

Navigating digital transformation in cultural heritage crafts: a hybrid socio-technical framework for Minangkabau wood carving

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Abstract

Cultural heritage crafts in a digital world are often characterized by the tension between technological effectiveness and the preservation of cultural identity and values. Despite growing interest in digital manufacturing technologies, limited empirical evidence exists regarding how production tasks can be allocated between automation and manual craftsmanship while maintaining both efficiency and cultural authenticity. This study explores such tensions in the context of Minangkabau wood carving, a traditional craft facing pressure from market forces, declining apprentice training, and increasing demands for scalability. The objective was to investigate how digital manufacturing tools could be integrated into this existing cultural practice without compromising its authenticity. A sequential explanatory mixed-methods approach was employed, combining socio-cultural data from surveys and interviews with 17 master craftsmen, and a technical comparison of hand-carving, CNC-based V-carving, and 3D carving. Results indicated that artisans strongly resisted full automation but were conditionally open to hybrid manufacturing systems aligned with cultural values. Technically, CNC V-carving reduced fabrication time by 66–82% and costs by up to 43%, particularly in the simple patterning phase. However, hand-carving was consistently judged superior in fine detail, surface characteristics, and perceived cultural authenticity. This study synthesizes these findings into a stage-based hybrid socio-technical production model, wherein digital tools are employed for repetitive and scalable tasks, while human craftsmanship remains central to artistic refinement and cultural expression. The findings provide empirical support for task allocation decisions in heritage-based manufacturing systems and identify cultural fit as a major determinant of perceived usefulness in digital transformation. While the study offers valuable insights, its focus on a specific cultural context and relatively small sample suggests caution in broader generalization.

Keywords:

*Cultural heritage crafts;
Digital transformation;
Hybrid manufacturing;
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INTRODUCTION

The preservation of intangible cultural heritage today extends beyond merely safeguarding traditions. It requires a nuanced equilibrium, enabling cultural crafts to respond to

technological and market pressures while preserving their essence and meaning [1][2]. This paper examines this challenge within the context of Minangkabau woodcarving from West Sumatra, Indonesia, an art form embodying local

artistic expertise and societal philosophy [3, 4, 5]. Its continuity is increasingly at risk due to dwindling interest among youth, market preference for mass-produced ornaments over handcrafted pieces, and modern consumer demand for quicker, scalable production [6, 7, 8].

Digital technologies such as CAD, CAM, and CNC machining offer potential solutions to these pressures in the production chain [9, 10, 11]. While their technical and economic merits are clear, adoption decisions must not be based solely on technological simplification or cost reduction. The introduction of CNC technology can provoke concern among master craftsmen, who fear it may dilute the cultural identity, narrative depth, and spiritual and aesthetic values embedded in each relief motif, thereby undermining traditional carving methods [12][13].

These opposing perspectives have resulted in a stalemate, both empirically and practically. Debates are often framed in binary terms: vehement rejection of technological intervention versus full automation. This dichotomous thinking is counterproductive. Moreover, existing literature tends to align with one camp or the other, detailing either the technical opportunities of CNC or the cultural resistance to it, with few studies integrating both perspectives into a single framework that addresses technological capability and cultural acceptance [14][15].

From a manufacturing engineering perspective, another important limitation remains. Although previous studies have demonstrated the potential of CNC technologies to improve productivity and support digital preservation efforts, limited empirical research has systematically quantified stage-level production performance, cost implications, quality trade-offs, and workflow allocation decisions within traditional craft manufacturing [16][17]. Consequently, practical guidance remains scarce regarding which production stages are most suitable for automation and which should remain dependent on artisan expertise. As a result, the implementation of CNC technology in heritage crafts often proceeds without a clear engineering basis for balancing efficiency gains with quality preservation.

In traditional Minangkabau woodcarving, production can be broadly divided into two stages: Base Shaping and Relief Detailing, as shown in Figure 1. The Base Shaping stage focuses on establishing the primary geometry of the motif through rough shaping and contour formation, whereas the Relief Detailing stage

emphasizes artistic refinement and fine decorative features. Because these stages require different combinations of technical precision and artisan expertise, they provide a useful basis for evaluating alternative allocations between manual and CNC-based production.

Previous studies have investigated digital manufacturing technologies in traditional crafts from several complementary perspectives. Early engineering studies primarily focused on CNC machining performance, production efficiency, and CAD/CAM optimization. More recent research has expanded toward technology adoption among artisans and the digital preservation of cultural heritage. Collectively, these studies demonstrate substantial progress in both manufacturing technology and heritage preservation; however, they also reveal important research gaps. Table 1 summarizes representative studies relevant to the present research.

As summarized in Table 1, previous studies have demonstrated substantial progress in applying digital technologies to traditional crafts from three complementary perspectives. Engineering-oriented studies consistently reported that CAD/CAM and CNC technologies improve machining accuracy, production efficiency, and manufacturing consistency [18, 19, 20, 21, 22]. Meanwhile, heritage-oriented studies emphasized the importance of preserving cultural identity, documenting traditional knowledge, and facilitating artisans' adaptation to digital technologies [23, 24, 25, 26, 27].

Despite these advances, the existing literature remains fragmented. Engineering studies have largely focused on machining performance while providing limited consideration of artistic craftsmanship and cultural acceptance. Conversely, heritage studies have primarily addressed documentation, preservation, and technology adoption without quantitatively evaluating manufacturing performance or production workflow optimization.

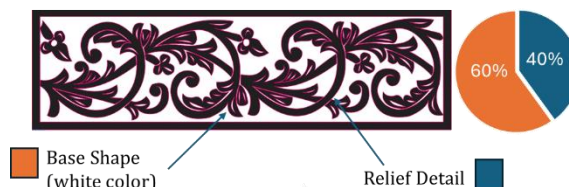


Figure 1. Conceptual decomposition of Minangkabau woodcarving production stages

Table 1. Summary of Previous Studies on Digital Manufacturing in Cultural Heritage Crafts

Author (Year)	Method	Key Findings	Limitation / Research Gap
Anggoro et al. (2022) [18]	Virtual machining	Accurate digital fabrication	Fully digital production only
Bangse et al. (2020) [19]	CNC router fabrication	High machining accuracy	No hybrid finishing workflow
Bawono et al. (2023) [20]	Machining optimization	Reduced production time	No manual quality assessment
Dwinugroho et al. (2019) [21]	CNC automation	Improved machining consistency	Ignored artistic craftsmanship
Fergiawan et al. (2020) [22]	CAD/CAM optimization	Higher productivity	No collaborative manufacturing framework
Ciptandi et al. (2022) [23]	Participatory action research	Supported digital adaptation	No adoption model for woodcarving
Haji Harun et al. (2023) [24]	Field investigation	Confirmed cultural significance	No hybrid production strategy
Junaidy et al. (2025) [25]	Photogrammetry	Captured tacit craftsmanship	Focused on documentation only
Putra et al. (2024) [26]	AI-based reconstruction	Enabled digital preservation	No manufacturing integration
Rahmat et al. (2026) [27]	Qualitative case study	Digital culture adaptation	No production workflow analysis

Consequently, limited empirical evidence is available to support stage-based process allocation between manual and CNC operations, and no operational hybrid manufacturing model has yet integrated engineering performance, artisan acceptance, and cultural authenticity into a unified decision-making framework. These unresolved issues constitute the primary motivation for the present study.

Addressing these research gaps requires a perspective that extends beyond conventional manufacturing engineering. Improving production efficiency alone is insufficient if technological interventions are perceived as incompatible with cultural values, while preserving cultural authenticity without considering engineering performance offers limited practical guidance for sustainable manufacturing [28]. Consequently, this study adopts an integrated conceptual perspective combining Diffusion of Innovation (DoI), the Technology Acceptance Model (TAM), and Socio-Technical Systems (STS) theory. Together, these complementary perspectives explain how digital technologies can be accepted by artisans, integrated into traditional production systems, and translated into an operational hybrid manufacturing model [29].

Diffusion of Innovation (DoI) theory explains technology adoption through five principal characteristics: relative advantage, compatibility, complexity, trialability, and observability [30]. Among these dimensions, compatibility is particularly important in heritage manufacturing because artisans evaluate new technologies not only according to their technical advantages but also according to their consistency with traditional values and artistic

practices. Previous studies have shown that incompatibility with cultural identity often outweighs potential productivity gains, thereby limiting the adoption of digital technologies in traditional crafts [31]. Consequently, this study interprets CNC adoption as a process of socio-cultural adaptation rather than merely technological substitution.

While DoI explains technology diffusion at the community level, the Technology Acceptance Model (TAM) focuses on individual technology acceptance through the constructs of Perceived Usefulness (PU) and Perceived Ease of Use (PEOU) [32, 33, 34, 35, 36]. Because conventional TAM primarily emphasizes functional considerations, several studies have argued that socio-cultural factors must also be considered when analysing technology adoption in heritage contexts [37][38]. Accordingly, this research incorporates Cultural Compatibility as an external construct influencing both PU and PEOU. The extended conceptual model adopted in this study is illustrated in Figure 2.

Beyond technology acceptance, this study addresses the engineering problem of allocating manufacturing tasks between human artisans and CNC technologies. Socio-Technical Systems (STS) theory therefore provides the overarching perspective by emphasizing the joint optimization of the social subsystem (artisans, cultural values, and craftsmanship) and the technical subsystem (CAD/CAM/CNC technologies) [39, 40, 41]. Rather than replacing one subsystem with the other, STS views hybrid manufacturing as a socio-technical design problem in which production stages are allocated according to their technical characteristics and cultural significance.

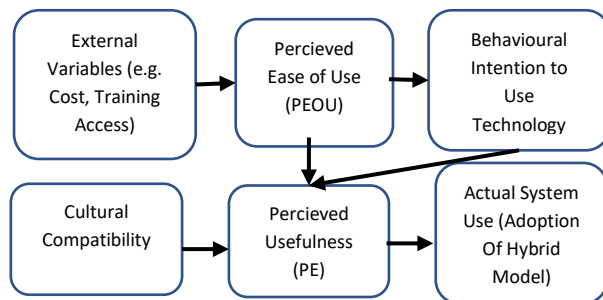


Figure 2. Extended Technology Acceptance Model for Cultural Heritage Crafts

This perspective provides the theoretical basis for the stage-based hybrid manufacturing model proposed in this study.

Collectively, these complementary theories provide the conceptual foundation of the present study. DoI explains technology diffusion at the community level, TAM interprets individual technology acceptance, and STS guides the joint optimization of human craftsmanship and digital manufacturing. Their integration forms the conceptual basis of the framework illustrated in Figure 3 and supports the development of an operational hybrid manufacturing model that combines engineering performance with cultural sustainability.

Building upon the identified research gaps, this study approaches technology adoption not merely as a cultural or technological issue, but as a manufacturing system design problem involving the strategic allocation of tasks between human craftsmanship and digital production technologies. Specifically, it investigates how manual carving, CNC V-carving, and CNC 3D machining can be integrated to improve manufacturing performance while preserving the artistic and cultural authenticity of Minangkabau wood carving. To achieve this objective, a mixed-methods approach was employed, combining quantitative measurements of processing time, production cost, and output quality with qualitative evidence on artisans' perceptions of technology adoption.

The novelty of this research lies in the development and validation of a stage-based hybrid manufacturing model that integrates engineering performance with socio-cultural considerations. Rather than treating hybridization simply as a compromise between tradition and technology, the proposed model provides an operational framework for allocating production stages according to their technical and cultural characteristics.

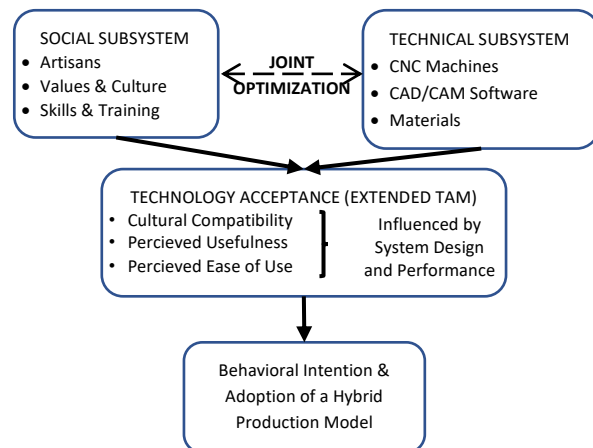


Figure 3. Integrated Socio-Technical Adoption Framework

The study contributes theoretically by extending technology adoption through Cultural Compatibility, methodologically by integrating engineering experiments with artisan perception analysis, and practically by providing evidence-based guidance for hybrid manufacturing implementation in cultural heritage production.

METHOD

This study employed a two-phase sequential explanatory mixed-methods design to gain in-depth insight into the social and technical aspects of digital transformation [42][43]. The first phase involved a socio-cultural investigation of artisan perceptions and barriers. The second phase consisted of a quantitative-technical experiment to empirically assess the efficiency of different production methods. Findings from both phases were synthesized to formulate an evidence-based socio-technical framework for hybrid adoption, ensuring the proposed system is both technically optimized and culturally grounded [44][45].

Phase 1: Socio-Cultural Inquiry into Artisan Perceptions

Design: A descriptive cross-sectional survey was used to quantitatively gauge technology adoption levels and perceived barriers among traditional artisans. Supplementary interviews provided qualitative depth to illuminate the quantitative data.

Participants and Sampling: Purposive expert sampling was employed to recruit 17 (N = 17) master Minangkabau woodcarvers, representing the active population of recognized master artisans involved in the transmission of traditional carving knowledge within the study area. Because the objective of Phase 1 was to investigate expert perceptions rather than

estimate population parameters, information-rich expert sampling was considered more appropriate than probabilistic sampling. Similar sampling strategies have been widely adopted in cultural heritage and traditional craft research involving specialized artisan communities [23][24]. Inclusion criteria were: (1) active traditional woodcarver for at least five years, (2) recognized as a master artisan (tukang ukir tuo) within their community or workshop, (3) no prior use of CNC devices in their production process, and (4) willingness to provide informed consent. This approach aimed to capture information-rich cases for deep qualitative insight. While not statistically generalizable, this subset offers a valuable understanding of core socio-cultural dynamics.

Instrument and Validation: A structured questionnaire comprising 20 items measured on a five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree) was used. Items represented five dimensions based on the theoretical framework:

1. Innovation Benefit (IB): Perceived relative advantage of digital tools (DoI).
2. Technology Acceptance (TA): Perceived usefulness and ease of use (TAM).
3. Adoption Barriers (AB): Perceived complexity and incompatibility (DoI/TAM).
4. Technology Utilization (TU): Current and past technology use.
5. Hybrid Model Openness (HMO): Willingness to adopt a culturally compatible, blended approach (STS).

To ensure a strong theoretical-empirical link, these dimensions were mapped onto the integrated socio-technical framework (see [Table 2](#)).

Data Collection: Data were collected at artisans' workshops to ensure ecological validity. To establish a common baseline and reduce knowledge bias, participants were first introduced to CNC technology via a standardized video demonstration and visual aids. Subsequently, face-to-face surveys and semi-structured interviews were conducted to gather quantitative ratings and rich qualitative explanations.

Data Analysis: Quantitative questionnaire data were analyzed using SPSS (Version 26). Descriptive statistics (mean, standard deviation, frequency distribution) were calculated for each dimension (IB, TA, AB, TU, HMO). Qualitative interview data were transcribed and subjected to thematic analysis to identify patterns explaining quantitative scores, particularly the tension between perceived benefits (IB, TA) and barriers (AB, TU), and to elucidate openness to hybrid solutions (HMO).

Table 2. Operationalization of Theoretical Constructs into Questionnaire Dimensions

Theoretical Construct	Corresponding Questionnaire Dimension	Conceptual Focus
DoI: Relative Advantage	Innovation Benefit (IB)	Perceived efficiency, cost, and quality improvements.
TAM: Perceived Usefulness/ Ease of Use	Technology Acceptance (TA)	Belief that technology enhances performance and is easy to use.
DoI: Complexity/ Compatibility	Adoption Barriers (AB)	Perceived skill gaps, costs, and threats to cultural values.
STS: Technical Subsystem	Technology Utilization (TU)	Current level of technological integration in practice.
STS: Joint Optimization	Hybrid Model Openness (HMO)	Openness to a model that fits both social and technical subsystems.

Phase 2: Technical-Economic Experimental Comparison

Design: A comparative experimental study evaluated the efficiency, economic viability, and output quality of manual versus CNC-based wood carving.

Material and Motif: Four archetypal Minangkabau motifs, Aka Tengah Duo Gagang (ATDG), Sikambang Manih (SM), Kaluak Paku Kacang Balimbiang (KPKB), and Aka Cino (AC)—were selected for their cultural significance and varying geometric complexity.

Production Methods Compared:

1. Hand Carving: Execution by skilled carvers using traditional tools (chisels, gouges, mallets).
2. CNC V-Carving: A 2.5D machining technique using a V-bit to create precise, tapered reliefs based on vector designs.
3. CNC 3D Surface Machining: Three-dimensional routing with a ball-nose end mill to create complex reliefs from 3D models.

CNC Machining Procedures: Digital models were processed with CAM software to generate toolpaths. Milling was performed on a 3-axis CNC router (spindle speed: 22,000 rpm). Key parameters were optimized through iterative test runs to balance speed and surface quality. Finalized parameters are listed in [Table 3](#).

Table 3. CNC machining parameters

Operation Type	Tool Type	Toolpath Strategy	Feed Rate (mm/min)	Step Over (mm)	Depth Cut (mm)
V-Carving Base	3mm Endmill	Pocket	1,200	-	6
V-Carving Relief	90 ° V-Bit	Pocket	1,200	-	6
3D Surface	3mm Ballnose	Raster	2,000	0.6	6

Metrics and Measurement:

1. Time: Total active machine time (CNC) or carving time (manual) per motif was recorded precisely.
2. Cost: Calculated from direct material costs, artisan labor (based on local rate: IDR 200,000/piece for manual work), and CNC operating costs (IDR 3,000/minute, covering energy, tooling, and amortization).

Output Quality: Assessed through blinded qualitative evaluations by three independent master craftsmen. Using open-ended assessment guidelines, the evaluators compared surface smoothness, detail clarity, carving authenticity, and overall aesthetic quality. The resulting observations were synthesized descriptively to identify common judgments across evaluators.

Analysis: Descriptive statistics were used to analyse time and cost data. Qualitative quality evaluations were analyzed using thematic comparison to identify recurring observations, areas of agreement among the three evaluators, and perceived differences between manual carving, CNC V-Carving, and CNC 3D Surface machining.

Integration Phase

Results from both phases were systematically integrated using a "threading" approach. Quantitative Phase 1 findings (e.g., moderate hybrid model openness, $M=3.13$) were detailed and enriched by qualitative interview data (e.g., conditional acceptance based on manual finishing). These socio-cultural insights were then juxtaposed with Phase 2 technical-economic results, providing empirical evidence for hybrid model implementation. For instance, V-Carving's 75%-time reduction for base shaping confirms its feasibility for initial stages, while manual carving's superiority in detail resolution justifies its retention for final refinements. This synthesis informed the design of a practical, culturally acceptable socio-technical hybrid workflow.

RESULTS AND DISCUSSION

This section integrates socio-cultural and technical findings to reveal the benefits and challenges of digital transformation in Minangkabau wood carving, moving from evidence to a synthesized viable hybrid pathway.

The Social Challenge: Resistance Rooted in Cultural Identity

Artisans' perceptions of digital transformation were assessed across five constructs: Technology Use (TU), Adoption Barriers (AB), Innovation Benefits (IB), Technology Acceptance (TA), and Hybrid Model Openness (HMO). Descriptive statistics are presented in Table 4, and the corresponding perception profiles are illustrated in Figure 4. Technology Use (TU) recorded the lowest mean score (1.37 ± 0.24), whereas Innovation Benefits (IB), Technology Acceptance (TA), and Hybrid Model Openness (HMO) received consistently higher ratings. Adoption Barriers (AB) also remained relatively high (3.18 ± 0.54), indicating that although artisans recognize the potential benefits of digital technologies, cultural values and practical implementation challenges continue to constrain broader adoption. The relatively small standard deviations indicate that artisans exhibited reasonably consistent perceptions across each construct, despite differences in their individual experiences.

Open-ended responses revealed that this resistance reflects not technophobia but concern for cultural identity. Artisans believed that the carving's "soul", its aesthetic warmth, philosophical meaning, and authenticity, lies in the mastery of the human hand. This aligns with studies showing that manual craftsmanship transmits cultural values and safeguards intangible cultural heritage [46].

This resistance is explicable through the extended Technology Acceptance Model (TAM). For these artisans, the Perceived Usefulness of a technology is contingent on its Cultural Compatibility.

Table 4. Descriptive Statistic of Survey Construct

Construct	No. of Items	Mean	SD
Technology Use	4	1.37	0.24
Adoption Barriers	4	3.18	0.54
Innovation Benefits	4	3.22	0.42
Technology Acceptance	4	3.31	0.46
Hybrid Model Openness	4	3.13	0.33

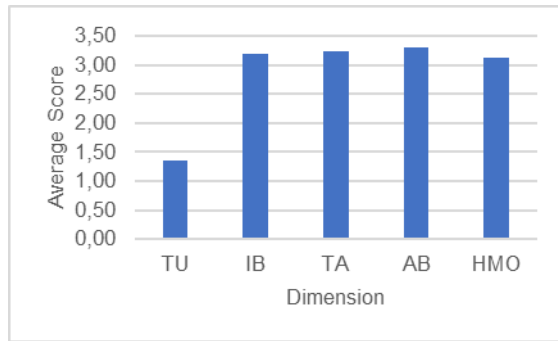


Figure 4. Artisan Perception Scores on Technology Use and Adoption

Although CNC offers operational advantages, its perceived conflict with the Minangkabau philosophy of *alam takambang jadi guru* (nature as teacher) constrains acceptance. However, resistance is not absolute. The conditional acceptance of a hybrid approach (Mean = 3.13), where technology handles mechanical tasks and manual craft defines critical artistic aspects, illustrates a pragmatic pathway towards integration that respects cultural fundamentals.

The Technical Benefit: Empirical Evidence for Strategic Automation

Experimental results quantify the potential of CNC technology while identifying the production stages in which automation provides the greatest engineering and economic benefits. Descriptive statistics summarizing the machining performance are presented in Table 5, whereas Figure 5 and Figure 6 visualize the corresponding comparisons of processing time and production cost. This observation is consistent with previous studies reporting that V-carving is especially effective for producing geometric decorative features because of its shorter toolpaths and efficient material removal characteristics [47].

The statistical summary was derived from machining experiments conducted on four representative Minangkabau carving motifs, namely Aka Tengah Duo Gagang, Sikambang Manih, Kaluk Paku Kacang Balimbiang, and Aka Cino. As summarized in Table 5, V-Carving consistently outperformed manual carving in both production stages. The greatest improvement was observed during Base Shaping, where processing time was reduced by 80.5%, whereas Relief Detailing achieved a reduction of 68.4%. Overall, V-Carving reduced total processing time by approximately 75%, while 3D Surface machining achieved a more modest reduction of 17.8%. Unlike manual carving and V-Carving, 3D Surface machining was executed as a single continuous operation; therefore, only the overall processing time is reported.

Table 5. Statistical summary of machining performance

Stages	Manual Mean $\pm$ SD (min)	V-Carving		3D Surface	
		Mean $\pm$ SD (min)	Time Reduced (%)	Mean $\pm$ SD (min)	Time Reduced (%)
Base	107.5 $\pm$ 21.0	21.0	80.5	—	—
Shaping	15.0 $\pm$ 2.2	29.3	—	—	—
Relief	92.5 $\pm$ 29.3	29.3	68.4	—	—
Detailing	25.0 $\pm$ 6.5	29.3	—	—	—
Overall	200.0 $\pm$ 33.7	50.3 $\pm$ 8.7	74.9	164.5 $\pm$ 4.2	17.8

Figure 5 demonstrates that the productivity advantage of V-Carving was consistently observed across all four representative motifs despite differences in motif geometry and carving complexity. Although the magnitude of time reduction varied among motifs (66–82%), V-Carving consistently outperformed manual carving, indicating that the observed productivity advantage is inherent to the machining strategy rather than to a specific carving motif.

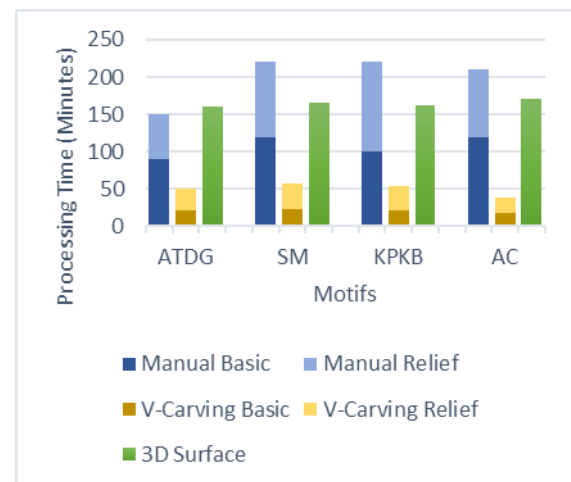


Figure 5. Total Processing Time by Production Method and Motif

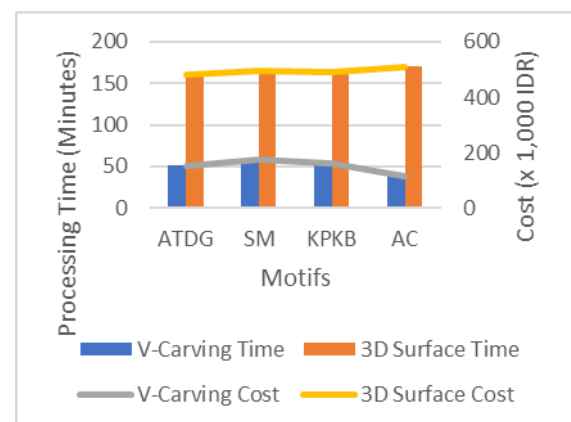


Figure 6. Comparative Production Cost and Time by CNC Method

Figure 6 shows that the reduction in machining time achieved by V-Carving translated directly into lower production costs, with savings reaching approximately 43% compared with manual carving. In contrast, 3D Surface machining generally required longer machining times and consequently higher production costs. Although economically less attractive for routine production, this method remains appropriate for manufacturing highly complex relief geometries where faithful reproduction of intricate surfaces is prioritized over production efficiency. Consequently, the productivity advantage of CNC technology is concentrated in repetitive geometric operations rather than artistic detailing. This stage-dependent performance demonstrates that the engineering suitability of CNC machining varies according to the functional characteristics of each production stage.

The Central Tension: Validating the Artisan Perspective on Quality

Despite efficiency gains, the technical investigation validated artisans' qualitative concerns regarding quality. Hand-carved pieces consistently achieved finer detail resolution (approximately 1 mm) and superior surface finish, free from the tooling marks, fibre pull-out, or burning sometimes present on CNC-produced parts. As illustrated in Figure 7, the constraints of tool geometry limited CNC resolution to 2–3 mm.

The Path Forward: An Operational Socio-Technical Hybrid Model

The social and technical findings converge to support an operational hybrid manufacturing model that balances engineering efficiency with cultural preservation.

This evidence confirms that artisan resistance is not merely ideological but also technical and artistic. The 'soul' of the craft appears intrinsically linked to the subtle imperfections and nuances of hand-made work. The question, therefore, is not whether CNC can reproduce a motif, but whether it can do so without stripping away the cultural and artistic essence that defines the product's value.

Rather than advocating full automation, the proposed model allocates each production stage to the manufacturing approach that best matches its technical and artistic requirements. As illustrated in Figure 8, the model translates the empirical findings into a practical workflow that can assist artisans and small cultural manufacturing enterprises in selecting appropriate production strategies while preserving the authenticity of Minangkabau wood carving.

The model consists of two complementary components. The first comprises socio-technical enablers, including training and capacity building, financial mechanisms, and cultural authenticity. These elements create the institutional and social conditions necessary for successful technology adoption. The second component is the operational production workflow, which guides the sequence of manufacturing activities from digital design to final inspection.

Within the operational workflow, CAD/CAM technology is first employed to generate digital design data and prepare machining operations. Based on the geometric characteristics of the carving, repetitive base-shaping operations are allocated to CNC V-Carving, whereas relief detailing and finishing remain manual processes.

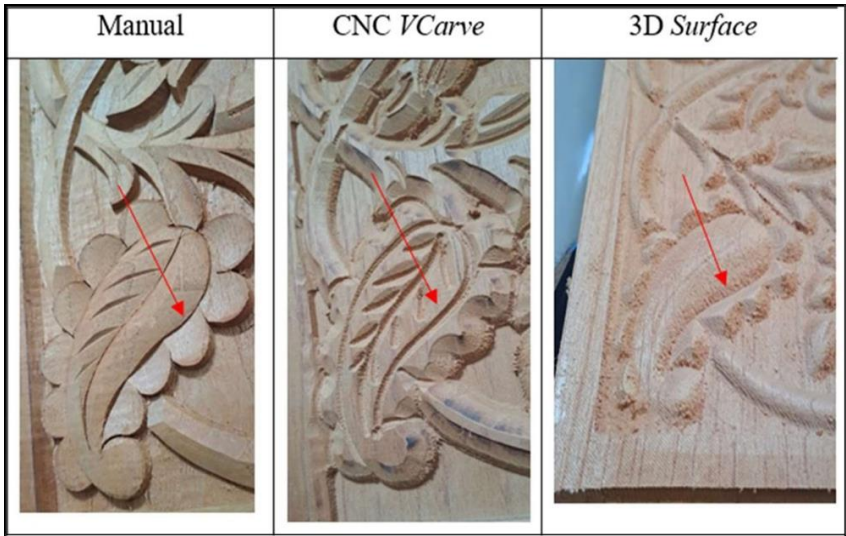


Figure 7. Comparison of Detail Resolution and Surface Finish

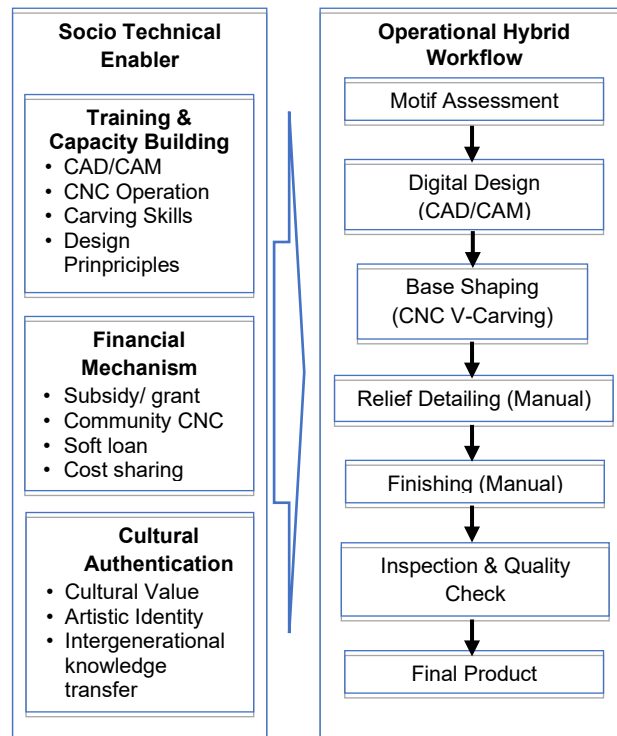


Figure 8. Operational Hybrid Manufacturing Model for Minangkabau Wood Carving

This allocation reflects the experimental findings that CNC provides its greatest productivity advantage during repetitive geometric machining, while manual craftsmanship remains essential for preserving fine detail, artistic expression, and cultural authenticity.

Beyond improving manufacturing efficiency, the model also supports long-term knowledge preservation. By digitizing the geometric foundation of traditional motifs into reusable CAD/CAM files while retaining manual craftsmanship for artistic refinement, the model enables systematic documentation of carving knowledge without replacing the cultural role of master artisans. This dual function strengthens both production capability and intergenerational knowledge transfer, thereby contributing to the long-term sustainability of Minangkabau wood carving.

Implementation Consideration: A Systems Thinking Approach

Although the proposed operational model provides a practical production workflow, its successful implementation depends on coordinated institutional and technical support. Training programs should integrate CAD/CAM operation with traditional artistic knowledge to ensure that digital competencies complement rather than replace craftsmanship. Financial support mechanisms, including shared CNC

facilities, government incentives, or microcredit schemes, are equally important for reducing the economic barriers faced by small cultural enterprises. From an engineering perspective, continued optimization of machining parameters for local wood species is required to minimize tool wear, improve surface quality, and increase artisan confidence in CNC-assisted production.

Theoretical Contribution: Extending Technology Adoption Models

This study supports extending TAM with the Cultural Compatibility construct, demonstrating that Perceived Usefulness is a function of both technical performance and cultural alignment. Furthermore, it operationalises the core STS principle that optimal outcomes arise from the joint optimization of social and technical subsystems. The operational hybrid manufacturing model serves as an interface between the social subsystem (artisan values and skills) and the technical subsystem (CNC capabilities).

Ultimately, this research demonstrates that the digital practice of Minangkabau wood carving need not succumb to a simplistic technology-versus-tradition dichotomy. The evidence suggests a viable third way: a hybrid model that is both technically efficient and culturally sustainable. By strategically integrating digital tools with the irreplaceable artistic judgment of skilled artisans, this path offers a template for

revitalising traditional crafts in the digital age, ensuring their relevance and vitality for the future.

CONCLUSION

This research demonstrates that digital transformation in Minangkabau wood carving offers substantial benefits, yet these advantages are contingent upon addressing concomitant socio-cultural challenges. Technically, CNC, particularly V-carving, significantly enhances efficiency, reducing processing time by 66–82% and production costs by up to 43%. However, hand-carving remains superior in surface quality, detail preservation, and perceived cultural authenticity. Socially, artisans strongly resisted full CNC automation but were conditionally open to hybrid models, indicating a pathway that protects the craft's symbolic and identity-related knowledge.

To harmonise these findings, we propose a Hybrid Socio-Technical Framework for sustainable transformation. In this model, CNC is deployed for base shaping (leveraging its efficiency and scalability), while manual craftsmanship governs artistic refinement and elaboration (ensuring cultural fidelity). The findings therefore, provide empirical support for stage-based process allocation as a viable design principle for hybrid heritage-manufacturing systems. This is not a middle ground but a joint optimization, harnessing the respective strengths of digital and manual work within a balanced socio-technical system.

The study contributes to technology adoption models by highlighting cultural compatibility as a critical construct directly influencing perceived usefulness in heritage contexts. It also underscores the value of a socio-technical lens for analysing digital transformation in cultural crafts, bridging technical performance studies and socio-cultural acceptance research.

Beyond this specific case, the proposed hybrid socio-technical model shows potential for generalization to other cultural heritage crafts grappling with similar tensions between efficiency and cultural identity. For crafts like batik, Jepara woodcarving, or traditional weaving, digital technology could support repetitive preparatory tasks (e.g., pattern creation, material roughing) while keeping core creative practices human-centered. Successful transfer depends not on the technology itself, but on its contextual adaptation to local cultural values, skill sets, and production logics. Thus, hybrid manufacturing should be viewed as a sociotechnical design challenge rather than a fixed technical configuration. By emphasizing cultural compatibility and artisan agency, this framework provides a valuable

blueprint for other heritage crafts seeking to navigate digital transformation in a way that ensures their meaningful continuity.

Practical Implications

- **Artisans and Cooperatives:** The hybrid model offers an operational structure that balances efficiency with cultural legitimacy, enabling market competitiveness without sacrificing identity.
- **Policymakers:** Findings underscore the need for targeted subsidies to lower entry barriers and for integrated training programs that combine technical (CAD/CAM) and traditional artistic instruction.
- **Cultural Institutions:** This approach establishes a preservation method where motifs are digitally archived (as CAD files), ensuring both the scalability of the practice and the safeguarding of authentic design knowledge.

Limitations and Future Research

While enriching our understanding, this study has limitations. The sample size was small (N=17 master carvers), and only four motifs were tested. Although purposive sampling yielded deep insights, the findings are not statistically generalizable to all Minangkabau woodcarvers or designs. The proposed framework is thus a guiding proposition rather than a definitive conclusion.

Future research should focus on three key directions. First, longitudinal pilot implementation studies are needed to evaluate the practical feasibility of the hybrid workflow in real production environments, including its effects on productivity, skill transfer, artisan regeneration, and long-term cultural preservation. Such studies would provide stronger evidence regarding the sustainability of the proposed socio-technical model.

Second, further technical investigations should optimize CNC machining parameters and manufacturing quality. Future work may examine the effects of spindle speed, feed rate, cutting strategy, and tool geometry on machining performance, surface quality, dimensional accuracy, and defect formation across different local wood species. This would strengthen the engineering basis for hybrid production systems and improve artisan confidence in digital technologies.

Third, future studies should investigate the economic scalability and broader applicability of the hybrid model across different heritage craft sectors and production contexts. Particular attention should be given to production costs,

market acceptance, economic viability, and adoption dynamics in small-batch manufacturing environments. Such research would help determine the conditions under which hybrid manufacturing can contribute simultaneously to cultural sustainability and economic resilience.

Addressing these directions will support the transition of the proposed framework from a conceptual model toward a validated socio-technical strategy for the sustainable digital transformation of cultural heritage crafts.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized DeepSeek and ChatGPT to assist in polishing the English language and improving the academic tone of the manuscript. After utilizing this tool/service, the author(s) conducted a comprehensive review and made necessary edits to the content, thereby assuming full responsibility for the final version of the published article.

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