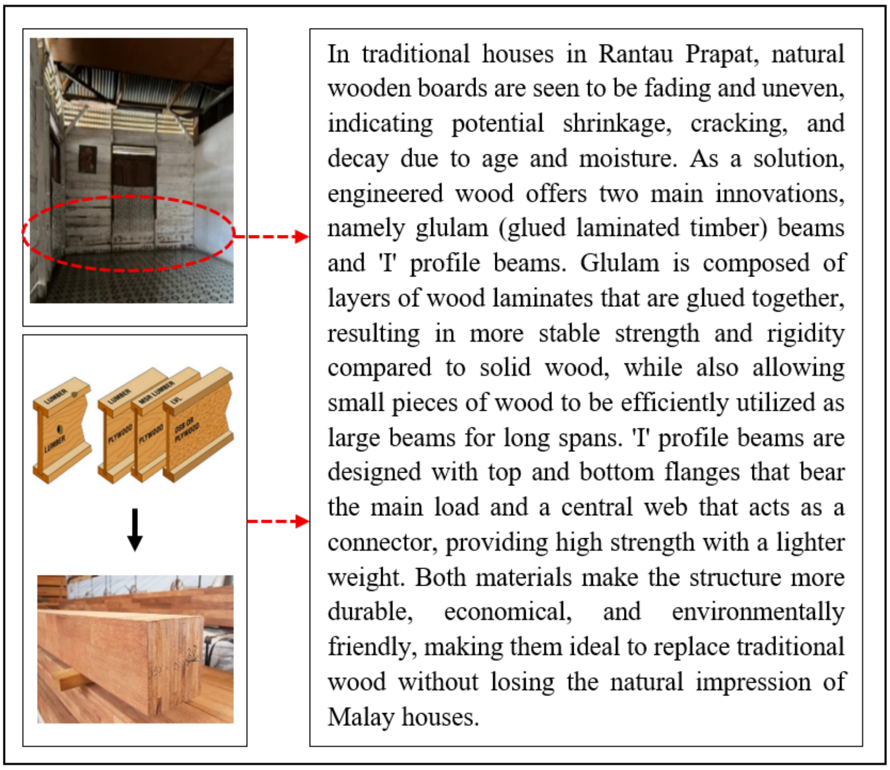


Figure 8. Engineering Wood. Source: Personal documentation

Despite their advantages, innovative materials may pose a risk to architectural authenticity [21]. Therefore, this study emphasizes the necessity of a hybrid approach, combining the structural performance of adaptive materials with a commitment to preserving cultural identity. The findings suggest that engineered wood and LBL can function as adaptive materials that enhance long-term durability without altering the visual character of traditional Malay houses.

It is important to note that the evaluation of innovative materials in this study does not constitute laboratory-based mechanical testing, but rather a technical feasibility assessment based on field observations, durability characteristics, moisture resistance, and visual compatibility with traditional Malay architecture. These findings are intended to serve as a foundation for future studies involving experimental testing and quantitative structural analysis.

3.9. Research Limitations and Implementation Challenges

This study has several limitations that should be considered when interpreting the results. Geographically, the research focuses exclusively on traditional Malay houses in the urban area of Stabat, which does not represent the full diversity of Malay architecture across East Sumatra. In addition, the limited number of respondents and expert informants restricts the generalizability of the findings. Although triangulation through field observations, interviews, questionnaires, and digital documentation enhances internal validity, the scope of the study remains contextual.

Furthermore, this research does not include laboratory-based mechanical testing of materials, which is recommended for future studies in line with the scope and funding constraints. Subsequent research should expand the study area and incorporate laboratory testing to strengthen external validity. From an implementation perspective, despite the strong potential of the proposed adaptive framework, several challenges remain. Financial constraints pose a significant barrier for homeowners, who often can only afford minor repairs. Additionally, limited human resources—particularly professionals capable of integrating traditional conservation methods with modern technologies such as BIM, AR/VR, and IoT—restrict the effective application of advanced technologies.

Another critical challenge is cultural resistance at the community level. Technology-based interventions are often perceived as threats to symbolic meaning and architectural authenticity. This condition highlights that conservation success depends not only on technical solutions but also on policy support, educational programs, sustained community dialogue, and social acceptance [9]. Consequently, conservation efforts require collaboration among local governments, educational institutions, and communities to provide technical assistance, educational initiatives, and policies responsive to local dynamics.

The findings of this study have direct implications for conservation practice and policy formulation at the regional level. The integration of BIM and AR/VR can serve as a new standard for digital heritage documentation, potentially adopted by local governments for inventory systems, building condition monitoring, and restoration planning. Moreover, recommendations for the use of innovative materials such as engineered wood and laminated bamboo require regulatory incentives, technical guidelines, and training programs for local communities and construction practitioners.

Strengthening the policy dimension aligns with the mandate of Law No. 11 of 2010 on Cultural Heritage and relevant regional regulations. Accordingly, the adaptive framework proposed in this study facilitates the synchronization of value-based conservation approaches with technology-driven strategies, enabling more effective implementation in regional heritage conservation programs. Ultimately, this research provides an empirical foundation for policymakers, planners, and stakeholders to formulate conservation policies that are responsive, inclusive, and sustainability-oriented.

4. Conclusions

This study demonstrates that the sustainable conservation of Traditional Malay Houses requires an adaptive framework that integrates digital technologies, material innovation, and community participation. Such an approach is essential for addressing the challenges of modernization, the scarcity of traditional materials, and the declining engagement of younger generations in architectural heritage preservation.

The AHP results indicate that immersive technologies act as the primary drivers of conservation, as reflected by the highest priority weights assigned to Virtual Reality (VR) and the quality of immersiveness and digital media (each 0.273), with user impact identified as the most influential parameter. These findings suggest that conservation success is determined not only by physical restoration, but also by the ability of conservation strategies to enhance cultural education, heritage literacy, and public engagement through interactive digital media.

Meanwhile, general digital technologies, spatial pattern adaptation and material reuse, as well as material-related aspects such as historical value and authenticity, received lower yet equal weights (0.091), positioning them as supporting factors within the hierarchy. At the parameter level, spatial pattern adaptation contributes significantly to functional sustainability in urban contexts (0.03640), while precision documentation through BIM, laser scanning, and photogrammetry provides a critical technical foundation for digital conservation (0.02730). These results indicate that while authentic materials remain essential as carriers of cultural identity, conservation priorities in urban settings are increasingly shaped by the effectiveness of digital strategies and realistic functional adaptation.

Methodologically, the AHP analysis exhibits very high internal consistency (CR = 0.000), confirming the robustness of the priority structure as a basis for conservation decision-making. Nevertheless, the findings remain contextual due to the geographically focused study area in Stabat and the limited sample size (n = 100). Future research is recommended to expand the study area, conduct laboratory-based testing of innovative materials, and develop predictive monitoring systems using IoT and digital twins to enhance external validity and implementation readiness at a district or regional scale.

This research contributes a methodological framework that integrates mixed methods, BIM modeling, AR/VR technologies, and AHP-based priority analysis within a single analytical structure. The proposed model is replicable for other conservation studies that require a comprehensive assessment of technical, social, and cultural dimensions.

The findings provide a practical foundation for local governments and stakeholders to establish heritage digitalization as a standard for documentation and conservation planning, promote the use of adaptive materials such as engineered wood and laminated bamboo, and strengthen community-based conservation programs to improve local acceptance. Overall, the adaptive framework supports conservation decision-making that is more responsive, inclusive, and oriented toward long-term sustainability.

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