Transforming Digital Archives of Cultural Artifacts into Physical Assembly Models as a Participatory Medium for Preservation

Abstract
Millions of digitized cultural artifacts remain dormant in heritage archives long after their initial documentation. This paper presents an exploratory post-digitization design framework that transforms existing 3D-scanned artifacts into participatory reconstruction experiences, where physical assembly functions as a material entry point for developing awareness, curiosity, and personal connection with cultural heritage. Applied to four sacred Indonesian artifacts, Barong Bali, Patong Dayak, Hampatong Biji, and Patong Laki Asmat, the framework segments each artifact into 11–14 interlocking parts, supported by augmented reality guidance and printed instructions. The design and evaluation process also surfaced several emergent considerations, including the role of recognition anchors and guidance preferences during assembly. A user study with 24 Indonesian participants revealed that assembly difficulty varied meaningfully across artifacts, with structural characteristics becoming perceptible through the reconstruction process in a way that screen-based viewing alone does not make apparent. Participants rated the experience as actively involving and culturally meaningful, with all 24 recommending it to others. These findings suggest that physical reconstruction extends the capacity of digital archives beyond representation, not by replacing the archive, but by giving it a form that demands engagement. For institutions holding underused 3D heritage collections, this framework offers a concrete and accessible path toward participatory cultural experience.

Keywords: digital heritage, participatory archives, tangible interaction

1 Introduction

Digital technologies have become an important tool for documenting and preserving cultural heritage. Advances in 3D scanning and photogrammetry enable detailed geometric and visual information from physical artifacts to be captured and archived as detailed digital models [1]. These digital representations allow artifacts to be studied, shared, and exhibited without requiring direct physical interaction with fragile objects.

Many digital heritage projects continue to emphasize accurate representation over experiential engagement. Digitized artifacts are commonly accessed through screen-based platforms such as virtual museums, online databases, or visualization tools, where users are positioned primarily as viewers of cultural content rather than active participants. Research in human-computer interaction suggests that interactive and embodied engagement can support deeper understanding by allowing users to actively explore the structure and meaning of cultural objects [2] [3].

Efforts to move beyond this representational model already exist. Projects such as the Hiroshima Archive [4] have demonstrated that digital archives can function not only as repositories of recorded information but also as systems that re-activate memory, testimony, and spatial experience, allowing users to navigate survivor accounts layered onto historical maps and reconstruct cultural narratives through digital interaction. These works reveal that the role of an archive is not limited to documentation but includes the capacity to evoke and re-experience cultural knowledge. However, most existing archive activation approaches remain screen-based or spatially navigable, positioning users as witnesses or explorers of reconstructed content. What remains largely unexplored is a form of activation that requires users to physically reconstruct the artifact itself, where the act of reassembly, not navigation or observation, becomes the primary mode of cultural engagement. When a user physically reassembles a sacred artifact piece by piece, they are not witnessing a cultural narrative, they are enacting one. The structural logic, symbolic features, and material form of the artifact become directly felt through the hands, offering a form of engagement that screen-based archive activation, however experiential, cannot fully replicate.

This research explores a design approach that transforms 3D-scanned Indonesian cultural artifacts into participatory reconstruction experiences, where physical assembly serves as a material entry point for engaging with cultural heritage. The artifacts Barong Bali, Patong Dayak, Hampatong Biji, and Patong Laki Asmat as shown in figure 1 are sacred figurative wooden objects from distinct cultures across different islands of Indonesia. Rather than reproducing digital models as static replicas, each artifact is segmented into eleven to fourteen components that users reconstruct through a puzzle-like assembly process. Because these objects are sacred and carry symbolic significance, segmentation boundaries are treated as careful design decisions rather than technical operations, preserving visually significant features such as faces and ritual marks as recognition anchors that support orientation and progress during reconstruction. Augmented reality guidance and printed manual supports the assembly process, connecting digital information with physical interaction and extending digital archives beyond screen-based representation toward participatory systems of exploration and interpretation. In our user study, participants found the assembly process more challenging than expected, and through that challenge, they discovered aspects of the artifacts that screen-based viewing cannot.

Figure 1 The four Indonesian sacred artifacts used in this study: Barong Bali, Hampatong Biji, Patong Dayak, and Patong Laki Asmat.

1.1 Research Aim

1. Explore a design framework for transforming existing 3D-scanned cultural artifacts into assembly-based physical experiences.
2. Explore how hands-on reconstruction can extend the role of cultural archives from representation toward participatory engagement.

2 Related Works

2.1 Digital heritage activation

The use of 3D scanning and photogrammetry in cultural heritage has grown significantly over the past two decades. Researchers have shown that these technologies can capture accurate geometric and visual data from physical artifacts, creating digital records that support conservation, research, and remote access [5] [6]. Large-scale documentation projects have demonstrated how digital archives can preserve heritage that is at risk from environmental threats, conflict, or physical deterioration [7]. However, most of these efforts focus on producing accurate representations rather than designing for engagement. Once a digitization project ends, its outputs are typically stored in databases and accessed through passive viewing interfaces such as virtual museums or online repositories [8]. The archived models remain available but largely inactive, accessible to look at, but not to interact with in any meaningful physical sense.

Some projects have moved beyond this representational model by treating archives as systems for re-activating cultural experience. The Hiroshima Archive [4] demonstrates how digital archives can layer survivor testimonies, photographs, and spatial data onto historical maps, allowing users to navigate and reconstruct cultural memory through digital interaction. Such projects establish that archives can function as platforms for cultural re-experience rather than static records. However, these experiential archives operate primarily through screen-based navigation and storytelling. The transformation of archived digital artifacts into physical, assemblable objects, where users must reconstruct the cultural form with their hands, represents a distinct and largely unexplored form of archive activation.

2.2 Tangible and embodied interaction in heritage

A growing body of research in human-computer interaction argues that physical engagement with objects supports deeper understanding than screen-based viewing alone. Dourish [2] established that meaning emerges through physical interaction with the world, not just through observation. In museum and heritage contexts, tangible interaction has been explored as a way to reconnect visitors with the material qualities of objects that are normally behind glass or restricted from handling [3]. Studies show that when people can manipulate physical representations of artifacts, turning them, feeling their weight, exploring their structure, they engage differently than when viewing the same objects on a screen [9]. Hornecker and Ciolfi [10] provide a comprehensive review of two decades of tangible interaction research in museums, showing that physical engagement consistently supports richer and more memorable experiences. Despite this, most heritage systems still treat digital artifacts as informational overlays rather than objects that can be physically reconstructed or explored.

2.3 Assembly, model-making, and material engagement

Tangible interaction research explains why physical manipulation matters, but it does not fully explain what changes when a user must *construct* an object rather than simply handle a finished one. Work on Japanese model-kit culture offers one way into this distinction. Steinberg's study of character merchandise and build-it-yourself kits shows that these objects function as material entry points into media franchises: owning and assembling a kit lets a person participate in a fictional world rather than only view it from outside [11]. Sacred cultural artifacts carry a comparable structure, they encode symbolic worlds, religious, ancestral, ritual, that a general audience does not necessarily understand on sight. We suggest assembly may work in an analogous way here, offering a physical route into a symbolic system that is entered by building rather than by reading or watching.

Constructionist learning theory offers a related but distinct explanation, grounded in cognition rather than media culture. Papert argued that people build a stronger internal understanding of a concept when they are actively constructing an external artifact, rather than only receiving information about it [12]. Applied here, assembling a segmented sacred figure is not simply reproducing a known form. It is a process in which the user encounters the artifact's structure one part at a time, and through that process, engages in a form of active meaning-making about how the object is put together.

Hornecker and Buur's framework on tangible interaction adds a further distinction relevant to this study [3]. Their account of physical space and manipulation largely concerns how people interact with objects that already exist in complete form. Assembly-based interaction differs: it requires users to work out how parts relate to one another, how they orient, and how they connect, before the object exists as a whole. This distinction supports our framing in Section 5.1, that assembly difficulty is not incidental to the experience but a direct consequence of asking users to reconstruct structural relationships rather than observe a finished one.

3 Design Framework

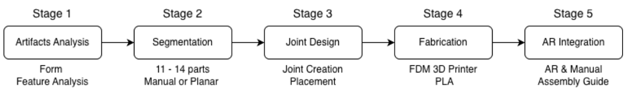

Figure 2 Post-digitization transformation pipeline applied to Indonesian sacred artifacts.

This study follows a design and evaluation approach. We developed a framework for transforming 3D-scanned cultural artifacts into assembly-based physical experiences, then evaluated the framework through a user study with 24 Indonesian participants. The framework consists of five stages applied sequentially to each artifact: artifact analysis, segmentation, joint design, fabrication, and AR integration as shown in figure 2.

3.1 Starting from existing archives

The four artifacts used were 3D-scanned during earlier fieldwork and stored as digital models. This research reused those existing files as its primary input, without requiring new scanning. This reflects a broader opportunity in heritage work: many institutions hold large collections of 3D-scanned artifacts that remain inactive after the initial documentation project ends. By designing from archived data, this framework proposes a post-digitization practice, a way to activate dormant digital heritage assets into participatory physical experiences.

3.2 Transformation pipeline

1. Artifact analysis: Each digital model was examined to understand its overall form, identify plausible transition points between body regions suitable for reconstruction, and locate visually significant features, such as faces, ritual marks, and symmetrical elements, that could serve as recognition anchors during reconstruction and should therefore remain intact within a single part. For these figurative sacred objects, significant features include faces, important sign, ritual markings, hand gestures, and posture-defining elements. This analysis was conducted through close examination of the digital model alongside reference study of each artifact's cultural background.
2. Reconstruction oriented segmentation: Each artifact was divided into 11-14 parts. Part count was set at 11-14 to balance accessibility for general museum visitors with sufficient complexity to make the assembly experience meaningful. Boundaries were placed at structurally logical transition, between limbs and torso, between body regions, genitals, important marks, and deliberately avoided cutting through symbolically significant features. This was treated as a design decision rather than a geometric or technical operation. The purpose of segmentation was not to recover an original physical structure of the artifact, since these wooden artifacts were originally created as continuous carved objects. Instead, segmentation was introduced as a design layer that transforms a preserved object into a reconstructable experience. The goal was to create meaningful moments of observation, comparison, and interpretation during assembly.

   Certain visual features were kept intact within a single part rather than split across segmentation boundaries, since these features function as recognition anchors during assembly. A face, for instance, helps a participant judge orientation and recognize how close the assembly is to completion. Ornamental details encourage closer attention to the artifact's surface as parts are handled and compared. Symmetrical elements, such as paired limbs or matched carvings, invite participants to compare parts directly against one another, supporting careful observation rather than guesswork.

   Each artifact presented different challenges as shown in table 1: the Barong Bali required careful segmentation around its wide wings; the Patong Dayak had ambiguous limb-body transitions; the Hampatong Biji had ritual carvings distributed across the body surface; and the Patong Laki Asmat required careful segmentation due to its thin-shaped body. The method used for segmentation is Boolean using planar, manual shaped hard surface geometry, and organic geometry.

Table 1 Summary of segmentation decisions across the four artifacts

Artifacts	Parts	Key Segmentation
Barong Bali	13	Head, wing, necklace, body feature
Hampatong Biji	13	Ritual carvings, symmetrical
Patong Dayak	11	Limb-body transition, head
Patong Laki Asmat	14	Thin shaped leg and hand, earrings, neck

3. Joint design: Joint geometry was refined through fabrication trials prior to the study, an initial box shaped joint form was replaced with a rounded cylinder boolean, which improved assembly tolerance and print reliability. Placement, joint count, and orientation varied per artifact depending on segmentation, connection geometry, and the expected direction of assembly.
4. Fabrication: As shown in figure 3, all parts were 3D printed using FDM printing using PLA material and test-assembled before finalizing each set.
5. AR guide & Printed Instruction: An augmented reality layer was developed to guide assembly. When viewed through a mobile device, the AR system displays the original scanned artifacts with color. Figure 4 shown the AR cards sample, marker visual, and example AR scan view. Printed instruction sheets were also prepared as an alternative guidance method as shown in Figure 5.

Figure 3 Artifact exploded view of the four assembly models showing segmented parts and joints placement.

Figure 4 AR card sample, marker visual, & AR scan view.

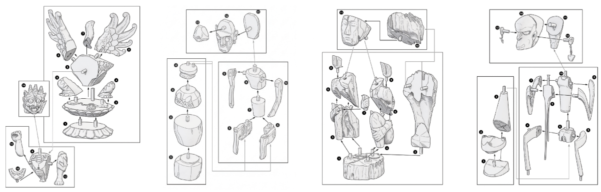

Figure 5 Printed instruction with step-by-step assembly.

3.3 Tools and Technologies

The segmentation and joint placement were designed in Autodesk Maya, where the rounded cylinder joint geometry was positioned at each connection point. Boolean operations were executed in ZBrush to cut joint cavities into each part, and organic slicing was also handled in ZBrush to follow the natural surface curvature of each artifacts. The parts were fabricated using a Bambu Lab H2D FDM printer with standard grey eSUN PLA filament at approximately one quarter to one half of the original artifact's scale. The AR guidance layer was built in WebAR Studio using image markers created in Procreate. This can be accessed through a standard mobile browser, so no dedicated hardware or app installation is required. Exploded views were then rendered for documentation and study purposes.

4 User Study

4.1 Participants

Twenty-four participants took part in the study, all of whom were Indonesian nationals who were either studying or working. They came from different islands and cultural backgrounds across Indonesia, so while they shared a nationality, they were not necessarily familiar with all four artifacts used in the study. This profile represents a realistic approximation of an educated, general museum visitor: someone with cultural awareness, but not necessarily specialist knowledge of the origin of each artifact. Each participant was assigned one artifact and completed the assembly task individually.

4.2 Procedure

Each session followed the same structure. Participants first completed a short pre-study questionnaire measuring their self-reported familiarity with the assigned artifact and its cultural context. They were then given the historical context and disassembled printed parts and asked to reconstruct the artifact. Two guidance resources were available throughout: an AR application viewable through a mobile device, and a printed instruction sheet. Participants could use either resource freely, in any order, or not at all. Sessions were observed and timed from the moment the participant began assembly to completion or voluntary stopping. Immediately after the task, participants completed a post-study questionnaire and a short interview. Figure 6 shows examples of product packaging for the assemble-based 3D printed artifacts.

Figure 6 Product packaging sample.

4.3 Data collection

Assembly time was recorded for each session from start to completion. Each participant's artifact selection and guidance preference, AR application or printed instruction sheet were noted. Following the assembly task, participants completed a post-study Likert-scale questionnaire covering perceived difficulty, engagement, and their sense of cultural learning through the experience.

5 Findings

5.1 Assembly difficulty varies by artifact

All 24 participants completed the assembly task, with six assigned to each artifact. Participants represented a diverse range of ages and backgrounds, including younger participants, students, and older adults, reflecting varied levels of familiarity with cultural heritage. The majority (15 of 24) reported rarely visiting museums, and four had never visited at all, suggesting the assembly experience engaged audiences beyond typical museum visitor.

As shown in figure 7, assembly time varied noticeably across artifacts. All six participants assigned to Patong Dayak completed assembly within 0-5 minutes, making it the fastest artifact to reconstruct. Patong Laki Asmat was the most challenging, four of six participants required 6-10 minutes to complete it. Barong Bali and Hampatong Biji fell in between, with two of six participants each taking 6-10 minutes. Twenty-three of 24 participants reported that the assembly time felt comfortable, suggesting that difficulty did not translate into frustration. These patterns suggest that structural complexity varies meaningfully across artifacts, consistent with the segmentation challenges described in section 3.

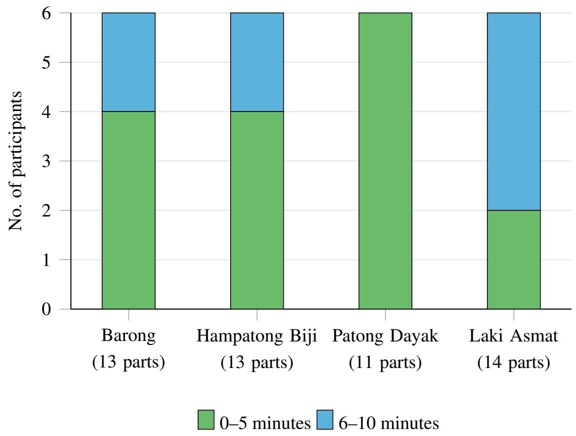

Figure 7 Assembly time distribution per artifact (n=6 per artifact). Higher proportion of 6–10 min indicates greater structural complexity.

5.2 Physical assembly as embodied engagement

Participants rated both the archive activation and embodied understanding constructs highly. As shown in figure 8, the archive activation construct (Section 2) achieved a mean score of 4.63 out of 5, with the item "this experience feels different from viewing a digital archive on screen" receiving the highest score in the construct (M = 4.83). The embodied understanding construct (Section 3) scored similarly (M = 4.61), with "assembling the model makes the artifact feel more real" rated highest (M = 4.79). Together these results suggest that participants perceived physical reconstruction as a qualitatively different form of engagement than screen-based viewing. Participant responses reinforced this pattern, one noted that assembly allowed them to "understand the anatomical structure of the artifact more deeply" while another described how "physical interaction makes you more connected to the artifact".

5.3 Cultural meaning-making and guidance preference

Participants reported a strong sense of cultural meaning and preservation awareness following the assembly experience (M = 4.62). The two highest-scoring items were "I am interested in exploring other cultural archives in a similar way" and "this approach can help younger or non-expert audiences appreciate cultural heritage," both scoring M = 4.71. This suggests participants not only valued the experience personally but also recognized its broader potential for heritage engagement. All 24 participants indicated they would recommend the experience to others such as museum visitors.

Regarding guidance, 16 of 24 participants chose printed instructions and 8 chose AR inspection. Printed instructions were preferred across all four artifacts. Notably, AR guidance was least

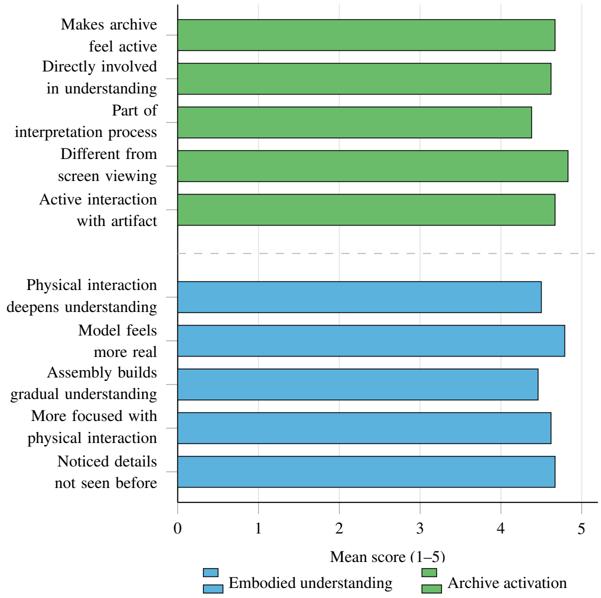

Figure 8 Mean Likert scores for archive activation and embodied understanding constructs (scale 1–5, n=24).

used among participants assigned to Patong Laki Asmat (1 of 6), the artifact with the highest assembly difficulty, suggesting that participants managing complex tasks preferred the lower cognitive load of printed instructions. Instruction usability was rated positively overall (M = 4.46), indicating that guidance method was not a significant barrier to the assembly experience. The full mean scores for the cultural meaning-making construct are shown in Table 2.

Table 2 Mean Likert scores: cultural meaning-making construct (scale 1–5, n=24).

Item	Mean
This experience makes the artifact feel more meaningful	4.58
I became more aware of the importance of cultural preservation	4.46
This artifact has stronger cultural value after this experience	4.67
I am interested in exploring other cultural archives this way	4.71
This approach can help younger or non-expert audiences	4.71
Construct mean	**4.62**

6 Discussion

Model-kit cultures offer a useful comparison for understanding what assembly may contribute beyond task completion. In Gunpla and similar hobbyist practices, building a physical model of a fictional machine is understood to create a personal attachment to that fictional world, an attachment that a person who only views the same character on screen does not develop in the same way [11]. Our findings suggest a parallel possibility for cultural heritage: reconstructing a sacred artifact by hand may shift it, for the participant, from a distant object of representation toward something personally handled and understood. This is consistent with the recognition-anchor design described in Section 3.2, where features such as faces, ornaments, and symmetrical elements were deliberately kept intact to give participants moments of observation and comparison throughout the process, not only at completion.

The findings from this study suggest that transforming digitized cultural artifacts into assembly-based physical models creates a form of engagement that participants perceived as distinct from screen-based heritage access. Participants perceived the experience as actively involving, culturally meaningful, and distinct from passive digital viewing across all four artifacts. These results held consistently regardless of educational background or prior museum experience. The fact that most participants rarely or never visited museums yet reported high levels of cultural engagement through the assembly process points to a meaningful design opportunity: participatory physical experiences may reach audiences that traditional heritage formats do not.

The assembly time data offers one of the clearest illustrations of this pattern. The difference in assembly time between Patong Dayak, where all six participants finished in under five minutes, and Patong Laki Asmat, where four of six participants took six to ten minutes, was not simply a function of part count. Both artifacts have a comparable number of parts, yet their structural complexity differs significantly. The symmetrical proportions and elongated form of the Patong Laki Asmat artifact appear to involve a spatial logic that becomes perceptible only when reconstructing it piece by piece. Screen-based viewing does not make this structural complexity as apparent. Assembly does not merely display this complexity; it forces the user to confront it directly through their hands. The fact that 23 out of 24 participants found the time comfortable suggests that this confrontation was productive rather than discouraging.

The sacred nature of the artifacts shaped the segmentation process, though not as an attempt to recover or preserve an original structure. Because faces, ritual markings, and posture-defining elements were treated as no-cut zones, these features remained intact as recognition anchors, points where participants could judge orientation, notice detail, and register progress during assembly. Participants consistently rated the cultural value of the artifacts highly after assembly. The meaning-making construct scored M = 4.62, with cultural value and interest in further exploration being among the highest-rated items. This suggests that treating sacred features as anchors rather than divisible geometry may be a design consideration worth further investigation, rather than merely a constraint to manage.

The finding regarding guidance preference deserves honest reflection. Participants preferred printed instructions to AR for all four artifacts, with the strongest preference for the most difficult artifact. One interpretation is that, as implemented in this study, AR guidance added cognitive load precisely when participants needed the least friction: when managing a structurally complex assembly. A further possibility is that printed instructions preserved a degree of uncertainty that AR's more direct visual guidance removed. Unlike efficiency-oriented assembly tasks, where ambiguity is simply a cost to minimize, cultural reconstruction may benefit from moments of uncertainty that slow participants down and encourage closer observation of the artifact's form. Under this reading, the value of a guidance system in this context is not only how precisely it directs assembly, but how much space it leaves for the participant to notice and interpret on their own. This is not a failure of AR technology, but rather a design finding about where AR guidance is most useful. Future iterations might explore AR guidance that activates on demand rather than requiring active navigation or that provides spatial cues rather than sequential steps. The broader implication is that, in assembly-based heritage experiences, the guidance system is a design problem in its own right and not merely a support feature, one that must balance assistance against the discovery that comes from productive uncertainty.

Taken together, these findings support the idea that activating 3D scans after digitization, transforming them into hands-on, participatory experiences, creates a different kind of relationship between users and cultural heritage. The digital archive is neither replaced nor supplemented, but rather given a new form that demands active engagement. Where existing experiential archive systems evoke and re-experience cultural narratives through screen-based navigation, assembly-based physical reconstruction extends this capacity into the tangible domain, participants do not witness the artifact's cultural form but actively reconstitute it through their hands. For institutions holding large collections of 3D-scanned artifacts that have seen little use since their documentation, this represents a concrete and accessible direction for extending the value of existing digital assets.

7 Limitation

As an exploratory design study, this study has several limitations that should be considered when interpreting the findings, including a sample of 24 participants which, while sufficient for this design evaluation, limits the generalizability of the results. All participants were Indonesian nationals, which means the findings reflect engagement within a shared cultural context, it remains unclear how participants from outside Indonesia, or without any prior familiarity with Indonesian cultural forms, would experience the assembly process. Additionally, segmentation decisions were guided by formal design analysis and historical context from the collector rather than consultation with cultural practitioners or community representatives, which limits the claim that boundaries were placed with full cultural authority.

Future work should address these gaps in three directions. First, replicating the study with a larger and more culturally diverse sample would allow stronger claims about the framework's generalizability. Second, involving cultural practitioners in the segmentation process would strengthen the cultural sensitivity of the design decisions and open a more genuine dialogue between design research and heritage communities. Third, deploying the assembly models in an actual museum or community setting, rather than a controlled study session, would reveal how the experience performs in the context for which it was designed.

8 Conclusion

This paper demonstrates a post-digitization design framework that transforms 3D-scanned cultural artifacts into participatory reconstruction experiences, where assembly functions as a material entry point for developing awareness, curiosity, and personal connection with cultural heritage.

Addressing the first research aim, the framework's five-stage pipeline, artifact analysis, segmentation, joint design, fabrication, and AR integration, was successfully applied to four sacred Indonesian artifacts with differing forms and structural characteristics. This demonstrates that existing 3D-scanned archives, even when originally created for documentation rather than interaction, can be systematically transformed into physical, assembly-based experiences without requiring new scanning or fieldwork.

Addressing the second research aim, the user study with 24 Indonesian participants suggests that hands-on reconstruction can extend the role of cultural archives from representation toward participatory engagement. Participants rated the experience as actively involving and culturally meaningful, and all 24 recommended it to others. These results suggest that physical reconstruction offers a form of engagement with digitized heritage that is distinct from passive, screen-based viewing.

Beyond these two aims, the design and evaluation process surfaced several additional insights that were not the direct object of the study but emerged through it. First, assembly difficulty varied noticeably across artifacts, with structural characteristics becoming perceptible through the reconstruction process in a way that screen-based viewing did not reveal. Second, segmentation choices that kept visually and symbolically significant features, such as faces and ritual marks, intact as recognition anchors emerged as a design consideration that may support orientation, observation, and interpretation during assembly. Third, participants preferred printed instructions over AR guidance, particularly for the most difficult artifact, pointing to productive uncertainty as a possible factor in how guidance systems shape the assembly experience.

Together, these findings position this work as an exploratory design study rather than a confirmatory evaluation. As heritage institutions continue to accumulate 3D-scanned artifacts with limited post-digitization use, frameworks of this kind offer a concrete starting point for further investigating how activating dormant digital heritage assets can extend their value for broader audiences.

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