Integrating digital technologies for values-driven adaptive reuse of built heritage

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Imagine what built heritage could look like if digital technologies were used to even a small fraction of their potential…

Abstract

This research investigates the role of digital technologies in improving the adaptive reuse of built heritage through more informed, values-driven, and sustainable decision making. It introduces the Digital Adaptive Reuse of Built Heritage (DARBH) framework, developed to assist practitioners in selecting and implementing appropriate digital technologies throughout the different stages of adaptive reuse projects. The framework is structured around five functional pillars: Capture, Create, Conserve, Communicate, and Control, which together articulate how digital technologies contribute to the understanding, transformation, and management of heritage assets.

A mixed-methods research design was used to construct and validate the framework. The study began with a systematic literature review to identify trends, gaps, and challenges in the application of digital technologies within heritage reuse. This was followed by an expert workshop involving professionals from architecture, engineering, and digital innovation sectors, complemented by a case study of the Paradiso music venue in Amsterdam. Insights from these activities were summarized and examined through a SWOT analysis to assess the feasibility, barriers, and enablers of technology adoption across various project contexts. The findings indicate that accessible technologies, such as 3D scanning, photogrammetry, environmental sensors, and collaborative data environments, are gradually integrated into practice, mainly due to their ease of use and clear value delivery. On the other hand, more complex systems, including digital twins and broad HBIM models, face significant barriers related to cost, required expertise, interoperability, and unclear governance structures. The DARBH framework responds to these challenges by providing a structured, step-by-step methodology that links technological functions with project objectives, heritage values, and stakeholder engagement processes.

Overall, this research provides a theoretical and practical roadmap for integrating digital technologies into the adaptive reuse of built heritage. It positions digital technologies not only as a technical solution but as a strategic enabler that supports decision making based on evidence, facilitates value alignment, and improves the long term sustainability of heritage interventions across cultural, social, and environmental dimensions.

Keywords: digital technologies, built heritage, adaptive reuse, heritage values, stakeholders engagement

TABLE OF CONTENTS

Contents

AI SATEMENT

Generative AI tools were used in a supporting role during this research: Canva AI and Napkin.ai assisted in the design and refinement of some graphics, while proprietary AI tools, ChatGPT and Google Gemini were used to support the searching and screening of academic publications. Interview recordings and workshop transcripts were read in full by the researcher and then condensed into short summaries using proprietary AI tools to facilitate recall of who had said what, and both ChatGPT and proprietary AI were used to revise wording and improve readability. All AI-generated outputs were reviewed, amended and approved by the author, who retains full responsibility for the accuracy and interpretation of the material presented.

1. INTRODUCTION

1.1. THE EVOLVING LANDSCAPE OF BUILT HERITAGE CONSERVATION

We live in a time when climate change continues to be contested (Hulme, 2010), while countries and cities are becoming more divided (Chou, 2024) and national identities are often defined by fear (Rokem & Gentile, 2024). In this context, protecting built heritage can enable people not only to build more sustainable cities (Rostami et al., 2014) but also to reconnect with their surroundings, shared values and one another (Labadi, 2013; Pereira Roders, 2007). Built heritage reveals the complex history and cultural significance conveyed by society to everyday spaces (Assmann, 2011; Australia ICOMOS, 2013), carrying with them the values, skills, and materials of past generations. As such, they can be powerful tools for shaping more liveable and sustainable cities today (ICOMOS, 2011; Pereira Roders & Oers, 2011).

Traditional preservation approaches and their limitations

For much of the 20th century, the protection of built heritage focused on the conservation or restoration of individual buildings and urban areas, following an object-based approach (Jokilehto, 1998; Whitehand & Gu, 2010). This method mostly emphasized the tangible aspects of built heritage, its physical integrity and authenticity. While this approach successfully preserved numerous historic buildings and sites (Liang et al., 2023), it often neglected the intangible dimensions of heritage, as well as the broader spatial and social processes that shaped these places (Veldpaus et al., 2013; Pereira Roders, 2007; Li, 2025). As a result, although buildings were preserved in the name of society, society itself came to view them as static entities, detached from everyday life and the ongoing transformations of urban environments (Ashworth, 2011; Bandarin & Oers, 2012).

This object-based approach resulted in issues such as musealization, gentrification, and domestic migration, as it prevented buildings and their surroundings from evolving and integrating organically (Pereira Roders, 2013; Nelle, 2009). Viewing built heritage as static and detached from its living context revealed that traditional methods were no longer suited to contemporary cities and changing social values (Labadi, 2013; Tarrafa Silva & Pereira Roders, 2012). This realization triggered a shift from managing built heritage itself to managing the cultural significance that society conveys to it (Pereira Roders, 2013). A new theoretical framework emerged, understanding built heritage as a diverse and continuously evolving social construct (Pereira Roders, 2018). This perspective requires a more democratic process involving multiple stakeholders working collectively to define what holds significance (Rosetti et al., 2020). However, participation alone is insufficient; this transformation also demanded new systems of governance and collaboration. Research such as that of Chen (2022) examines how these stakeholder-driven approaches can be implemented, particularly within complex urban regeneration processes, offering models for integrating heritage values directly into urban planning.

As cities continue to expand, buildings designated as cultural heritage play an important role in preserving collective memory while at the same time adapting to contemporary needs (Pintossi et al., 2021). Achieving this balance requires a proactive approach to heritage preservation (Goncalves et al., 2019), based on a deep understanding of its significance (Australia ICOMOS, 2013) and guided by adaptation practices that respect its core values (Jokilehto, 2006). To ensure that built heritage remains relevant in the future, this process must include all stakeholders (Pereira Roders, 2010;

Chen, 2022) and employ a wide range of knowledge and experience that extends beyond the traditional domains of architecture, engineering, and construction (Ratti, 2025).

The need for a new approach: focus on value

In the 21st century, emerging challenges such as climate change, fewer resource, and the growing number of empty buildings have exposed the limitations of approaches which focus on preservation (Azzopardi et al., 2023; Pintossi et al., 2021). Short-term, economically driven interventions fail to promote material reuse or the adaptive transformation of existing structures, leading to unnecessary waste and causing both social and environmental harm (Cetin et al., 2021; De Wolf et al., 2024). In response, efforts to address these issues led to a shift toward values-driven conservation, which integrates ecological, social, cultural and aesthetic priorities, among others, into the decision-making and management of built heritage (Ginzarly et al., 2019; Nyaupane, 2019). This approach recognizes that the cultural significance of built heritage emerges from dynamic value systems that evolve over time and differ across contexts (Mason, 2006; Azzopardi et al., 2023). These systems may include social, economic, political, historical, aesthetic, scientific, age-related, or ecological values, expressed through both tangible and intangible attributes (Tarrafa Silva & Pereira Roders, 2012; Li, 2025). Since these values are socially constructed and vary among communities, conservation becomes a continuous, adaptive process rather than a one-time intervention (Ceccarelli, 2017).

By recognizing heritage conservation as an ongoing process, values-driven approaches ensure that heritage management remains relevant and responsive to current day needs while also contributing to sustainable urban development (Azzopardi et al., 2023; Chen & Li, 2021). This principle is reflected in frameworks such as UNESCO's Historic Urban Landscape (HUL) approach, which connects heritage conservation with economic, social, and environmental planning at the urban scale (Ginzarly et al., 2019; UNESCO, 2011).

Technology has the potential to improve values-driven heritage interventions by making community values visible through improved data collection, mapping, and feedback tools. These innovations expand participation, allowing a broader range of voices to shape decisions, and promote transparency and traceability from value assessment to implementation. Historic urban environments are complex and need solutions that are integrated across different actor groups (Artopoulos et al., 2024), data-driven (Tsilimantou et al., 2020), and collaborative (Graham et al., 2018). Digital tools such as BIM, IoT sensors, cloud platforms, and digital twins enable the combination of data into interoperable repositories (Baharuddin et al., 2023; Chow & Fai, 2017). Such data-based infrastructures improve monitoring and coordination across disciplines by facilitating shared visuals, workflows, and insights among teams (Artopoulos et al., 2024; Mazzetto, 2024). They also help reduce redundant work and support more transparent decision making, which is evidence-based. (Graham et al., 2018; Dhanda et al., 2017). Moreover, digitalisation can advance circularity and adaptive reuse by recording material stocks and lifecycles, providing the foundation for actions that reduce waste and minimise environmental impact (Cetin, 2023; De Wolf et al., 2024; Aigwi et al., 2023).

1.2. PROBLEM DEFINITION

Although digital technologies have the potential to transform modern construction and renovation, their application in the adaptive reuse of built heritage remains limited. Currently, there is no systematic or widely adopted framework that integrates digital tools across all stages of the adaptive reuse process. Technologies such as HBIM, Digital Twins, AI, and IoT hold great promise for documentation, monitoring, collaboration, and analysis (Chen et al., 2023; Mazzetto, 2024; Crisan et al., 2025). However, they are often applied in isolation or restricted to early phases such as surveys or compliance assessments (Savitri & Amalia, 2024). As a result, most uses remain highly technical and narrow in scope, reducing their capacity to support the full adaptive reuse process. As a result, these tools rarely contribute to broader objectives such as stakeholder collaboration, sustainability, or the integration of cultural values (Plevoets & Van Cleempoel, 2019). Existing adaptive reuse frameworks also rarely illustrate the potential of digital tools or provide guidance on their use throughout all stages, from initial assessment to post-use evaluation (Cucco et al., 2023; Arfa et al., 2022). This lack of clarity leaves professionals in the architecture, engineering, and construction (AEC) industries without practical direction on how to implement these technologies effectively, thus limiting their contribution to achieving values-driven transformations of built heritage (Dastgerdi et al., 2024; Jadresin Milic et al., 2022; Noronha et al., 2024).

1.3. RESEARCH QUESTIONS

The main research question is:

How can digital technologies be effectively integrated into the adaptive reuse process of built heritage to support values-driven approaches?

Three key research sub-questions (RSQs) are designed to fill the research gaps and reach this aim.

RSQ1: How have digital technologies been systematically integrated into each step of the adaptive reuse process for built heritage?

This question explores how various technologies can be connected to each stage of the adaptive reuse process. It considers all phases, from assessment and design to implementation and monitoring, in order to address key challenges in the reuse of built heritage. Section 4.1 responds to this by developing a framework that maps technologies to the different stages of the process.

RSQ2: What are the main opportunities and challenges faced by practitioners when using digital technologies in the adaptive reuse of heritage?

This question examines how digital technologies both add value and create challenges within the adaptive reuse process of built heritage. It considers practitioner perspectives on data quality, skills and accessibility, costs and return on investment, cultural values, and governance. The aim is to identify the key enablers and barriers to using digital technologies more effectively. Sections 4.2 and 4.3 address this by presenting an overview of the main opportunities and challenges to inform decision-making.

RSQ3: How can a practical framework support the effective use of digital technologies to achieve values-driven outcomes in adaptive reuse?

This question further investigates the application of values-driven approaches in interventions involving built heritage. It integrates insights from previous chapters to develop a practical framework designed to help architects, engineers, constructors, and other professionals and researchers apply digital technologies more effectively throughout the reuse process. The ultimate goal is to support improved project outcomes. Section 4.4 introduces this framework.

1.4. RESEARCH AIM, OBJECTIVE, AND SCOPE

This study addresses the gap described in the problem definition by examining how digital technologies can support the adaptive reuse of built heritage. Its objective is to develop a structured and practical framework that enables the integration of digital technologies across all stages of the adaptive reuse process.

The research explores how these technologies can extend beyond basic documentation to assist with analysis, design, public participation, decision-making, and long term management. The aim is to improve values-driven outcomes, by promoting the more effective use of technology throughout project development. Using an analysis of previous adaptive reuse projects and a case study in Amsterdam, the research proposes a structured framework that links digital technologies to each stage of heritage transformation and connects their application to value creation.

It also responds to three key gaps in existing research:

1. The lack of integrated digital approaches connecting documentation, planning, monitoring, adaptation, and reuse.
2. Unequal access to digital skills and tools among heritage professionals.
3. Limited attention to how digital technologies can record and safeguard both tangible and intangible heritage values.

1.5. RESEARCH RELEVANCE

Academic relevance

This research makes several contributions to academic literature. First, it addresses a key gap in existing studies, which often focus on individual digital technologies or isolated stages of heritage reuse. Rather than treating digital tools as stand-alone solutions for documentation or visualisation, this study offers a broader, step-by-step framework that illustrates how different technologies can be applied across the entire reuse process.

Second, it advances the discussion on values-driven heritage conservation. While tangible and intangible values are increasingly recognised as central to understanding why places should be preserved, there remains a need to explore how these values can be integrated into the reuse process itself.

By connecting digital technologies with cultural, social, ecological, and economic values, this research demonstrates that technology can act as a driver, rather than only a tool, for achieving improved outcomes. Its emphasis on intangible heritage values, which are often overlooked in technically oriented studies, represents an important contribution that aligns with contemporary conservation frameworks such as the HUL approach.

Practical relevance

For professionals in architecture, engineering, construction, and urban planning, this research provides a clear and practical guide. The Digital Adaptive Reuse of Built Heritage (DARBH) framework offers a structured roadmap to help project teams understand and apply digital tools more effectively. It summarizes the main opportunities and challenges (through a SWOT analysis) associated with each technology, supporting professionals in selecting appropriate technologies, planning resources, and meeting design objectives.

The study also addresses real-world barriers to technology adoption, such as limited digital skills and unequal access. By introducing a clear and systematic structure, it helps heritage professionals move from ad hoc tool use toward a more coordinated, strategic, and efficient approach.

This method can lead to improved project outcomes, reduced costs, and stronger collaboration among diverse stakeholders, from property owners and policymakers to local communities. The Amsterdam case study demonstrates the framework in practice, ensuring that the findings are relevant and applicable to professionals working in real project contexts.

Societal relevance

In a world facing urgent issues like climate change and resource depletion, the preservation and reuse of existing buildings have become more crucial than ever. This research promotes adaptive reuse as a sustainable alternative to new construction and demonstrates how digital technologies can support the creation of more resilient and liveable cities.

The framework developed through this study also provides guidance for urban planners and policymakers, helping them design more sustainable and efficient development models through the effective use of digital technologies.

Beyond the environmental advantages, the research highlights the importance of community participation and the protection of intangible heritage values. This approach helps ensure that heritage remains an active and meaningful part of everyday life. By using digital technologies to promote broader engagement, the study encourages shared ownership and stronger connections between people and place, allowing heritage to play a fundamental role in shaping the cities of the future.

1.6. STRUCTURE OF THE THESIS

After introducing the current challenges and opportunities in heritage conservation, Chapter 2 presents the theoretical background of this study. It explains how values-driven heritage interventions have evolved and how adaptive reuse serves as a way to apply these principles in practice. It also examines the role of digital technologies in supporting and improving these interventions.

Chapter 3 describes the research methodology used in this thesis. It defines the literature review, the case study design, and the steps for operationalizing the research. The methods for collecting and analyzing data are detailed, as well as the ethical considerations followed throughout the process.

In Chapter 4, the results of the study are presented. This includes the proposed framework for Digital Adaptive Reuse of Heritage (DARBH), findings from the workshop and case validation, and an overview of the enabling digital technologies with their limitations. A complete list of technologies linked to each stage of the framework is also provided.

Finally, Chapter 5 discusses and concludes the research. It connects the results to the theoretical background, reflects on the findings, and highlights their relevance for both academic and professional practice. The chapter also presents recommendations for future research and practical implementation to support more values-driven and digitally informed heritage reuse.

2. THEORETICAL FRAMEWORK

2.1. VALUES-DRIVEN HERITAGE INTERVENTIONS

Today, the importance of heritage is understood primarily through its values, rather than its physical form. Its significance results from both tangible and intangible elements, such as traditions, skills, memories, languages, and shared meanings (Labadi, 2013; Liang et al., 2023; Azzopardi et al., 2023). Since these values are held by different groups and evolve over time, heritage is seen as dynamic rather than fixed within the object itself (Whitehand & Gu, 2010; Veldpaus et al., 2013). This shift has important practical implications. First, assessing heritage significance must include diverse community perspectives and take into account social, cultural, and spiritual contexts alongside physical condition (Tarrafa Silva & Pereira Roders, 2012; Chen & Li, 2021). Second, heritage management should be flexible and participatory, extending beyond expert-driven approaches and moving past an exclusive focus on physical aspects (Pereira Roders, 2007; Azzopardi et al., 2023).

A comparison between object-based and value-based approaches, along with their main outcomes and critiques, is presented in **Table 1** below.

Table 1. Summary of paradigms: core focus, approach, and outcomes or critique

Paradigm	*Core focus*	*Approach*	*Outcomes/Critiques*
Object-based preservation	Tangible structures, monuments, physical integrity, often as a whole (Pereira Roders, 2007; Mason, 2006; Whitehand & Gu, 2010; Labadi, 2013; Tarrafa Silva & Pereira Roders, 2012).	Static, often leading to musealization. Primarily expert-led assessment and management (Labadi, 2013 Azzopardi et al., 2023; Nelle, 2009; Pereira Roders, 2013).	Neglect of intangible dimensions, larger scales, and processes. Contributes to gentrification and domestic migration by depriving properties of development (Veldpaus et al., 2013; Pereira Roders, 2007; Tarrafa Silva & Pereira Roders, 2010).
Values-driven interventions	Dynamic cultural significance, including both tangible and intangible qualities, and a broad range of values including social, economic, political, historic, aesthetical, scientific, age, and ecological (Pereira Roders, 2007; Liang et al., 2023; Tarrafa Silva & Pereira Roders, 2012; Azzopardi et al., 2023; Nyaupane, 2019).	Dynamic, integrated with broader urban development goals; supports participatory and multi-stakeholder engagement (Bandarin & Oers, 2012; Ginzarly et al., 2019; Chen & Li, 2021. Spoormans et al., 2024).	Supports "lifespan consciousness," contributes to sustainable urban development, integrates circular economy principles, increases community well-being, and builds urban resilience (Pereira Roders, 2007; Azzopardi et al., 2023; Pintossi et al., 2021; De Wolf et al., 2024; Mocerino, 2024).

The HUL approach

The HUL approach, officially adopted by UNESCO in 2011, represents a significant shift in the understanding and practice of heritage conservation (Bandarin & Oers, 2012). It connects urban heritage conservation with broader social, cultural, economic, and environmental goals, while emphasising the importance of cultural diversity and local community values (Ginzarly et al., 2019; Pintossi et al., 2021). Rather than relying on traditional zoning methods that separate historic areas from the rest of the city, the HUL approach views heritage as an integral component of sustainable urban development rather than a constraint (Bandarin & Oers, 2012; Ginzarly et al., 2019). It recognises heritage as the product of the historical layering of cultural and natural values and attributes (Veldpaus et al., 2013), expanding the focus beyond the "historic centre" to include the broader urban context and its surroundings (Ginzarly et al., 2019; Veldpaus et al., 2013). The HUL framework operationalizes value-based principles at the scale of entire urban areas, establishing a clear connection between heritage conservation, sustainable development, and urban resilience (Ginzarly et al., 2019; Pintossi et al., 2021; Bandarin & Oers, 2012).

The role of participatory processes and stakeholder engagement in the shift towards values-driven interventions

Modern heritage management is becoming more dynamic and requires more bottom-up approaches rather than being only guided by expert-led assessments (Mason, 2006; Veldpaus et al., 2013; Bandarin & Oers, 2012). Building shared values for more effective heritage management depends on open participation from diverse stakeholders and citizens (Chen, 2018; Labadi, 2013; Chen & Li, 2021). Such involvement helps discover multiple perspectives on heritage, its meanings for different groups, and potential risks, while also supporting policy frameworks such as the Faro Convention (Azzopardi et al., 2023; Ginzarly et al., 2019; Labadi, 2013).

Spoormans et al. (2024) demonstrated the value of this approach by using a mobile application to engage citizens in identifying important tangible and intangible characteristics of residential areas. This process revealed shared features that had not been anticipated by the original designers (Spoormans et al., 2024). Beyond simply gathering opinions, participatory approaches, particularly those supported by digital technologies, can help uncover previously unrecognized heritage elements, address conflicts early, and identify common interests across different stakeholder groups (Spoormans et al., 2024; Chen et al., 2023).

2.2. ADAPTIVE REUSE AS A MANIFESTATION OF VALUES-DRIVEN INTERVENTIONS

Defining adaptive reuse of heritage and its strategic role

Adaptive Reuse (AR) refers to the planned transformation of an existing building for a new purpose that differs significantly from its original one, while retaining and managing its heritage values (Douglas, 2006; Arfa et al., 2022; Australia ICOMOS, 2013). As a conservation strategy, AR helps preserve the significance of heritage assets while increasing their functionality over time (Arfa et al., 2022; Australia ICOMOS, 2013). By extending the life cycle of existing structures, AR positions built heritage as a renewable resource within the urban landscape (Pintossi et al., 2021; Aigwi et al., 2023). This perspective aligns with circular economy principles, recognizing adaptive reuse as a vital step toward circular cities and sustainable urban development (Pintossi et al., 2021).

AR brings multiple environmental, social, and cultural benefits. Environmentally, it minimizes demolition and construction waste while maximizing the reuse of existing materials (Arfa et al., 2022). Socially and culturally, it sustains place identity and community continuity while allowing for new functions and activities (Plevoets & Van Cleempoel, 2019; Remoy, 2014; Arfa et al., 2020).

However, adaptive reuse is not a fixed or linear process (Arfa et al., 2022). It should be flexible and cyclical, incorporating feedback loops between planning, design, implementation, and long-term management (Cetin, 2023; Arfa et al., 2024). Reuse is an evolving practice shaped by changing values, needs, and urban conditions (Arfa et al., 2023; Remoy, 2014). Each project involves a wide range of participants—architects, engineers, owners, policymakers, and citizens—each bringing different goals and resources (Pintossi et al., 2023). Therefore, adaptive reuse projects should extend beyond simply assigning new functions to buildings; they should also reflect the broader cultural, ecological, and economic roles of heritage (Plevoets & Van Cleempoel, 2019; Pereira Roders, 2007; Cucco et al., 2023).

Challenges and solutions in adaptive reuse practices

The adaptive reuse of built heritage faces a range of interconnected challenges (Pintossi et al., 2021; Bandarin & van Oers, 2012; Ginzarly et al., 2019). These can be broadly grouped into five key areas: participation, capacity, regulation, finance, and knowledge (Pintossi et al., 2023; Arfa et al., 2022). Common issues include limited or absent stakeholder participation, insufficient practical guidance, a shortage of skilled professionals in both public and private sectors, overlapping strategies, and unclear long-term economic models (Bandarin & van Oers, 2012; Ginzarly et al., 2019; Arfa et al., 2022).

Financial barriers often delay or stop projects, creating dependency on external funding sources that can undermine long-term viability (Aigwi et al., 2023; Bianchi & De Medici, 2023). Funding shortages also accelerate physical deterioration, increase future restoration costs, and deepen other existing challenges (Pintossi et al., 2021). Knowledge gaps occur across building, city, and system levels, often taking the form of missing, fragmented, or inaccessible data, as well as weak mechanisms for data storage and sharing (Chen et al., 2023; Tsilimantou et al., 2020; Ni et al., 2024). Regulatory complexity adds another layer of difficulty, as conflicting policies and legal frameworks can delay coordinated action (Jokilehto, 1998; Tostoes, 2018; Lin et al., 2025). Addressing these challenges requires an integrated approach that connects governance, capacity building, stable funding, and shared data systems. Such an approach aligns with the principles of the HUL framework, as well as circular and digital built environment strategies (Pintossi et al., 2021; Bandarin & van Oers, 2012; Veldpaus et al., 2013).

2.3. THE ROLE OF DIGITAL TECHNOLOGIES IN THE ADAPTIVE REUSE PROCESS

Digital technologies are becoming increasingly important in the adaptive reuse of built heritage. Tools such as Building Information Modelling (BIM/HBIM), digital twins, virtual reality (VR), photogrammetry, 3D scanning, and artificial intelligence (AI) are introducing new methods for documenting, analyzing, managing, and conserving heritage assets. For instance, HBIM platforms have been used to integrate Earth observation data with non-destructive testing to analyze historic urban areas (Artopoulos et al., 2024). BIM workflows have supported the structural assessment and restoration of heritage bridges (Crisan et al., 2025) and improved safety planning in industrial heritage rehabilitation projects (Gurcanli et al., 2025). VR tools and digital kiosks improve public engagement by presenting conservation and rehabilitation work in accessible and interactive formats (Graham et al., 2018). Similarly, 3D scanning enables the creation of highly detailed digital models of heritage artefacts (Jesus et al., 2025), while AI applications are being developed to manage seismic risks and improve the energy efficiency of historic buildings (Cantagallo & Sangiorgio, 2025). Digital twins, such as the one implemented at the Republican

Museum in Brazil, facilitate predictive maintenance and real-time monitoring, showing the benefits of live data for heritage conservation (Noronha et al., 2024). Collectively, these technologies not only improve technical processes but also provide stronger platforms for data-driven and informed decision-making.

Current challenges in adoption

Despite growing interest, the use of digital technologies in heritage projects remains inconsistent. They are still mostly applied for documentation or visualisation purposes rather than being fully integrated into planning, management, or reuse strategies (Marzouk & Metawie, 2023). While studies such as those by Baharuddin et al. (2023) demonstrate the potential of digital technologies, their practical implementation in real-world contexts is still limited. Many heritage professionals face barriers such as restricted budgets, insufficient training, and unclear policy guidance (Jadresin Milic et al., 2022). Efforts to share data across different platforms, such as in the Sintra Chalet BIM case study (Machete et al., 2021), have discovered ongoing technical and compatibility challenges that hinder collaboration and information flow. Furthermore, many existing reuse frameworks overlook social and cultural dimensions, focusing primarily on structural integrity or environmental performance while neglecting broader human and cultural values (Bianchi & De Medici, 2023; Metawie & Marzouk, 2023).

3. RESEARCH METHODOLOGY

This chapter describes the research processes and methods that were used to achieve the research aims:

to create a practical framework that connects digital technologies to each stage of the adaptive reuse process for built heritage,

to find the main opportunities and challenges professionals face when using these technologies in a real case, the Paradiso project in Amsterdam, and

to see how the framework can be improved so that digital technologies act as value drivers in adaptive reuse.

The study is exploratory since there is little research on how digital technologies are fully integrated into the adaptive reuse of heritage. Most existing work is still either theoretical or focusing on very niche technology solutions. The research began deductively by identifying existing theories on the adaptive reuse process, heritage values, and enabling digital technologies to construct an initial framework. Based on the gathered theory, data was collected and analysed from an expert workshop and the real-life case of the adaptive reuse of the Paradiso in Amsterdam. Using a mixed-methods design involving a literature review (SCOPUS), an expert workshop, and a case study (with semi-structured expert interviews), the practical opportunities and barriers were identified. The research then became more inductive, drawing conclusions and critically discussing the workshop and case study results to refine the framework and answer the main research question: "How can digital technologies be effectively integrated into the adaptive reuse process of built heritage to support values-driven outcomes?"

This chapter is structured as follows: Section 3.1 explains how the literature was reviewed to create the first version of the framework and SWOT analysis. Section 3.2 describes the case study and explains why Paradiso was selected. Section 3.3 outlines how the research sub-questions were applied in practice. Section 3.4 describes the expert workshop and interviews as data collection methods. Section 3.5 explains how the data were analysed using thematic coding, SWOT integration, and synthesis. The chapter ends with a discussion of the ethical considerations of the research.

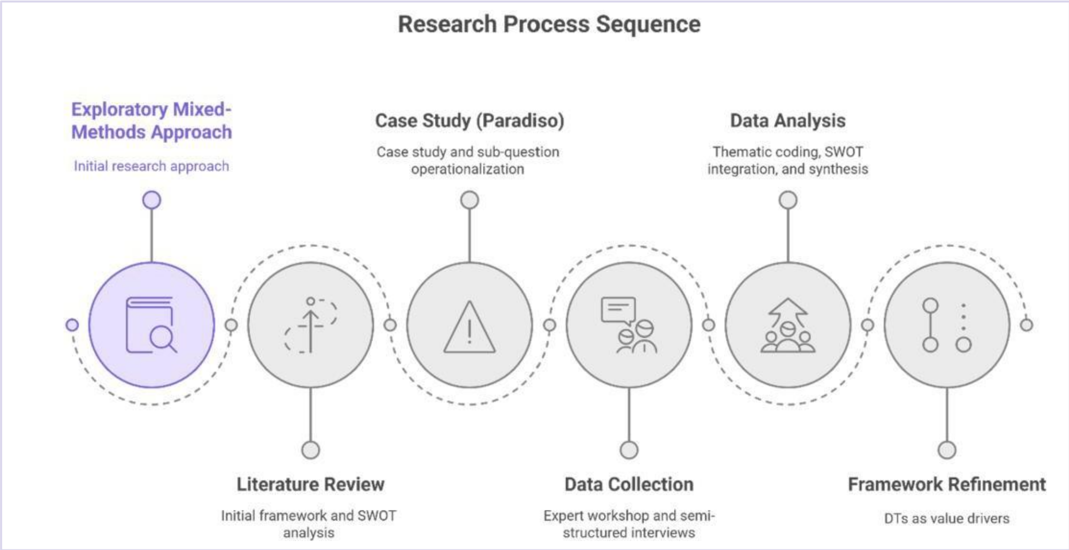

Figure 1. Research process sequence. Stages from the initial mixed-methods approach through literature review, case study (Paradiso), data collection, data analysis, and framework refinement.

3.1. LITERATURE REVIEW

The initial phase of this research was based on a literature review, which was conducted in two main steps.

The first step focused on exploring how adaptive reuse of heritage can become more values-driven by identifying ways to integrate digital technologies into each stage of the process. The aim was to develop a simple framework that links the main phases of adaptive reuse with a clear overview of relevant digital technologies, enabling professionals in the AEC industry and policymakers to apply them more effectively. The framework was developed by first defining key objectives based on a holistic understanding of heritage and its associated challenges, rather than limiting the focus to the physical characteristics of buildings. It was structured around three core principles:

- **The HUL approach:** This provided wider context, showing that adaptive reuse should be seen as part of the whole urban and social system, not just as a single architectural action (Bandarin & Oers, 2012; Yung & Chan, 2012).
- **Heritage values:** The challenges of reuse were analysed through existing heritage value theories as introduced by Pereira Roders (2007), Veldpaus et al. (2013) and Azzopardi et al. (2023). This helped keep the focus on conservation and on protecting cultural and historical meaning.
- **The adaptive reuse process:** A step-by-step process model inspired by Arfa et al. (2024) provided a clear structure for actions and decisions.

An initial version of the framework was created by combining these three pillars. This early model established a conceptual matrix that linked each reuse stage with appropriate digital technologies. It was later tested and improved in an expert workshop.

The second step of the literature review analysed how digital technologies contribute to the values-driven approach. To define the intersection among adaptive reuse, heritage, and digital tools, four SCOPUS query sets, as shown in **Figure 2** below, were executed, and the results were analysed.

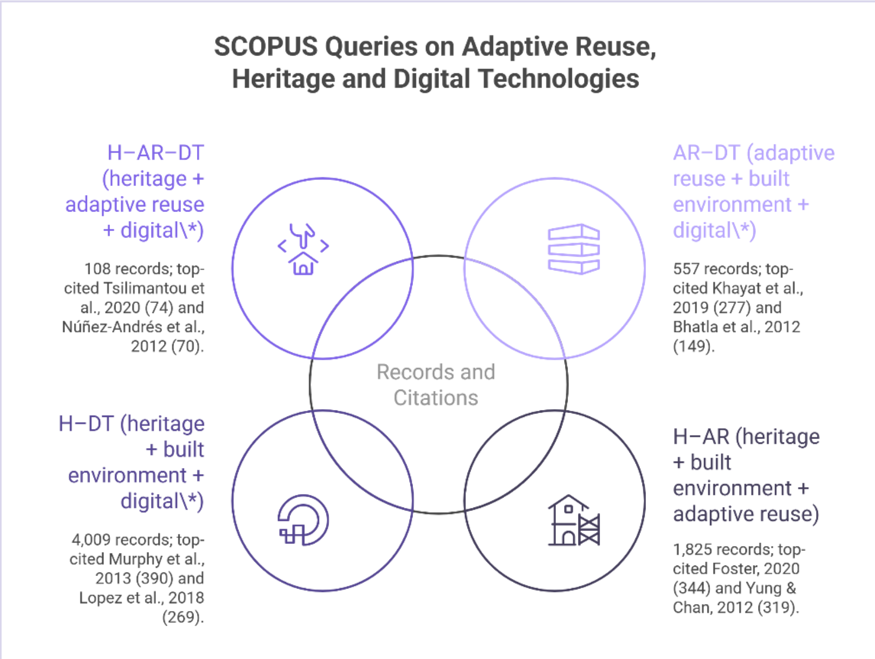

Figure 2. SCOPUS query results for heritage (H), adaptive reuse (AR), and digital technologies (DT). Venn diagram of four query sets with record counts and example top-cited papers. Centre shows the combined set.

- **H–AR–DT:** The main set, showing direct links between digital technologies, heritage, and adaptive reuse (Tsilimantou et al., 2020; Núñez-Andrés et al., 2012).
- **H–DT:** Focused on technical methods used in heritage, such as laser scanning, photogrammetry, HBIM, and digital twins.
- **H–AR:** Identified drivers, barriers, and stakeholder roles in reuse projects.
- **AR–DT:** Looked at reusable digital practices from non-heritage contexts.

Duplicate and repeated records were removed to keep only studies that showed real applications of digital tools, including workflows, data, and outcomes. The complete list of analysed papers is available in **Appendix D**. To make the review more practical, academic papers were complemented with a case study on digital use in heritage projects.

The findings were then summarized in brief SWOT notes for each digital technology, highlighting the strengths, risks, and adoption conditions. This produced a clear overview of how each technology can support adaptive reuse in practice.

3.2. CASE STUDY CRITERIA AND SELECTION

Once the initial framework was designed, a case study was selected to further validate the use of digital technologies in a running adaptive reuse project. The goal was to evaluate how the proposed framework works in practice and to understand how digital technologies are applied throughout the reuse process.

Based on the literature review and the aims of this research, several criteria were established to guide the case selection. These criteria ensure that the chosen case provides relevant insights into the use of digital technologies for values-driven adaptive reuse of built heritage. The criteria are divided into three categories: building-related, project characteristics, and involved stakeholders as shown in Figure 3 below.

Case Selection Criteria

Characteristic	Context	Location	Potential
Building	Recognized as built heritage, listed or identified as having cultural value	Located in an urban context with redevelopment or regeneration activities	Demonstrates potential for adaptive reuse rather than demolition or static preservation
Project	Integrates or experiments with digital technologies (e.g., BIM, HBIM, Digital Twin. IoT)	Involves multiple stages of the reuse process, from assessment to design, implementation, and management.	Aims to achieve sustainable and value-driven outcomes
Stakeholders	Involves collaboration between public and private actors (e.g., municipality, developers, architects, engineers)	Includes or allows for engagement of local communities or users	Demonstrates openness to knowledge sharing or innovation in digital workflows

Figure 3. Case selection criteria. Matrix of characteristics (building, project, stakeholders) by dimensions (context, location, potential). Each cell lists the inclusion criteria used for selecting cases.

The case selected is Paradiso, a heritage building in Amsterdam, which represents a protected 19th-century heritage building in the center of Amsterdam that has gone through several adaptations over time while maintaining its historic character. It continues to serve an important cultural role and is currently undergoing a major renovation.

As the site chosen, Paradiso matches the case selection criteria as described in **Figure 4** below. An additional reason for selecting Paradiso, beyond the initial criteria, was the willingness of its stakeholders to take part in the research. In contrast, five other shortlisted built heritage cases in Amsterdam received limited interest or response from their main contact persons.

Rationale for Selecting Paradiso

Characteristic	Context	Location	Potential
Building	Paradiso, located in Amsterdam, is a former church building officially recognized as cultural heritage	The building retains significant historical, architectural, and social value within the city	It demonstrates a successful transformation from a religious space into a multifunctional cultural venue
Project	Represents a long-term example of heritage reuse that continues to evolve with changing cultural and technological need	Located in a dense urban area where heritage reuse supports sustainable urban development	Offers potential for exploring the integration of digital technologies to support ongoing management, accessibility, and conservation planning
Stakeholders	Involves collaboration among the municipality of Amsterdam, cultural institutions, and private organizations	Includes active engagement with users, local communities, and visitors as part of its ongoing operation	Demonstrates openness to digital innovation, creative industries, and cultural participation—key aspects for testing (DARH) framework

Figure 4. Rationale for selecting the Paradiso case. Matrix of characteristics by dimensions. Cells summarize why Paradiso fits the study.

The framework developed through this research was applied to the case study to test its relevance and explore how digital technologies can support values-driven outcomes in practical, real-world contexts.

3.3. DATA COLLECTION

This section describes how data were collected to answer the research sub-questions. A mixed-method approach was used, combining an expert workshop, semi-structured interviews from the Paradiso case study, and a SWOT analysis. Together, these methods helped test and refine the draft Digital Adaptive Reuse of Heritage (DARBH) framework by linking theoretical knowledge with professional experience and real-world application. The overview below shows how each method contributed to the research design and outcomes. **Table 2** summarizes the methods, analysis techniques, data types, and sources used to answer each sub-research question.

The research design followed a mixed-method approach. The literature review, as described in Section 3.1 above, provided the theoretical foundation and an initial inventory of digital technologies relevant to adaptive reuse. The expert workshop gathered professional insights to refine the framework and validate this list of technologies, while the semi-structured interviews provided case-based evidence from the Paradiso project to confirm how digital tools are applied in practice. Finally, the SWOT analysis was used.

to organize and interpret data across all sources, highlighting the strengths, weaknesses, opportunities, and threats of each digital technology.

Using these methods together created a link between theory and practice and strengthened the reliability of the results. The next sections describe each method in more detail.

Table 2. Study design overview: research questions, method, instruments, analysis, data type, and sources.

Research method	Data collection instrument	Data analysis	Type of data	Source
RSQ 1 - How have digital technologies been systematically integrated into each step of the adaptive reuse process for built heritage?				
Qualitative	Literature review	Thematic review and mapping of digital technologies across process stages	Secondary data	SCOPUS database, TU Delft and WUR Digital Libraries
Qualitative	Expert workshop	Thematic analysis of expert inputs and framework validation	Primary data	Heritage, architecture, and digital technology professionals
Qualitative	Semi-structured interviews (Paradiso case)	Thematic coding and process-stage mapping	Primary data	Paradiso project stakeholders
RSQ 2 - What are the main opportunities and challenges experienced by practitioners in using digital technologies in the adaptive reuse of heritage?				
Qualitative	Expert workshop	Thematic analysis of professional input	Primary data	Workshop participants
Qualitative	Semi-structured interviews (Paradiso case)	Thematic coding and identification of barriers and enablers	Primary data	Paradiso project stakeholders
Quantitative & qualitative	SWOT analysis	Categorization of findings into strengths, weaknesses, opportunities, and threats	Secondary and primary data	Literature, workshop, and interview data
RSQ 3 - How can a practical framework support the effective use of digital technologies to achieve values-driven outcomes in adaptive reuse?				
Qualitative	Literature review, expert workshop, semi-structured interviews, SWOT	Comparative and cross-mapping analysis for framework refinement	Secondary and primary data	All data sources combined (literature, workshop, and case study)

Expert Workshop

A 60-minute online workshop was conducted to refine the draft framework and validate the digital technology list derived from the literature review. The workshop aimed to connect expert knowledge from different domains, such as adaptive reuse, architecture and construction, and digital technology, to evaluate how DTs align with the different stages of the adaptive reuse process.

Three professionals participated in the call, while another one provided feedback offline, which was integrated into the workshop. Each participant represented one of the three expertise areas. All had at least seven years of combined academic and work experience in their field. Before the session, participants received a short briefing document summarizing the HUL approach, known barriers to digital adoption, and an initial list of DTs such as BIM/HBIM, 3D scanning, digital twins, AI/ML, IoT, VR/AR, material passports, blockchain, and 3D printing.

During the session, participants collaborated on a shared digital whiteboard to map technologies across reuse stages, identify overlaps, and comment on usability. The workshop concluded with a short discussion on simplifying the framework for professional application. The main outputs were a refined DT list, updated process mapping, and notes on barriers and enablers, which later informed the SWOT analysis.

Table 3. Expert workshop summary: duration, format, participants, domains, and output

ASPECT	DESCRIPTION
Duration	60 minutes
Format	Online (Miro shared whiteboard)
Participants	4 experts (1 offline) + moderator
Domains represented	Adaptive reuse/heritage, architecture/construction, digital technologies
Main outputs	Updated DT list, refined mapping, identification of barriers and enablers

Semi-Structured Interviews (Paradiso Case Study)

To complement the expert feedback, two semi-structured interviews were carried out with stakeholders involved in the Paradiso project in Amsterdam. Each interview lasted about one hour and focused on how digital technologies were used, or could be used, during the building's adaptive reuse and renovation.

The interviewees were the **head architect** of the renovation projects Paradiso is undergoing and the **head of strategy and innovation** from the Paradiso Foundation. The questions aimed to:

1. Identify whether any digital technologies have been applied in the various stages of the

adaptive reuse process at Paradiso or in similar projects;

2. Assess the perceived usefulness of each technology for renovation work (rated 1–5); and

3. Explore the main enablers and barriers to their adoption, including skills, costs, data access, policy, and stakeholder support.

The interviews provided practical insights into how digital technologies are applied in real projects, the limitations they face, and how the DARBH framework could reflect the challenges and opportunities of adaptive reuse of built heritage.

Table 4. Semi-structured interviews: participants, roles, duration, focus, and key outputs.

Participant	**Role**	**Duration**	**Focus**	**Key Output**
Interviewee 1	Head Architect, Paradiso renovation	60 min	Application of DTs in design and construction	Identification of applied tools and practical barriers
Interviewee 2	Head of Strategy and Innovation, Paradiso Foundation	60 min	Long-term digital strategy and management	Enablers and potential applications
Interviewee 3	Paradiso Fund	10 min	Collaboration, inclusion and coordination, funding AR interventions	Didn't participate in answering the questions

The interviews provided insight into the technologies in use at Paradiso, the practical barriers to adoption, and the areas where DTs could have a greater impact on the adaptive reuse of built heritage. An overview of the two interviews outflow and outcomes is shown in Annex B.

3.4. DATA ANALYSIS

This section explores how the collected data were analysed. The analysis began with the preparation and review of all data sources. Notes and transcripts from the workshop and interviews were examined and organized, while academic papers from SCOPUS were reviewed to gather information on digital technologies used in adaptive reuse, their main advantages, and their limitations. Together, these materials provided the foundation for subsequent analysis.

The interviews and workshop sessions were transcribed using Microsoft Teams, which generated automatic verbatim transcripts labelled by speaker and timestamped. In the next step, a preliminary summary was automatically produced, which was then manually verified for accuracy. The workshop was conducted on a virtual Miro board, and all digital sticky notes and chat entries were included in the dataset.

The data were then analysed using thematic analysis. Initial coding combined deductive codes derived from the research questions with inductive codes that emerged from the workshop and interview discussions. These codes were grouped into themes and mapped to identify patterns and relationships. Recurring topics were consolidated into broader categories, including how digital technologies are used at different stages of the adaptive reuse process, the factors that support or hinder their adoption, and the perceived value of these tools in professional practice. This process helped identify both similarities and differences between expert insights and findings from the case study.

SWOT analysis

A SWOT analysis was then performed for each digital technology identified through literature, workshop, and case study. Information from the SCOPUS review was compared with expert and case inputs to describe the strengths, weaknesses, opportunities, and threats for each technology. For example, strengths referred to what a technology does well, such as improving collaboration; weaknesses referred to its limitations, such as high technical requirements; opportunities described potential benefits for wider use; and threats covered risks such as high costs or limited adoption. The results helped understand where each digital technology fits best in the adaptive reuse process.

Integration and framework development

After each data source was analysed separately, the results were combined. This integration followed a layered approach. The literature review first defined the stages of the adaptive reuse process and provided a list of digital technologies. The expert workshop refined this list and mapped the technologies to each process stage. The SWOT analysis and the Paradiso case study added practical insights, showing which tools are used, what supports or blocks them, and how they contribute to values-driven outcomes. All findings were then merged into one framework that links specific digital technologies to the different stages of adaptive reuse. The framework also highlights where each technology is most effective, and the challenges or opportunities associated with its use.

Validity and limitations

Using multiple methods and data sources strengthened the research's validity. Each source contributed a different type of evidence. The literature gave theoretical foundations, the experts confirmed the relevance and usability of technologies, and the case study provided real examples. Each source also had limitations. The literature did not cover every part of the adaptive reuse process, the number of experts interviewed was small, and the case study focused on only one building. However, combining them tries to balance these weaknesses.

3.5. ETHICAL CONSIDERATIONS

The use of digital technologies in heritage reuse raises several ethical challenges. The first relates to data privacy and ownership. Many technologies, including AI, IoT, and Digital Twins, depend on collecting detailed information about buildings, users, and their environments. Clear guidelines are needed to determine who controls, stores, and accesses this data in order to protect privacy and ensure responsible use (Mazzetto, 2024). A second challenge concerns balancing modernisation with preservation. While digital tools can enhance the performance, management, and monitoring of built heritage, excessive technological intervention may risk compromising historical authenticity and cultural significance (ICOMOS, 2011). Accessibility and inclusivity present another important issue. Technology should simplify participation rather than create new barriers. All stakeholders, including local communities, should have the opportunity to engage in decision-making and benefit from digital innovation. A further ethical consideration involves the ecological impact of technology. Digital systems require energy and materials, contributing to environmental footprints. It is therefore essential to ensure that technological progress aligns with sustainable heritage practices.

These ethical dimensions were integrated into the design and interpretation of this research, with the goal of encouraging responsible, inclusive, and environmentally sustainable use of technology in heritage projects.

4. RESULTS

This chapter presents the research results, which aim to structure how digital technologies can support more values-driven interventions in the adaptive reuse of built heritage. The results are based on a combination of a literature review, a workshop, and expert validation, as described in Section 3. The results in this chapter are presented across four main sections. Section 4.1, *The Framework – Setting Up the Heritage Reuse Process for Digital Integration*, explains how the DARBH framework was developed, refined, and simplified based on expert feedback. Section 4.2, *Digital Technologies' Use at Paradiso*, focuses on the case study application, showing how digital technologies were implemented and assessed in the transformation of the Paradiso site. Section 4.3, *The Pros and Cons of Digital Technologies in Adaptive Reuse of Heritage*, outlines the main benefits, limitations, and challenges identified through the case study, expert workshop, and literature. Finally, Section 4.4, *The Mapping of Technologies on the DARBH Framework*, connects the case study findings to the final framework, showing how each technology aligns with the adaptive reuse process and the five digital heritage functional pillars.

4.1. THE FRAMEWORK – DIGITAL INTEGRATION OF THE HERITAGE REUSE PROCESS

4.1.1. Literature review results

This chapter summarizes the academic literature behind the Digital Adaptive Reuse of Built Heritage (DARBH) framework. It aims to explain the key ideas, review practical and technical work on adaptive reuse, and show how digital technologies have been used, and where gaps remain, so the framework is grounded in existing research.

1. The literature shows a move away from conserving buildings as isolated objects towards approaches that focus on the values communities attach to places and on embedding heritage in wider urban processes. Pereira Roders (2007) and Mason (2006) describe this shift to values-centered preservation; Veldpaus et al. (2013) and Azzopardi et al. (2023) emphasize that values are multiple and change over time (social, cultural, ecological, economic). UNESCO's HUL puts conservation into broader planning and development (Bandarin & van Oers, 2012; Ginzarly et al., 2019). HUL and related work call for participatory, multi-stakeholder governance and decision-making that accepts change as part of living cities (Bandarin & van Oers, 2012; Chen & Li, 2021). These points support a framework that links digital technologies to values and stakeholder engagement rather than treating technology as just a technical add-on.

2. Adaptive reuse is presented as a conservation strategy that extends built heritage life cycles and supports circular urban development (Douglas, 2006; Arfa et al., 2022; Pintossi et al., 2021). Process models from Arfa et al. help map stages from assessment to implementation and monitoring post-use (Arfa et al., 2022; Arfa et al., 2024). Common barriers across cases are weak stakeholder participation, limited institutional and technical capacity, fragmented regulation, insecure finance, and poor integration of knowledge (Pintossi et al., 2023; Ginzarly et al., 2019). These findings support including feedback loops, governance

checkpoints and capacity measures within the DARBH process.

3. More research looks at technologies for reuse and groups them into clusters. For capture and creation, 3D laser scanning and photogrammetry are standard for reliable as-built capture and feed HBIM workflows (Metawie & Marzouk, 2020; Triviño Tarradas et al., 2024; Yuan et al., 2024). HBIM adds a semantic layer to store historical, material and condition data and helps cross-disciplinary coordination (Machete et al., 2021; Marzouk, 2023). But HBIM struggles with irregular historic geometry, requires intensive labor and has interoperability issues (Tsilimantou et al., 2020; Jadresin Milic et al., 2022). Photogrammetry is cheaper but sensitive to conditions and needs extensive processing (Costantino et al., 2022; Triviño Tarradas et al., 2024). For operation, digital twins and IoT enable continuous monitoring and predictive maintenance, which can be used for long-term conservation and lifecycle planning (Noronha et al., 2024; Baeriswyl et al., 2023). AI and machine learning add analytical power for energy simulation, risk assessment and decision support (Akyol & Şimşek, 2024; Cinquepalmi et al., 2023). However, these require high upfront integration costs, specialist skills and robust HBIM/IoT baselines (Metawie & Marzouk, 2020; Alshboul et al., 2024). For communication and governance, digital platforms and Common Data Environments (CDEs) are essential for collaboration and public engagement; immersive tools (VR/AR) help stakeholders understand proposals (Graham et al., 2018; Jadresin Milic et al., 2022; Li, 2024). Material passports and blockchain support traceability and circular economy aims (Gómez-Gil et al., 2024; Rashid et al., 2023). Studies also warn about procedural complexity, the need for standards, and ethical concerns (data permanence, privacy, misrepresentation) (Vileikis, 2023; Mocerino, 2024).

4. Despite benefits, many studies report fragmented and limited use of digital tools, many times only for surveys, documentation or visualization rather than full lifecycle management (Marzouk & Metawie, 2023; Baharuddin et al., 2023). Interoperability and data governance remain major problems (Chow & Fai, 2017; Jadresin Milic et al., 2022). Socio-institutional barriers also appear: different vocabularies between technologists and heritage practitioners, lack of training, and weak business cases (Pintossi et al., 2023; Dastgerdi et al., 2024). These gaps show why an operational framework must address technology choice, skills development, governance standards and implementation paths which are sensitive to the context.

5. The literature supports organizing technologies around functional pillars. Empirical work justifies mapping technology to process stages (Arfa et al., 2022; Noronha et al., 2024; Machete et al., 2021). Key design requirements for DARBH are: embed heritage values and participatory steps; prioritize interoperable, open standards and CDE governance; apply digital adoption to deliver early wins (for example, start with capture and simple CDEs before scaling to HBIM and digital twins); and include ethical and obsolescence measures (data migration, open formats) to protect long-term access (Vileikis, 2023; Gómez-Gil et al., 2024).

The academic literature gives a clear rationale for a values-driven, participatory approach and offers a fragmented but useful evidence base on digital technologies. To be practical, the DARBH framework must bridge technical workflows and socio-institutional practice: focus on interoperable capture and data management, plan investments to match cost and skill limits, and put governance in place to protect values, privacy and long-term data integrity. The framework's five pillars come directly from this review and respond to the documented potentials and barriers.

As described above, the literature identified three main elements that together form the foundation for developing the Integrated Digital Adaptive Reuse of Built Heritage (DARBH) Framework. These elements, were analysed to explore how they could be connected to structure the use of digital technologies in heritage adaptive reuse (see **Table 5**). This analysis resulted in the first version of the framework, which modified the adaptive reuse process to address key barriers and highlight where digital technologies can add value and reduce risks.

Together, these three layers address the gap between abstract planning principles and the operational needs of heritage projects.

Table 5. The three principles of the framework design: incorporating heritage in the urban process, recognizing challenges, and structuring adaptive reuse.

Incorporating heritage in the urban process	Recognizing challenges	Structuring adaptive reuse
• Focuses on managing heritage within its wider urban, cultural, and social context. • Considers six key dimensions: context, value, vulnerability, integration, prioritization, and management. • shifts preservation from a static activity to a dynamic urban transformation process. • In digital terms: promotes use of 3D scanning, data platforms, and immersive tools to strengthen, not replace, cultural and spatial identity. *(UNESCO, 2011; Bandarin & van Oers, 2015)*	• Highlights five recurring barriers: ○ Limited stakeholder participation ○ Weak institutional and technical capacity ○ Fragmented or unclear regulation ○ Financial instability ○ Poor knowledge integration • Case studies (Amsterdam, Rijeka, Salerno) show issues like lack of trust, legal inconsistencies, and skill shortages. • Fragmented data and funding challenges further reduce project feasibility and inclusiveness. *(Pereira Roders, 2007; Plevoets & Van Cleempoel, 2019; Pintossi, 2023)*	• Based on Arfa et al.'s (2022) ten-step process model. • Provides a structured sequence from assessment to implementation and monitoring. • Includes feedback loops for refinement and coordination between legal, financial, and stakeholder inputs. • Complemented by other models focusing on: ○ Conservation-led design (Plevoets & Van Cleempoel, 2019) ○ Decision tools (Li et al., 2021) ○ Post-reuse evaluation (Fanlei & Xiao, 2025; Abastante et al., 2020)

Through the literature review, this research identified a significant gap in how the disciplines underlying the three layers described above are integrated into the adaptive reuse process of built heritage. To explore how they could work together, the research mapped Arfa et al.'s (2022) ten-step adaptive reuse process against the main challenges and barriers identified in the literature, using the HUL approach as a guide. The goal of this mapping was to identify gaps and identify which steps in the reuse process could be improved to better address key issues, such as limited participation, lack of knowledge, regulatory complexity, and financial constraints.

Table 6 presents the results of this mapping. In the table, the columns represent the stages of the adaptive reuse process, and the rows list the main barriers. A checkmark shows where a particular challenge applies. This visualization helps identify which problems arise at each stage and where actions are needed to better apply a values-based approach to the adaptive reuse of built heritage. Further details are provided in **Appendix A**.

Table 6. Mapping of key adaptive-reuse challenges across process steps (0–9). Shaded cells mark the steps where each challenge is most pronounced.

		ADAPTIVE REUSE PROCESS STEPS*	0.Initiative	1. Analysis of the building	2. Value assessment of the building	3. Mapping level of significance	4. Adaptive reuse potential (function)	5. Defining the design strategy	6. Final decision-making	7. Execution	8. Maintenance	9. Evaluation after years
UNESCO HUL approach	Core challenges (barriers)	Description										
Mapping resources	Knowledge integration	Siloed or missing information, poor data-sharing	✓	✓	✓	✓		✓			✓	✓
	Knowledge & capacity	Lack of skills, expertise, and institutional knowledge	✓	✓	✓	✓				✓		
Reaching consensus	Participation	Lack of inclusive, effective stakeholder engagement	✓		✓			✓	✓			✓
Assessing vulnerability	Knowledge & capacity	Lack of skills, expertise, and institutional knowledge	✓	✓	✓	✓				✓	✓	
	Knowledge integration	Siloed or missing information, poor data-sharing		✓	✓	✓		✓				✓
Integrating into planning	Regulatory	Legal and policy barriers, or fragmented rules					✓		✓		✓	
	Economic & financial	Funding gaps, weak financial models					✓		✓	✓	✓	
Prioritizing actions	Economic & financial	Funding gaps, weak financial models					✓		✓	✓		
Establishing partnerships	Participation	Lack of inclusive, effective stakeholder engagement	✓		✓			✓	✓			✓
	Knowledge & capacity	Lack of skills, expertise, and institutional knowledge	✓			✓				✓	✓	

This mapping was then used to identify a list of proposed changes to the AR process, which are reflected in the **Table 7** below. A new set of steps is proposed as a an alternative, since the existing ones did not reflect the values that could be explored as part of the adaptive reuse process. To identify the values that could be driving the various activities, an adaptation was suggested for the framework. Further details in Appendix A.

Table 7. Proposed changes to each AR step with brief rationale and expected effect.

Step #	**Adjusted step description**	**Roders challenge focus**	**Justification of suggested adaptations** *(if Challenges are not fully addressed in the EARHB, add to framework)*
1	Map context + identify stakeholders	Participation, Knowledge &capacity	Focus on inclusion and participation to increase capacity and to understand relevance
2	Evaluate and assess building and its uses, map level of significance	Knowledge integration	No changes to the actions, but focus on integrating the knowledge resulted from the evaluation and value assessment of the building
3	Set up engagement process with stakeholders	Participation Economic & financial	Combine stakeholder engagement with needs analysis and conflict mapping. Understand economic drivers
4	Assess knowledge/capacity gaps	Knowledge & capacity, Knowledge integration	Add knowledge and capacity assessment which is not part of EARHB framework
5	Analyze legal/policy constraints	Regulatory	Add legal and policy framework limitations which are not part of the EARHB framework
6	Co-create reuse goals & values, define potential function and design strategy	Participation Knowledge & capacity	Map the adaptive reuse potential, adaptive function and decision of functional change with the reuse goals and values
7	Develop and test design scenarios	Economic & financial Regulatory	Add testing to developed design scenarios
8	Evaluate feasibility + adjust	Economic & financial Knowledge & capacity	Include feasibility analysis from an economic, capacity and other risks perspective

9	Make final decision and align proposal with policy	Regulatory Knowledge integration	Include alignment with legal framework and policy + community needs
10	Implement, maintain, monitor, and adapt	Knowledge & capacity, Knowledge integration, Economic & financial	Focus on long term impact assessment of the AR process, the KPIs/AR goals to be monitored and the knowledge to do so effectively

The adaptive reuse framework for built heritage was later reviewed in a workshop with experts in heritage, architecture, and digital technology.

4.1.2. Improvements of the framework based on the workshop results

As described in Section 3.3, a workshop in 2 steps was organized with 4 experts, of which one gave feedback offline, to evaluate the framework and the initial list of digital technologies. Details of the workshop, including the session structure and whiteboard results, can be found in **Appendix B.** The following chapters will describe the main results of the workshop, including the feedback that prompted changes to the framework and the list of evaluated technologies.

The workshop showed that participants agreed that digital technologies are helpful throughout the adaptive reuse process, but their use remains limited and inconsistent. They shared examples, such as scanning and visualizing damaged built heritage after earthquakes in Nepal. Still, they noted there's no clear or consistent way to select and combine tools for everyday work. The view was shared that the "long list" of technologies reviewed before the workshop mixes basic concepts (like machine learning) with final products like BIM, making it challenging to understand where each fits in the workflow.

In practice, participants described narrow and specific uses. For instance, laser scanning is often used to capture building geometry, but the data rarely carries forward detailed information about materials or heritage value. HBIM was seen as helpful for coordination across disciplines, yet restrictive, as it is built around standard construction logic, "BIM thinks in walls", and can miss unique heritage attributes. AR and VR are more common in museum or post-disaster contexts than in everyday reuse projects.

Overall, while some digital technologies are well adopted, many advanced ones remain at the research stage or are only partially used. Out of the 13 digital technology categories identified in the literature and discussed in the workshop, only 2 had a strong presence in participants' responses, indicating extensive use in practice. Four others have been identified as used, but less extensively and most often not in the heritage context, four technologies have been found rather useful theoretically but with no sufficient traction or with significant barriers such as (insufficient AEC knowledge to build the model and implement it, extensive time and resources needed to apply, not including immediate results which can be used) and two were discussed with overlaps with other areas and therefore can be considered in aggregate. An *overview of the workshop results is summarized in **Table 8** below.*

Table 8. Summary of workshop results for digital technology categories in AR

Category	**Number of DTs**	**Description / Notes**

Extensively used in practice	2	Strong presence in participant responses; widely adopted in daily work.
Used, but less extensively (often outside heritage)	4	Applied occasionally, mostly in general architecture or construction, not specifically in heritage contexts.
Theoretically useful but limited by barriers	4	Seen as promising but face challenges such as lack of AEC expertise, high time or resource demands, or unclear short-term benefits.
Overlapping / aggregated categories	2	Discussed together due to overlap with other tools or functions.
Total	13	

The challenges identified and how to make DTs understandable as part of the framework

Two areas of disconnect were discussed extensively in the workshop. First, developers and technology providers often do not understand the heritage context. Second, AEC teams are not always aware of what new technologies can do. Participants compared this to fields like pharmaceuticals, where experts and practitioners meet regularly to share knowledge. They suggested creating similar spaces where technology developers can demonstrate what their tools can do and practitioners can explain their needs and constraints, so that both sides can be better understood.

Participants also agreed that the language used around digital technologies should be simpler. One idea was to describe each technology in a single short sentence and use clear visuals, such as colors or icons, to make the information easy to follow. The detailed technical terms could still be available for researchers.

The group also recommended grouping technologies by their use, not by brand or algorithm, and showing only a few at a time to keep things clear. The main challenges identified were limited data sharing, gaps in technical, financial, and legal knowledge, limited stakeholder involvement, regulatory barriers to monuments, and short-term financial planning. Participants agreed that technology could help most with data sharing and coordination by creating shared platforms where everyone can contribute information and needs in one place.

Proposed digital technology toolboxes mapped to the adaptive reuse workflow

Another important topic discussed in the workshop was how each digital technology should be applied in the adaptive reuse process. Participants recommended grouping digital technologies into clearer areas that match the needs of different professionals. Based on the type of data and process requirements, five main toolboxes were identified as applicable for the adaptive reuse of built heritage:

- **Gather information to survey, document, and share**. Participants called for a broader and more connected source of information for reuse projects, not limited to geometry or surfaces. They suggested linking scans, drawings, archival material, annotations, and material passports so that context and sources are not lost. Blockchain was mentioned to secure traceability, but

participants were cautious since heritage data can change over time, and a permanent record could lock in errors.

- **Create and design to model and simulate options**. The group discussed the need for technologies that support exploration, not just representation. Digital twins were discussed as small-scale models for testing scenarios, such as safety or access, before applying changes to real buildings. AR and VR can also help stakeholders understand design options early, though they are still used primarily in cultural or exhibition settings rather than in everyday design work.

- **Decide and coordinate to assess feasibility, risk, and finance**. Participants suggested evaluating scenarios beyond short-term costs, including heritage values, social benefits, regulations, and lifecycle performance. They proposed a shared digital workspace that brings together inputs from survey, design, policy, and operations, enabling transparent, traceable decisions. Using larger datasets and machine learning to learn from similar projects, such as hospitals with strict regulations, was also mentioned to improve decision-making.

- **Monitor and operate to track performance.** The group considered using simple, measurable indicators, such as energy use or visitor numbers. Feeding operational data back into digital twins could help make ongoing adjustments and turn technology use into a routine part of operations. Tools such as digital twins and IoT-based systems can support this continuous monitoring.

- **Engage and communicate to support participation.** Participants discussed lightweight digital platforms to make participation easier for users and visitors. One idea was to connect a feedback tool to the ticketing system at heritage sites with events or tourism functions. This would help collect feedback effortlessly, keeping the process inclusive while providing valuable data to inform both design and operations.

How to improve the framework and future expert sessions (practical changes recommended)

Participants noted that digital technologies should also consider context, as adaptive reuse choices depend on building type, construction period and style, location, and future use. One suggestion was to reuse knowledge by classifying cases (e.g., “Amsterdam brick buildings from X period share issues A/B,” “Latin American buildings of Y era often have Z features”), so teams can anticipate typical constraints and reuse technologies based on more concrete similarities. This supports the idea of digital technology-enabled toolboxes tailored to context, not generic.

For the framework format and future interviews, participants suggested breaking the process into steps and showing only the “top three tools” per step. They also recommended grouping technologies that are likely to be used together, so the offer feels like a manageable kit rather than a catalogue. Finally, they endorsed a framing that is pragmatic and based on need-first, starting from problems and existing practices, then slot in technologies that clearly improve those steps.

Takeaway – key observations

1. One of the main observations of the workshop was that, despite the structure and the focus on understanding technologies and mapping them to the adaptive reuse process stages, rather than deep-diving into each technology, the conversation quickly moved to the key barriers. These barriers are not about the capabilities of the technologies themselves, but rather about communication and the level of understanding among the key stakeholder groups.
2. A second key observation was that the digital technologies most widely used in practice are those with a low barrier to entry, are easy to understand, require limited specialized skills, deliver quick results, and involve low implementation costs (such as sensors used for ongoing maintenance). More comprehensive, holistic solutions that take longer to implement, such as HBIM, are often considered too complicated, requiring significant time and resources, and demonstrating benefits that are harder to demonstrate immediately. As a result, there is less incentive to adopt these types of technologies.
3. A third key observation was that grouping digital technologies into toolboxes or their own categories is essential, as it not only simplifies the framework but also connects it to the appropriate stakeholder groups. In a complex project such as that of heritage adaptive reuse, there are many different teams with responsibilities in different parts of the process, and a grouping that suggests the type of data or information being handled, and what needs to happen to it, is highly relevant for simplification and for ensuring the framework remains meaningful. Visual prompts and better ways to present or showcase the potential of digital technologies are also relevant to the process of integrating them into a field that could benefit significantly from greater technological innovation. Convincing architects is especially important, as they are among the key stakeholders in driving these advancements.

Further awareness and understanding through simplification were therefore identified as necessary. The workshop suggested taking a pragmatic approach: using small, well-defined digital technology toolboxes aligned with real tasks, keeping descriptions plain and visual so they are understandable to a non-tech-savvy audience, creating shared spaces where technology and heritage expertise can meet, and testing ideas on live cases, such as Paradiso, so that the value is clear. In this way, technologies can be used to focus on outcomes that support better decisions and more inclusive engagement, rather than starting with the technology itself and identifying potential areas of application.

4.1.3. Adding digital heritage functional pillars to simplify the framework

As a result of the expert workshop, the concept of Digital Heritage functional pillars was added to the framework. This is a simplified way to explain how digital technologies can support the adaptive reuse of built heritage. The idea is based on how digital tools are used in practice and research, following the concept of the toolbox introduced in chapter 4.1.2. Organizing digital technologies around the core functional areas: **Capture, Create, Conserve, Communicate, and Control** was based on workshop input and on identifying common themes in the literature. UNESCO and ICOMOS, for example, explain the importance of documentation (Capture), conservation planning (Conserve), and inclusive public engagement (Communicate) as key components of sustainable heritage management (UNESCO, 2011; ICOMOS, 2014). The functional area has also been supported by large research initiatives. The INCEPTION Project (EU Horizon 2020), for example, developed workflows for HBIM that encompass data capture, modelling, enrichment, and dissemination, corresponding to the Capture, Create, and Communicate functions (Maietti et al., 2018). Organizations like CyArk and the Virtual Heritage Network follow similar processes: scanning (Capture), modelling (Create), visualizing (Communicate), and archiving or preserving data (Conserve). The CIPA Heritage Documentation Guidelines also divides work into steps for documentation, modelling, and data management, which align with Capture, Create, and Control.

The five main pillars are:

1. **Capture**: Focuses on collecting detailed information about a heritage site even before any work starts. Technologies like photogrammetry, 3D laser scanning, and UAVs (drones) are used to document the building's shape, condition, and materials. This information helps avoid damage and supports better planning. For example, Metawie and Marzouk (2020) and Shrestha et al. (2017) describe how laser scanning can be used to capture precise data from fragile buildings safely. Triviño-Tarradas et al. (2024) and Ardhiati and Hasan (2024) demonstrate how photogrammetry helps map decorative details and sculptures.

2. **Create**: Once data is captured, it can be used to build digital models. Tools like HBIM, and 3D printing help create accurate representations of built heritage. These models help architects, engineers, and conservationists design interventions, test ideas, and reproduce missing parts. For example, Crisan et al. (2025) show how HBIM helps restore steel bridges. Jesus et al. (2025) used 3D printing to recreate historical ornaments. Marzouk (2023) and Metawie and Marzouk (2023) explain how HBIM supports reuse planning and documentation.

3. **Conserve**: This pillar is about using technology to protect and manage built heritage over time. Digital twins, material passports, AI, and IoT sensors help monitor building performance, detect problems early, and plan maintenance. Noronha et al. (2024) and Baeriswyl et al. (2023) show how digital twins can simulate building behavior to prevent damage. Gómez-Gil et al. (2024) introduce the concept of material passports to support reuse and sustainability. Savitri and Amalia (2024) and Mocerino et al. (2024) describe how AI and smart systems can support long-term conservation.
4. **Communicate**: Digital tools also help engage the public and stakeholders. VR, AR, gamification, and digital platforms make it easier to share information and get feedback. These tools are used for operational data sharing, education, exhibitions, and community consultations. For example, Graham et al. (2018) and Dhanda et al. (2017) describe how VR is used to help people experience reuse projects before they're built. Li (2024) and shows how gamified platforms support better public understanding and participation. Jadresin Milic et al. (2022) highlight the use of VR in education and training.

5. **Control**: The final pillar focuses on managing data, processes, and responsibilities. Technologies such as HBIM, blockchain, AI, and risk platforms support transparency, accountability, and effective project management. Gómez-Gil et al. (2024) and Omar (2024) explore how blockchain can secure records and track changes. Dastgerdi et al. (2024) and Cantagallo and Sangiorgio (2025) describe how big data and IT tools help assess risks and performance. Machete et al. (2021) show how HBIM supports facility management after reuse.

These five digital heritage functional pillars (see **Table 9** below) were then directly integrated with the

10-step adaptive reuse process adapted from the model of Arfa et al. (2024). For instance, Capture technologies like UAV photogrammetry (Ardhiati & Hasan, 2024) and laser scanning (Shrestha et al., 2017) support early-stage site assessment. Tools like VR (Graham et al., 2018) improve engagement in Step 6 (co-design), while Control tools like blockchain (Gómez-Gil et al., 2024) and HBIM (Machete et al., 2021) improve data reliability during final project implementation.

Table 9. Five DTs pillars with functions and the process steps they support.

Pillar	Main function	Related steps of an adaptive reuse process
CAPTURE	Collect physical, material, and stakeholder data	1: Map context + identify stakeholders 2: Understand existing values & uses 4: Assess knowledge/capacity gaps
CREATE	Produce models, simulate reuse ideas, fabricate missing parts	6: Co-create reuse goals & values 7: Develop and test design scenarios
CONSERVE	Monitor performance, enable predictive maintenance, support lifecycle planning	8: Evaluate feasibility + adjust 10: Implement, monitor, and adapt
COMMUNICATE	Engage public and stakeholders, gather feedback, build consensus	3: Set up engagement process 6: Co-create reuse goals & values 9: Align final proposal with policy
CONTROL	Manage project roles, legal data, risk, and compliance	5: Analyze legal/policy constraints 9: Align final proposal with policy 10: Implement, monitor, and adapt

4.2. DIGITAL TECHNOLOGIES IN USE AT PARADISO

Context of Paradiso

To further validate the use of digital technologies in a running adaptive reuse project, **Paradiso**, a heritage building in Amsterdam, was selected as case study.

Paradiso is a 19th-century brick meeting hall built between 1879 and 1880 for the Vrije Gemeente, which became a pop venue in 1968 and is protected as a state monument. The building underwent multiple changes over the past 25 years. Yet, it retained its tall central hall, galleries, barrel-vaulted ceilings, and stained-glass windows – while taking on new uses. The changes improved performance by adding a second balcony in 2004 to increase capacity, installing acoustic secondary glazing to limit noise, and maintaining stained glass and facades. Technical upgrades for sound and lighting were also integrated within the old structure. Culturally, Paradiso is a core element of Amsterdam's music scene.

The selection of Paradiso as a case study was based on the following considerations: as a protected hall built in the 19th century in the center of Amsterdam, it has been adapted multiple times, and it is currently undergoing a significant renovation project. Its heavy music event schedule throughout the year, across two rooms, requires daily solutions for crowd management, noise, safety, and fast transitions, making the impact of digital technologies easy to see. As a symbol of Amsterdam and a stage for artistic, social, and political events, the adaptive reuse interventions at Paradiso conveyed social, economic, and ecological values, significance, and impact to the building and beyond. An initial analysis showed that the venue also uses modern technology such as digital audio systems, networked control, and 3D modelling for acoustics and planning.

2 interviews were organized with the head architect and the head of strategy and development of Paradiso,. An overview of the two interviews outflow and outcomes is shown in Annex xxx and the summary of the main observations is in the following chapter.

Key observations from the interviews

Use of digital technologies at Paradiso

One of the first discussion points in the interviews was that Paradiso currently makes extensive use of digital tools such as 3D laser printing and prefabrication. These help recreate complex architectural parts that are difficult to make by hand, which is becoming more important as skilled experts become fewer. Sensors and smart systems are mainly used to monitor sound and light levels during concerts. There is also interest in adding sensors to measure how the building moves during events, as this could help prevent structural issues.

BIM is widely used in construction but not very practical for historic buildings like Paradiso. The building's irregular details make creating BIM models difficult, expensive, and time-consuming. Even with significant effort, the digital model often does not fully match the real building. BIM works better for new or simpler buildings with repetitive structures.

3D laser scanning produces accurate data, but turning that data into usable models remains complex and costly. It also requires strong technical knowledge, so it cannot replace expert understanding. 3D printing can help reproduce decorative or missing parts, but cannot replace traditional craftsmanship, especially for fine details like plasterwork.

Material passports are primarily helpful for new buildings. For historic sites like Paradiso, collecting this information without damaging the structure is difficult, so their use is limited.

Experts noted that Paradiso already has an extensive paper archive with valuable building information. Digitizing and modelling this data could support future work. The idea of creating a digital twin—combining BIM and virtual reality to test changes before construction—was seen as very promising. However, such technologies remain difficult to implement due to high costs and technical challenges. A summary of Paradiso's use of digital technologies is provided in Table 10 below.

Table 10. Digital technologies at Paradiso: uses, limits, and future potential.

Digital Technology	Expert interview details
3D printing & prefabrication	Used to recreate complicated architectural parts that are hard to make by hand. Important as skilled experts are becoming rare.
Sensors & smart systems	Currently monitor sound and light levels during concerts. Interest in adding sensors to measure building movements (e.g., from jumping crowds) to detect structural risks.
3D laser scanning	Produces precise data but turning it into usable models is difficult and costly. Requires deep expert knowledge. Cannot replace experts' understanding.

3D printing (decorative parts)	Useful for replicating elements that are hard to source or make. However, it cannot fully replace traditional craftsmanship, especially for delicate features like plaster ceilings.
Paper archives & digitization	Paradiso has a large archive of building data. Digitizing and modelling this information could help future projects.
Digital twin	Seen as valuable for simulating interventions before real changes. Combines BIM with VR. Assessed for future use, however, currently too costly and technically complex to implement.

The following is the researcher's interpretation of the findings from the interviews as detailed above.

Challenges around expertise and workforce shortages

A key challenge raised in the interviews is the lack of skilled workers who understand historic buildings. Many experts are already busy, making it hard to find people for complex restoration work. Built heritage are becoming more complicated with added systems and installations, which makes expert knowledge even more important. Both experts agreed that, while digital tools are helpful, they cannot replace the detailed understanding and craftsmanship of experienced professionals.

Managing and organizing building information

Managing and storing building information remains a significant challenge. Even large organizations often find it difficult to keep digital records well organized. At Paradiso, documentation and archives are managed digitally through shared network folders, with the head architect maintaining detailed historical and technical records. There is clear potential to improve data accessibility and to use data analytics to support maintenance and planning. Both experts emphasized the importance of establishing a central digital system to store and share accurate building information, helping to prevent data loss and ensure continuity across projects.

Stakeholder communication and engagement

Stakeholder participation and communication were identified as key challenges. Paradiso attracts a diverse and changing audience, with each event drawing different visitor groups. At present, engagement is mostly informal and focused on small target audiences. Experts noted the potential of digital platforms to support broader participation through automated online surveys and virtual focus groups. These tools could help collect more diverse and detailed input, improving inclusivity and communication. Effective communication among stakeholders—such as the municipality, architects, and Paradiso's management—is also essential. Experts highlighted the need to balance these interests carefully, especially given the political context of upcoming municipal elections. Flexible visualizations and tailored presentations can help address different audiences and maintain continued support for future projects.

Privacy and ethical concerns

The use of sensors for tracking visitor behavior raises privacy concerns. Although this type of data could help understand how people use the space, ethical issues have so far prevented its use in monitoring visitor patterns inside the building.

Barriers to technology adoption

Barriers to adopting advanced digital technologies are mainly linked to limited time, skills, and project complexity, rather than budget or interest. However, justifying costs remains a concern. The experts also noted that coordination and communication among the many professionals and stakeholders involved are often challenging due to heavy workloads.

The interviews show cautious optimism about the potential of more digital technologies to be used in Paradiso. Technologies such as 3D laser scanning, photogrammetry, and prefabrication are already valuable and increasingly important. However, technologies like BIM and digital twins, while promising, have not yet been adopted due to their complexity and the difficulty of justifying the business case of investing in the, both in terms of costs and time required. Expert knowledge and traditional heritage skills remain essential and cannot be replaced by current digital tools.

4.3. THE PRO'S AND CON'S OF DIGITAL TECHNOLOGIES IN ADAPTIVE REUSE

This chapter begins by explaining what digital technologies are and how they have been applied in adaptive reuse projects(Section 4.3.1). It then presents a SWOT analysis to identify the main challenges and opportunities associated with each technology (Section 4.3.2). And concludes with an assessment of key questions related to digital technology use, providing input for integrating these insights into the overall adaptive reuse framework.

4.3.1. Understanding digital technologies in the adaptive reuse of heritage

The starting point is a list of the main digital technologies identified in the literature, which are either already in use or can be used in the adaptive reuse of built heritage. The list focuses on the technologies that are most discussed in the literature. Each section below describes a specific digital technology and its application in heritage conservation and reuse projects, supported by recent academic and practical references.

Heritage Building Information Modelling (HBIM)

BIM is used to create a digital 3D model of a building that includes data for design, construction, and maintenance. In adaptive reuse, BIM helps understand existing conditions and supports informed decision-making (Crisan et al., 2025; Cinquepalmi et al., 2023). It enables collaboration across teams and works well with tools like photogrammetry and laser scanning to build accurate models (Chow & Fai, 2017; Artopoulos et al., 2024). BIM also helps manage safety, maintenance, and planning in built heritage (Gurcanli et al., 2025; Bianchi & De Medici, 2023). Studies show that BIM helps reduce errors, supports better cost planning, and allows easier integration of structural assessments during reuse (Crisan et al., 2025; Cinquepalmi et al., 2023). Studies show that BIM helps reduce design errors, improve coordination among stakeholders, and enable real-time updates during adaptive reuse projects (Crisan et al., 2025). It streamlines project workflows and facilitates structural analysis and sustainable retrofit planning (Cinquepalmi et al., 2023; Balocco et al., 2020).

HBIM is a type of BIM focused on historical buildings. It adds historical data, materials, and damage information to the 3D model. HBIM helps preserve architectural value and supports planning reuse projects (Metawie & Marzouk, 2023; Marzouk, 2023; Micheloni et al., 2023; Alp, 2024). It also links with tools like laser scanning to create detailed and accurate models for better reuse decisions (Yuan et al., 2024; Machete et al., 2021). Recent studies also highlight its use in education and database development for heritage records (Alp, 2024; Baharuddin et al., 2024; Jadresin Milic et al., 2022; Marzouk & Metawie, 2023). Research confirms HBIM improves access to historical data, supports risk evaluation, and helps visualize damage or decay for restoration planning (Baharuddin et al., 2024; Machete et al., 2021; Metawie & Marzouk, 2020). HBIM platforms improve heritage conservation by storing damage data and enabling simulation of preservation scenarios (Metawie & Marzouk, 2023; Micheloni et al., 2023). HBIM also facilitates digital record-keeping and reconstruction support, as proven in case studies like the Chalet of the Countess of Edla (Machete et al., 2021; Marzouk, 2023).

Artificial Intelligence (AI) and Machine Learning (ML)

AI and ML are used to study complex building data, find patterns, and suggest the best reuse options. They help speed up design, predict future issues, and manage energy or maintenance needs (Akyol & Şimşek, 2024; Cinquepalmi et al., 2023). AI can be combined with digital twins for real-time analysis and improved building performance (Stone, 2017; Savitri & Amalia, 2024; Baeriswyl et al., 2023). AI has been shown to streamline analysis of energy performance and user behavior, helping select optimal reuse functions early in the design process (Akyol & Şimşek, 2024; Savitri & Amalia, 2024; Noronha et al., 2024). AI enhances decision-making by analyzing environmental, spatial, and structural data, recommending optimal reuse functions for buildings (Akyol & Şimşek, 2024). It also supports predictive maintenance scheduling and energy performance forecasting (Stone, 2019; Mocerino et al., 2024).

Big Data and Analytics

Big data tools analyze large datasets from built heritage. These tools help find patterns about how buildings are used and what users need (Dastgerdi et al., 2024; Liu et al., 2024; Artopoulos et al., 2024). This helps make better reuse decisions by combining building data, community input, and cultural values (Calzolari et al., 2025; Artopoulos et al., 2024; Bianchi & De Medici, 2023). It also supports tourism-based reuse and regional development through reuse analytics (Bianchi & De Medici, 2023; Artopoulos et al., 2024; Cantagallo & Sangiorgio, 2025). Big data tools help measure cultural value, user flow, and economic feasibility, improving adaptive reuse decision-making (Bianchi & De Medici, 2023; Artopoulos et al., 2024; Balocco et al., 2020). Big data applications have been used to evaluate building conditions and community needs, helping shape data-driven reuse strategies that align with local economic goals (Bianchi & De Medici, 2023). These tools allow real-time performance assessments and prioritize reuse based on social and environmental impact (Dastgerdi et al., 2024; Machete et al., 2021).

Photogrammetry

Photogrammetry takes multiple photos of a heritage building from different angles to create 3D models. It's affordable and useful for mapping details, detecting damage, or planning reuse (Yuan et al., 2024; Triviño-Tarradas et al., 2024). It's often combined with laser scanning and UAVs to reach hard-to-access places (Núñez-Camarena et al., 2011; Ardhiati & Hasan, 2024; Costantino et al., 2022). Additional research shows how it can be used to document and support detailed reuse proposals for specific building types (Costantino et al., 2022; Núñez et al., 2011; Núñez-Camarena et al., 2024). Studies show photogrammetry enables detailed documentation that guides accurate planning and reduces risks during construction (Triviño-Tarradas et al., 2024; Costantino et al., 2022; Ardhiati & Hasan, 2024). Photogrammetry supports detailed architectural analysis for reuse proposals, such as the accurate reproduction of façades and decorative elements (Triviño-Tarradas et al., 2024; Núñez-Camarena et al., 2024). It has been used successfully to survey inaccessible heritage areas using UAVs (Núñez-Camarena et al., 2024).

3D and Laser Scanning

3D and laser scanning use LiDAR to capture exact building details without touching the structure. It helps create accurate 3D models for reuse projects, detect damage or misalignment, and supports BIM or HBIM modeling (Metawie & Marzouk, 2020; Autodesk, n.d.; Arrival 3D, n.d.; Shrestha et al., 2017). It's helpful for fragile or complex sites (Kubacka et al., 2025; Shrestha et al., 2017). Laser scans have proven useful in capturing damage after natural disasters, like earthquakes, supporting faster and more precise restoration planning (Shrestha et al., 2017; Marzouk & Metawie, 2023). Laser scanning captures precise measurements for creating base BIM models. These scans enable engineers to detect structural deformations and plan reinforcements with minimal impact on heritage fabric (Shrestha et al., 2017; Micheloni et al., 2023). It also aids rapid documentation after natural disasters (Metawie & Marzouk, 2020; Marzouk, 2023).

Digital Twin Technology

Digital twins are live digital copies of built heritage. They show real-time performance, damage, or environmental data (Noronha et al., 2024; Baeriswyl et al., 2023). These models help manage maintenance and guide future updates to reused buildings, keeping heritage value intact (Baeriswyl et al., 2023; Stone, 2017; Vileikis, 2023). Memory and identity aspects can be captured through digital twin tools (Stone, 2017). Digital twins help simulate reuse interventions before they are built, reducing trial-and-error and long-term operational risks (Noronha et al., 2024; Stone, 2017). Digital twins offer predictive simulations of building behavior under various conditions. In the Republican Museum project, they helped optimize thermal comfort and conservation strategies (Noronha et al., 2024). These twins also support proactive maintenance and user-centered adaptation (Baeriswyl et al., 2023; Mocerino et al., 2024).

Heritage Material Passports

Material passports are digital records of a building's materials, including their reuse or recycling value (Gómez-Gil et al., 2024; Dos Santos Goncalves et al., 2025). They support sustainable reuse by helping identify valuable materials, promoting recycling, and guiding design decisions (Dos Santos Goncalves et al., 2025; Rashid et al., 2023). Material passports enable informed design by identifying recyclable or hazardous materials early, improving sustainability outcomes (Gómez-Gil et al., 2024). Material passports guide circular reuse strategies by identifying salvageable materials and reducing demolition waste (Gómez-Gil et al., 2024; Dos Santos Goncalves et al., 2025). They promote transparency and enable accurate environmental performance assessments in reuse projects (Dos Santos Goncalves et al., 2025; Marzouk, 2023).

Digital Platforms (CDEs, Metaverse, Gamification)

Digital platforms like CDEs help teams share information in real time. New tools like gamified platforms or VR environments let users explore reuse plans interactively (Davies et al., 2024; Li, 2024; Jadresin Milic et al., 2022). These platforms improve collaboration, transparency, and public engagement (Alshboul et al., 2024; Dhanda et al., 2017; Vileikis, 2023; Cantagallo & Sangiorgio, 2025; Balocco et al., 2020). Platforms also include tools for visual and spatial analysis, such as eye-tracking and spatial syntax for user interaction analysis (Balocco et al., 2021; Davies et al., 2024). Interactive platforms promote collaboration among experts and allow public input through virtual exploration of reuse scenarios (Li, 2024; Balocco et al., 2021). Platforms with spatial analysis tools (like eye-tracking) help design user-friendly reuse plans (Balocco et al., 2021). They enhance public participation and understanding of reuse outcomes by enabling stakeholders to interact with simulations (Li, 2024; Artopoulos et al., 2024).

Blockchain Technology

Blockchain can track important heritage building data securely. It creates trusted records of changes made during reuse and can support ownership tracking, material history, and multi-stakeholder coordination (Gómez-Gil et al., 2024; Omar, 2024; Rashid et al., 2023). It has also been considered in relation to circular economy principles and emotional heritage attachment (Rashid et al., 2023). Blockchain has the potential to increase trust in restoration projects by ensuring historical integrity and traceability of interventions (Omar, 2024; Marzouk, 2023). Blockchain enables transparent tracking of material provenance and changes made during reuse, ensuring historical data is not lost or altered (Omar, 2024). It secures responsibility sharing and data reliability among teams (Gómez-Gil et al., 2024).

3D Printing and Prefabrication

3D printing helps recreate missing or damaged historical elements. It allows for fast, low-cost reproduction of unique parts. Prefabrication speeds up construction, especially when accurate replicas are needed (Jesus et al., 2025; Triviño-Tarradas et al., 2024; Parracho et al., 2025). CNC and 3D scanning techniques have further expanded precision in architectural replication (Triviño-Tarradas et al., 2024). 3D printing enables fast prototyping of missing heritage parts, ensuring accuracy and reducing costs compared to manual restoration (Jesus et al., 2025). 3D printing restores heritage elements quickly and precisely, even when originals are missing (Jesus et al., 2025). Combined with CNC and photogrammetry, it ensures high-fidelity replication of ornamentation and supports rapid, cost-effective prototyping (Triviño-Tarradas et al., 2024; Núñez-Camarena et al., 2024).

Internet of Things (IoT) and Smart Systems

IoT systems monitor building conditions such as temperature, humidity, and air quality. These systems help optimize energy use and ensure reused buildings are safe and comfortable (Savitri & Amalia, 2024; Mocerino et al., 2024; Xiao et al., 2025). IoT is often linked to digital twins for ongoing monitoring (International Journal of Scientific Research and Engineering Trends, 2025). Recent examples apply smart sensors to tropical-climate-built heritage to improve energy efficiency (Xiao et al., 2025). IoT systems continuously monitor interior climate and usage patterns, supporting predictive maintenance and reducing energy waste (Xiao et al., 2025). Smart sensors help monitor thermal, moisture, and air quality levels in reused buildings. In tropical settings, IoT systems have been shown to reduce energy loads while preserving user comfort and heritage integrity (Xiao et al., 2025).

Virtual Reality (VR) and Augmented Reality (AR)

VR and AR offer virtual tours and overlays to explore reused spaces before construction. They help designers and the public understand changes, test ideas, and make better decisions through immersive visualization (Shanthini et al., 2023; Graham et al., 2018; Dhanda et al., 2017; Li, 2024; Jadresin Milic et al., 2022). Digital education efforts are integrating VR for heritage awareness and learning (Jadresin Milic et al., 2022; Vileikis, 2023). VR/AR tools enable immersive simulation of reuse options, improving public feedback and speeding up design revisions (Graham et al., 2018; Jadresin Milic et al., 2022). VR and AR have been used to simulate interventions and visualize reuse designs in public consultations (Graham et al., 2018). Educational tools like VR kiosks increase awareness and stakeholder support (Dhanda et al., 2017). They also help train professionals in preservation decision-making (Jadresin Milic et al., 2022). The preservation and adaptive reuse of cultural heritage pose complex challenges. Digital technologies are potential enablers in this domain, offering new capabilities for documentation, analysis, intervention, collaboration, and management. This report provides an analysis of the technologies identified based on the literature review and examines their integrated potential, the inherent challenges in their implementation, and their evolving role in shaping the future of heritage adaptive reuse.

4.3.2. Evaluating the potential of digital technologies: a SWOT perspective

The individual digital technologies discussed in this report could offer significant benefits for heritage adaptive reuse. However, their true potential to transform is often realized when they are integrated into workflows and strategies, which are being used by architects, constructors, engineers, but also regulators, policy makers, users and other stakeholders. This integration is not without its challenges, and understanding these is important for effective implementation, especially since these technologies are changing very rapidly. To help with this understanding, this research identified a set of initial questions derived from the workshop, expert interviews, and the literature reviewed, which can be used to evaluate the digital technologies:

LIST OF QUESTIONS FOR DT EVALUATION

1. **Do they enable the digital workflow, from scan to living model?**
2. **Do they offer data-driven decision support?**
3. **Are they enabling participation of different stakeholder groups?**
4. **Do they facilitate collaboration?**
5. **Are they enabling the circular economy?**
6. **Can data be easily acquired and kept accurate?**
7. **Is interoperability and data integration possible?**
8. **What are the costs and resource constraints?**

9. **Are the digital skills required difficult to acquire?**

10. **Do they get obsolete? (How do they safeguard data long term?)**

11. **Are there ethical and authenticity concerns?**

This research aims to answer the questions above by creating an initial Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of key digital technologies, specifically examining their application in heritage adaptive reuse (see **Table** below). The SWOT framework is a planning tool that helps identify internal (strengths and weaknesses) and external (opportunities and threats) factors relevant to achieving an objective. In the context of heritage adaptive reuse, it provides a structured approach to evaluate the viability and implications of adopting various digital technologies.

- Strengths are the internal positive attributes that give a technology an advantage in the adaptive reuse process.
- Weaknesses are the internal negative attributes that could hinder a technology's effectiveness in supporting the adaptive reuse of built heritage processes.
- Opportunities are external factors that could be leveraged for growth or advantage.
- Threats are external factors that could pose risks or challenges in the digitalization of the adaptive reuse of heritage.

Table 11. SWOT analysis of digital technologies from the literature review, workshop and interviews

DTs SWOT Analysis			
Strengths (S)	Weaknesses (W)	Opportunities (O)	Threats (T)
Heritage Building Information Modeling (HBIM)			
Provides extensive digital representation of characteristics, integrating historical and material data (Marzouk, 2023; Micheloni et al., 2023; Machete et al., 2021). Workshop - experts confirmed strong potential for centralized documentation and data sharing; Interview 1 – highlighted its value for long-term	Requires significant expertise for accurate modeling of complex, irregular historic geometries and delicate materials (Tsilimantou et al., 2020; Jadresin Milic et al., 2022). In the workshop, the lack of HBIM skills was seen as a major barrier.	Can evolve into dynamic Digital Twins by integrating real time IoT data for continuous monitoring and performance optimization (Noronha et al., 2024; Baeriswyl et al., 2023). Workshop viewed it as a path to predictive maintenance.	Risk of digital obsolescence, making long-term data accessibility and usability problematic (Vileikis, 2023).

maintenance.			
Enables creation of accurate, semantically detailed foundational models for built heritage (Yuan et al., 2024; Metawie & Marzouk, 2020; Marzouk & Metawie, 2023). Workshop noted HBIM improves multidisciplinary coordination when data standards are aligned. Workshop participants stressed HBIM's usefulness for risk planning across teams.	Faces challenges with interoperability and seamless data exchange between different software and platforms, leading to data silos (Chow & Fai, 2017; Jadresin Milic et al., 2022). Workshop, experts reported fragmented data flows between platforms.	Improves decision support through integration with AI/ML for complex analyses like energy performance simulation (Akyol & Şimşek, 2024; Cinquepalmi et al., 2023).	Potential for misrepresentation or overly invasive interventions if not managed ethically, compromising authenticity (Mocerino et al., 2024, Dastgerdi et al., 2024). Workshop warned of data ownership ambiguity; Interview 2 expressed concern over resource demands for smaller projects.
Facilitates complex project management, including health and safety aspects in industrial heritage (Gürcanlı et al., 2025; Crisan et al., 2025). Interview 2 - expert viewed HBIM as key to connecting design and facility management.	Involves substantial initial investment for software licenses and high-precision hardware (Metawie & Marzouk, 2020; Shrestha et al., 2017). Interview 1 -budget constraints at Paradiso limited adoption.	Supports circular economy principles by enabling detailed material cataloging and reuse potential when combined with Material Passports and Blockchain (Gómez-Gil et al., 2024; Rashid et al., 2023). Workshop – HBIM suggested for circular data tracking).	
Supports the development of sustainable adaptive reuse management models (Bianchi & De Medici, 2023).		Potential as "data backbone" for funding and governance Workshop insight.	

3D Laser Scanning

Enables rapid and accurate capture of complex geometries and detailed as-built conditions of heritage structures (Marzouk & Metawie, 2023). Workshop – experts confirmed scanning as most practically used technology	Can be time-consuming and costly, especially for large or intricate heritage sites (Shrestha et al., 2024). Workshop highlighted budget and processing burden.	Forms a foundational step in the digital workflow, generating data for HBIM and Digital Twins (Yuan et al., 2024; Noronha et al., 2024). Workshop sees it as entry-level digital tool.	Risk of data loss or inaccessibility due to digital obsolescence if not properly managed for long-term preservation (Vileikis, 2023).

in field.			
Provides objective, measurable data for documentation and analysis, reducing human error ((Micheloni et al., 2023). Interview 1 – Paradiso team used scans for complex roof and façade analysis.	Requires significant expertise for data processing and interpretation, particularly for complex historic fabric (Tsilimantou et al., 2020). Workshop noted need for cross-disciplinary training.	Facilitates precise restoration and remastering of intricate elements like sculptures (Ardhiati & Hasan, 2024; Triviño-Tarradas et al., 2024). Interview 1 – used for acoustic panel prefabrication.	Ethical concerns regarding potentially invasive data acquisition or mis-representation of heritage values (Mocerino et al., 2024). Workshop participants warned against unverified data being archived without context.

Photogrammetry

Cost-effective method for creating 3D models from 2D images, suitable for detailed documentation of heritage sites (Triviño-Tarradas et al., 2024; Costantino et al., 2022). Workshop praised it for affordability and ease of training.	Accuracy can be dependent on image quality, lighting conditions, and camera calibration (Triviño-Tarradas et al., 2024). Workshop noted weather and lighting limitations.	Complements laser scanning in reality capture workflows for comprehensive documentation and HBIM creation (Yuan et al., 2024; Metawie & Marzouk, 2020). Workshop recommended combined capture pipeline.	Risk of digital obsolescence and long-term data preservation challenges for the generated models (Vileikis, 2023). Workshop 4 flagged format migration risk.
Highly versatile, applicable to various scales from small artifacts to large buildings and landscapes (Núñez-Camarena et al., 2024; Ardhiati & Hasan, 2024). Interview 1 – used for archival visual records at Paradiso.	Processing large datasets can be computationally intensive and time-consuming (Artopoulos et al., 2024).	Enables virtual tours and immersive experiences for public engagement and education (Li, 2024; Jadresin Milic et al., 2022). Interview 2 – could enhance Paradiso's educational outreach).	Potential for misinterpretation if models are not accurately contextualized or if data quality is compromised (Mocerino et al., 2024).

Artificial Intelligence (AI) and Machine Learning (ML)

Automates complex analyses and leverages vast datasets for deeper insights in heritage adaptive reuse (Akyol & Şimşek, 2024; Cinquepalmi et al., 2023). Workshop experts saw AI as key for pattern recognition in	Requires significant computational power and large, high-quality datasets for effective training and operation (Akyol & Şimşek, 2024). Workshop - data scarcity limits training for heritage cases.	Transforms data into strategic intelligence, assisting in multi-criteria decision-making for sustainable reuse strategies (Akyol & Şimşek, 2024). Workshop suggested use for balancing value and energy criteria.	Ethical concerns regarding algorithmic bias, data privacy, and the potential for de-humanizing heritage interpretation (Mocerino et al., 2024). Workshop cautioned against untransparent AI outputs; Interview 1 – concern over loss of

maintenance data.			human interpretation.
Provides predictive analytics for maintenance needs and optimizes operational performance, such as energy use (Noronha et al., 2024; Baeriswyl et al., 2023). Interview 2 – valued for long-term asset planning.	Demands specialized knowledge and analytical skills for effective utilization and interpretation of results (Alshboul et al., 2024). Workshop described lack of analytical capacity within heritage teams.	Can optimize energy performance of retrofit options and assess structural integrity under new loads (Cinquepalmi et al., 2023; Noronha et al., 2024).	Risk of extreme reliance on automated systems potentially diminishing human expertise in qualitative heritage assessment (Mocerino et al., 2024).
Internet of Things (IoT)			
Enables real time monitoring of environmental conditions (e.g., temperature, humidity) and structural health in built heritage (Noronha et al., 2024; Xiao et al., 2025). Workshop 2 praised IoT for low-cost environmental sensing in heritage.	Installation in historic fabric can be challenging and potentially invasive, requiring careful consideration of minimum intervention (Mocerino et al., 2024; Xiao et al., 2025). Workshop highlighted ethical concerns about sensor placement on monuments	Integrates with Digital Twins to create dynamic, living models for continuous adaptive management (Noronha et al., 2024). Workshop viewed IoT as gateway for dynamic monitoring.	Data security and privacy concerns regarding sensitive real-time building data (Vileikis, 2023). Workshop called for clear governance policies around IoT.
Provides continuous data streams for proactive maintenance and performance optimization (Baeriswyl et al., 2023). Interview 2 – Paradiso considering IoT for audience flow and humidity control).	Requires solid network infrastructure and power supply, which may be difficult to implement in old buildings (Xiao et al., 2025). Interview 1 – historic walls limit signal coverage.	Enables predictive maintenance and early detection of deterioration, extending the lifespan of heritage assets (Baeriswyl et al., 2023).	Risk of system failure or sensor malfunction leading to unreliable data or missed critical events (Mocerino et al., 2024).
Digital Twins			
Provides a dynamic, real-time virtual replica of a heritage building, reflecting its current state and performance (Noronha et al., 2024; Baeriswyl et al.,	Requires significant initial investment in supporting HBIM, IoT sensors, and integration platforms (Metawie & Marzouk, 2020; Shrestha et al., 2017). Workshop	Integrates with AI for predictive analytics, optimizing maintenance schedules and energy efficiency (Akyol & Şimşek, 2024; Cinquepalmi	Vulnerable to digital obsolescence, posing risks to long-term data accessibility and model usability (Vileikis, 2023). Workshop warned

2023). Workshop recognized it as future direction for heritage monitoring.	found that cost and complexity limit use in small projects.	et al., 2023). Workshop discussed potential integration with AI for preventive maintenance.	against uncontrolled data sharing between vendors.
Enables continuous monitoring, simulation, and optimization of operational performance (e.g., energy use) (Baeriswyl et al., 2023). Interview 2 – could extend Paradiso asset lifecycle planning).	Demands high levels of digital literacy and specialized skills for setup, maintenance, and data interpretation (Alshboul et al., 2024)	Facilitates long-term adaptive management and performance optimization throughout the asset's extended lifecycle (Marzouk, 2023; Noronha et al., 2024).	Data security and integrity risks, as real-time data streams could be compromised or misused (Mocerino et al., 2024).

Virtual Reality (VR) and Augmented Reality (AR)

Provides immersive design review capabilities, allowing stakeholders to visualize and interact with proposed adaptive reuse changes (Li, 2024; Graham et al., 2018). Workshop participants said immersive walkthroughs improved consensus in reuse design discussions.	Requires high quality 3D models and significant computational resources for realistic rendering (Li, 2024). Workshop discussed how smaller firms lack compatible hardware.	Improves communication and facilitates more inclusive collective decision-making, especially when combined with CDEs (Li, 2024; Balocco et al., 2020). Workshop found it effective tool for interdisciplinary communication.	Potential for creating misleading or decontextualized representations of heritage if not carefully managed (Mocerino et al., 2024). Workshop warned of historical distortion risk.
Improves public engagement and understanding of complex heritage proposals through interactive experiences. (Dhanda et al., 2017; Jadresin Milic et al., 2022). interview 2 – Paradiso team noted potential for educational visitor experiences.	Can cause motion sickness or discomfort for some users, limiting widespread accessibility (Li, 2024).	Offers new avenues for heritage interpretation, education, and tourism experiences (Vileikis, 2023; Jadresin Milic et al., 2022). Interview 1 - Proposed for Paradiso exhibition planning.	High development costs for bespoke immersive content for specific heritage sites (Shrestha et al., 2017). Interview 1 discussed how budget limits hinder custom content.

Common Data Environments (CDEs)

Serves as a central digital backbone for integrating various software tools and datasets (Jadresin Milic et al., 2022; Artopoulos et al., 2024). Workshop expressed consensus that CDEs improve transparency across teams.	Requires robust interoperability standards to ensure seamless data exchange and prevent data silos (Tsilimantou et al., 2020). Workshop raised concern about inconsistent data schemas.	Improves communication and leads to more inclusive and robust collective decision-making when combined with immersive tools like VR/AR (Li, 2024; Graham et al., 2018).	Data security and access control concerns, as sensitive project data is centralized (Vileikis, 2023). Workshop - privacy protocols seen as underdeveloped.
Facilitates collaboration among diverse stakeholders (architects, engineers, conservators, community members) (Balocco et al., 2020; Bianchi & De Medici, 2023).	Implementation can be complex, requiring significant organizational change and training for effective adoption (Alshboul et al., 2024). Interview 1 – Paradiso cited long setup times	Streamlines workflows and enhances overall project efficiency in multi-disciplinary heritage projects (Artopoulos et al., 2024). Workshop identified potential for live collaboration and audit trails.	Risk of vendor lock-in if proprietary CDE solutions are adopted without open standards (Jadresin Milic et al., 2022). Interview 2 highlighted risk from proprietary platforms.

Blockchain Technology

Provides a secure, transparent, and unchangeable ledger for tracking and verifying data, improving trust and accountability (Rashid et al., 2023; Gómez-Gil et al., 2024; Omar, 2024). Workshop experts agreed it ensures material provenance.	High energy consumption for proof-of-work blockchains, posing sustainability concerns (Rashid et al., 2023). Workshop questioned environmental cost for heritage sector.	Secures and makes transparent the tracking of heritage materials for circular economy principles when combined with Material Passports and BIM/HBIM (Gómez-Gil et al., 2024; Marzouk, 2023). Workshop cited it as foundation for traceable reuse markets.	Regulatory uncertainty and legal complexities regarding digital ownership and intellectual property on a blockchain (Rashid et al., 2023; Omar, 2024). Workshop discussed unclear governance for digital ownership.
Offers strong data integrity and provenance tracking for digital heritage assets and material flows (Rashid et al., 2023). Interview 2 suggested it for recording adaptive reuse material flows.	Scalability issues and transaction speed limitations for large volumes of data (Rashid et al., 2023). Workshop expressed concern about integrating large datasets.	Can create solid and trustworthy frameworks for valuing and facilitating the reuse of heritage materials (Rashid et al., 2023). Interview 1 proposed it to ensure authenticity of reclaimed	Irreversibility of data entries means errors are permanent once recorded (Rashid et al., 2023).

		components.	

3D Printing & Prefabrication

Scan to print and prefabrication deliver exact-fit parts faster with better quality control and less waste (Triviño-Tarradas et al., 2024; Jesus et al., 2025; Parracho et al., 2025). Workshop praised it for efficient part replication and Interview 2 referred to the technology as being used for testing modular interior prototypes at Paradiso.	Needs specialized equipment and skills; material behavior and durability of printed mixes are still being validated (Parracho et al., 2025; Jesus et al., 2025).	Pair photogrammetry/UAV and laser scanning with HBIM to model and 3D-print accurate replacements linked to digital twins for planning (Núñez-Camarena et al., 2024; Marzouk & Metawie, 2023; Triviño-Tarradas et al., 2024). Workshop recommended workflow for small-scale replacements.	Concerns about authenticity of printed replacements and risk of digital obsolescence in files, formats, and toolchains (Vileikis, 2023). Workshop warned replicas may reduce perceived historical value.

Heritage Material Passports

Enables detailed digital cataloging of materials within a heritage structure, including characteristics, condition, and reuse potential (Gómez-Gil et al., 2024). Workshop confirmed its role in quantifying reuse potential.	Requires extensive initial effort for material identification, assessment, and data input for existing buildings (Gómez-Gil et al., 2024). Interview 2 – Paradiso noted difficulty maintaining consistent records.	Strongly supports circular economy principles within adaptive reuse projects, minimizing waste when combined with BIM/HBIM and blockchain (Gómez-Gil et al., 2024; Rashid et al., 2023). Workshop saw it as key for reuse certification.	Potential for inaccurate or incomplete data if initial surveys are insufficient, undermining trust in the passport (Mocerino et al., 2024). Workshop called for validation guidelines.

Big Data and Analytics

Supports sustainable practices by promoting the reuse and recycling of heritage building components (Gómez-Gil et al., 2024; Artopoulos et al., 2024). Workshop highlighted its role in evidence-based policy making.	Lack of standardized methodologies for material assessment and data representation across different regions (Tsilimantou et al., 2020). According to the workshop, fragmented data formats hinder analytics.	Creates new economic opportunities by facilitating the tracking, valuing, and trade of salvaged heritage materials (Rashid et al., 2023; Bianchi & De Medici, 2023). Interview 1 discussed the potential for heritage marketplace.	Legal and liability issues related to material quality, safety, and provenance during reuse (Rashid et al., 2023; Vileikis, 2023). Workshop discussed uncertainty over data use rights.

The SWOT analysis was then used to answer the initial questions set for the evaluation of digital technologies. Although not for every question an answer was clearly articulated in the 38 academic papers, a scorecard was created giving a neutral score to insufficient information areas. The result is summarized in Figure 5 and Figure 6 below and an overview of the scorecard and rationale used can be found in Appendix C.

SCORECARD DTs EVALUATION

Technology Average Scores

Technology	Average Score
HBIM	2,91
3D Laser Scanning	2,91
Photogrammetry	2,91
Digital Platforms CDEs	2,91
Big Data Analytics	2,82
IoT Smart Systems	2,82
AI ML	2,73
Digital Twins	2,73
Material Passports	2,64
3D Printing Prefab	2,55

Figure 5. Ranking of digital technologies (DTs) from the SWOT analysis. Scores combine strengths/opportunities and weaknesses/threats to rank DTs.

Digital Technology Adoption Pro's and Con's

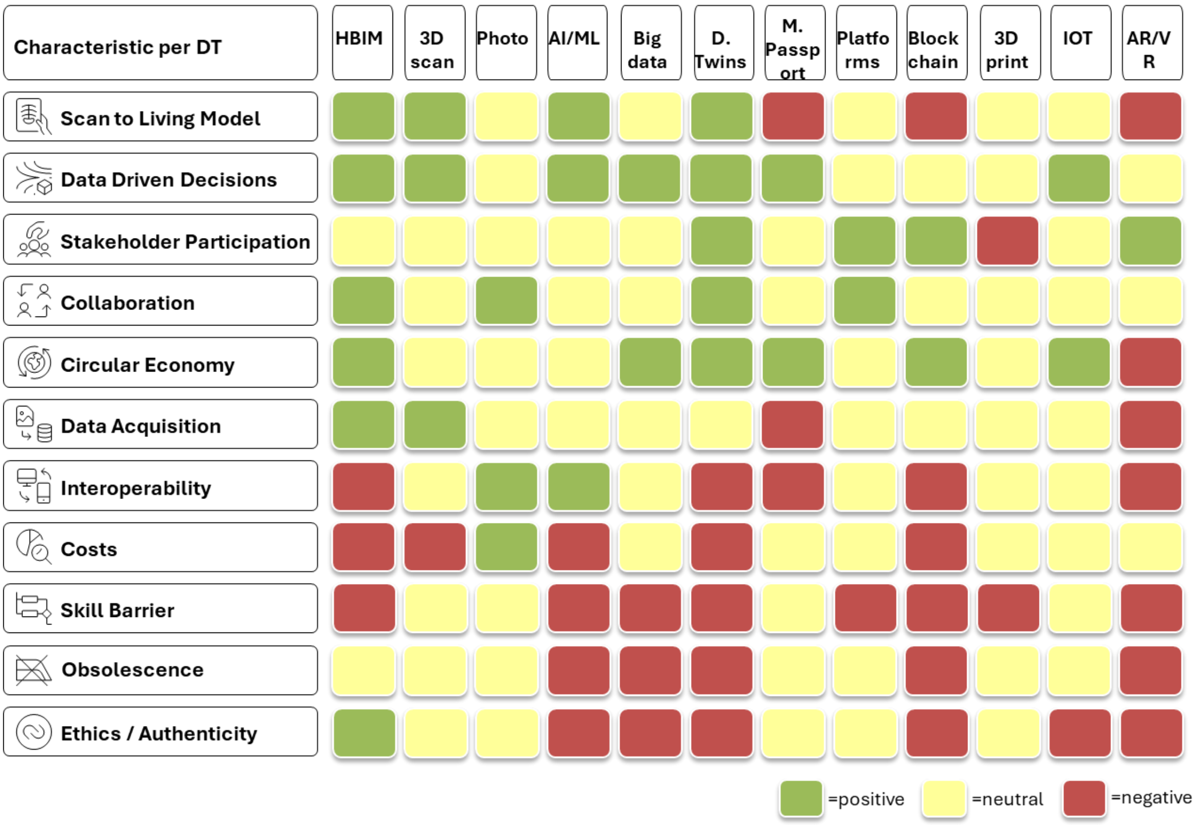

Figure 6. Comparative SWOT profile of DTs. Grid shows where each technology scores well or badly.

The following is a summarized list of best and least suited digital technologies depending on the driver (as expressed in the initial 11 questions used in the assessment criteria). It is important to reflect on the fact that while all technologies have been assessed for impact, their scope is different and the positive/neutral/negative impact in the adaptive reuse of heritage process should consider the scale of each technology.

Scan to living model

- The most reliable way to build a living model is to capture the site with 3D laser scanning and photogrammetry, model it in BIM/HBIM, and then add IoT data to obtain a real-time Digital Twin. VR/AR and blockchain do not create living models. Instead, they are layers that sit on top of other systems, to enhance them.

Data-driven decisions

- BIM/HBIM provides structured information, while AI/ML turns that information into analyses and predictions. IoT supplies real-time data, and Digital Twins bring these pieces together for ongoing, predictive decision-making. Scanning and photogrammetry support this by feeding accurate inputs, but they do not make decisions on their own.

Participation of different stakeholder groups

- Common Data Environments (CDEs) enable many disciplines to work from the same information. VR/AR helps non-technical stakeholders understand proposals and give feedback, which makes participation easier. Other tools contribute indirectly but are not designed primarily for participation.

Collaborative ecosystems

- CDEs act as the backbone for collaboration by connecting tools and teams. HBIM supports coordination around a shared model, and blockchain can add trust where verifiable exchanges of materials or provenance are needed. Collaboration weakens if open standards and clear rules are not enforced.

Enabling the circular economy

- Material Passports, combined with HBIM, can offer the strongest basis for reuse and recycling. Blockchain can help if a tamper-evident record of material provenance and transfers is needed. Other technologies are helpful, but they play a supporting role.

Data acquisition and accuracy

- Laser scanning is the most useful method for capturing complex geometry. Photogrammetry also works well, but results depend on image quality and conditions. IoT adds continuous measurements, although installing sensors in historic fabric needs careful planning. HBIM accuracy still depends on skilled modeling and good quality control.

Interoperability and data integration

- Interoperability is often a weak point for HBIM and Digital Twins, because different tools create data silos. CDEs improve integration, but only if open formats, shared naming conventions, and clear metadata rules are adopted. Without these, data gets stuck and collaboration slows down.

Costs and resource constraints

- HBIM, Digital Twins, large-scale laser scanning, and custom VR/AR content can be expensive and time-consuming. Photogrammetry is usually cheaper. IoT and CDEs bring ongoing costs for hardware, networks, and training, which should be planned for upfront.

Digital skills required

- The steepest learning curves are in BIM/HBIM, AI/ML, Digital Twins, and laser-scan processing. Photogrammetry, CDEs, and Material Passports require moderate skills. Viewing VR/AR experiences is easy for most users, but creating high-quality content requires expertise.

Obsolescence and long-term data

- All digital technologies face obsolescence risks. These can be reduced by choosing open formats, keeping clear export and migration paths, maintaining checksums and backups, and scheduling periodic media and software updates. Versioning the models used also helps preserve history.

Ethics and authenticity

- AI/ML can introduce bias and privacy risks, VR/AR can mislead if not contextualized, IoT can expose sensitive data, and blockchain makes errors hard to reverse. The recommendation is to set simple guardrails: define consent and privacy rules, validate models and visualizations, secure data flows, and document how decisions are made.

4.4. MAPPING DIGITAL TECHNOLOGIES ON THE DARBH FRAMEWORK

These final framework (DARBH) is the result from layering all stages of the research into one coherent view: first, the adaptive reuse process for built heritage was mapped and simplified into clear pillars (capture, create, conserve, communicate, control) aligned with practical project steps; then, each digital technology was reviewed in depth to understand what it does in that process, where it adds the most value, and where risks, costs, skills, ethics, and interoperability constraints appear. Through SWOT analysis, scoring, and cross-comparison, the technologies were positioned so that their strengths overlapped with specific reuse steps. At the same time, known weaknesses could be managed in real project conditions (for example, through governance, standards, or combined tools). The final pillar–technology map reflects patterns that recur across the literature, the Paradiso case study, and evaluations, and is designed to give practitioners a simple, actionable way to adopt digital tools into heritage reuse without losing sight of authenticity, feasibility, and long-term objectives.

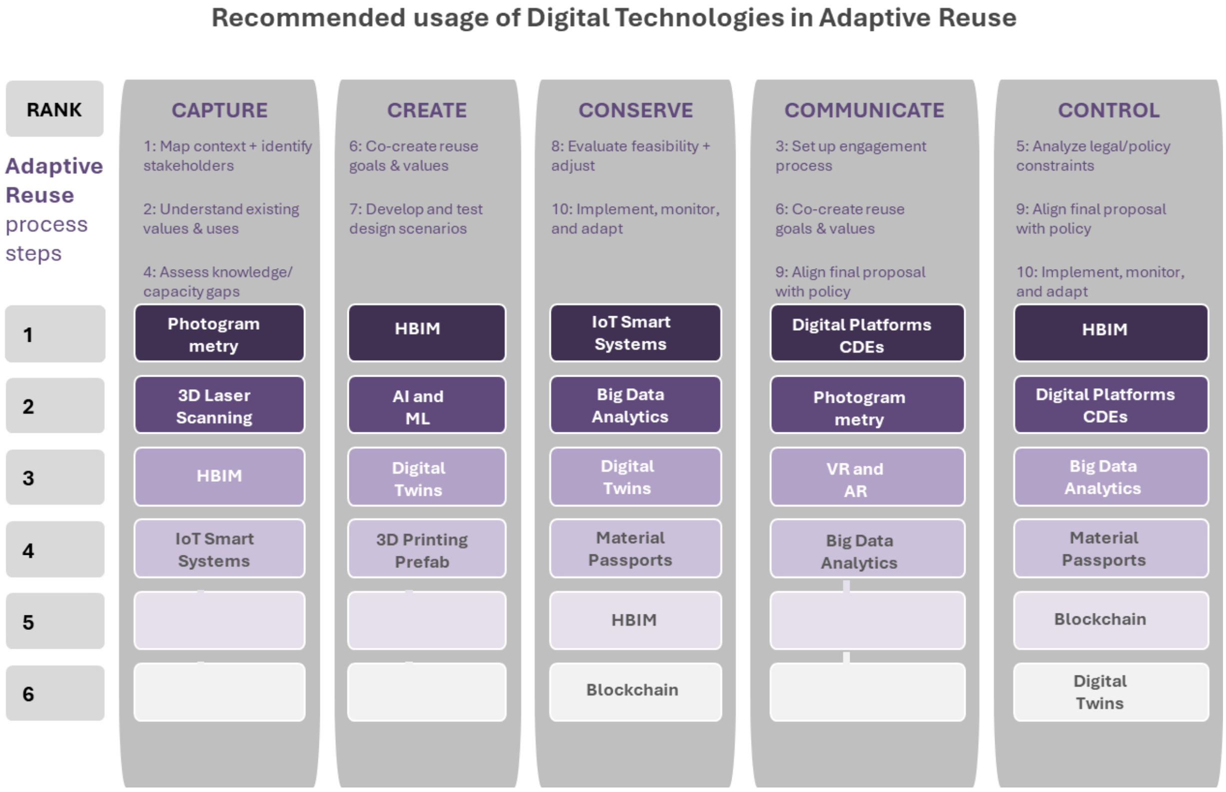

Figure 7. The DARBH (Digital Adaptive Reuse of Built Heritage framework) showing recommended digital technologies by pillar in adaptive reuse. Columns show pillars (Capture, Create, Conserve, Communicate, Control) with items ranked 1–6 by recommended use.

5. DISCUSSION AND CONSLUSION

5.1. CONCLUSIONS

This research investigated how digital technologies can be systematically and effectively integrated into the adaptive reuse process of built heritage to support values-driven approaches. The findings show that while digital tools are increasingly adopted in heritage projects, their use remains fragmented and focused primarily on technical documentation or visualization. The study shows that digital technologies have far greater potential when applied in a structured, broader framework that clearly connects technology use to the full adaptive reuse process and to the wide range of heritage values: social, cultural, environmental, political, economic, among others. Although the framework can be applied to any adaptive reuse project, its greatest strength lies in supporting values-driven heritage interventions. It helps reveal where digital technologies align, or fail to align, with the broader values embedded in built heritage. By making these gaps visible, the framework enables professionals to better assess and demonstrate the value their interventions create, preserve, or risk diminishing, ensuring that technological decisions are based on heritage significance and not only efficiency and economic gain.

The Digital Adaptive Reuse of Built Heritage (DARBH) framework developed here addresses this gap by categorizing digital technologies in five pillars: Capture, Create, Conserve, Communicate, and Control and mapping them to a step-by-step adaptive reuse process. This approach enables a more integrated use of technologies that goes beyond isolated technical steps. It helps grow multi-stakeholder collaboration and support participation in the heritage adaptation.

Insights from the expert workshop and the Paradiso case study show that one key barrier to effective digital integration is the divide between digital technology specialists and heritage professionals (architects, engineers, constructors, and policymakers) who often operate in different knowledge domains and speak different professional languages. Digital technologies, especially collaborative platforms and immersive visualization tools, bring opportunities to bridge these divides by creating shared spaces for communication and coordinated decision-making.

Answers to Research Questions

RSQ1: How have digital technologies been systematically integrated into each step of the adaptive reuse process for built heritage?

Although digital technologies have traditionally been applied in a fragmented way, focusing on the survey, documentation, and visualization phases, this research establishes a more systematic integration through the DARBH framework. Technologies are categorized into five functional pillars and mapped to a step-by-step adaptive reuse process:

- **Capture** technologies (e.g., 3D laser scanning, photogrammetry, IoT) support data acquisition and site assessment.
- **Create** technologies (e.g., HBIM, 3D printing) enable detailed modelling, design development, and accurate reproduction of heritage elements.

- **Conserve** technologies (e.g., digital twins, AI, IoT sensors) facilitate real-time monitoring, predictive maintenance, and lifecycle management.
- **Communicate t**echnologies (e.g., VR/AR, digital engagement platforms) improve stakeholder participation and public consultation.
- **Control** technologies (e.g., blockchain and Common Data Environments) improve data management, project coordination, and governance.

This integrated framework, which has been validated during the workshop and adjusted to consolidate DTs based on the overall objective of data use as part of the adaptive reuse process (see chapter 4.1 for specific changes to the framework based on received input), eliminates the siloed use of digital technologies by proposing their deployment across the adaptive reuse lifecycle, to support a values-driven approach.

RSQ2: What are the main opportunities and challenges experienced by practitioners in using digital technologies in the adaptive reuse of heritage?

Practitioners recognize several key opportunities brought by digital technologies: improved documentation accuracy, better stakeholder communication, and support for sustainable reuse strategies. Technologies also help mitigate workforce shortages by complementing expert skills and enabling more efficient project workflows.

At the same time, practical challenges remain significant, including limited digital literacy among heritage stakeholders, high upfront costs, interoperability issues, regulatory complexity, and concerns about data privacy and authenticity. Given the limited availability of heritage expertise and the complexity of historic buildings, digital technologies can complement human skills and save valuable time. However, building capacity and improving understanding between stakeholders remain very important. Given this, alignment and more effective information management are the priorities for wider technology adoption and achieving more predictable, values-driven project outcomes.

In the Paradiso case, the interviews confirmed these findings. Paradiso already uses 3D printing and prefabrication to recreate intricate parts as craft skills become scarce, and relies on sensors to manage sound and light. Scanning delivers accurate data, but converting point clouds into usable models is costly and specialist, and BIM was judged as not suited to the building's irregular geometry. A substantial paper archive exists and digitizing it and exploring a digital twin were viewed as promising, but current costs and technical burden are barriers. Adoption challenges come less from the lack of interest and more from time, skills, and coordination across many actors, alongside privacy concerns around visitor analytics and the need to tailor communication to diverse audiences and a changing political context.

RSQ3: How can a practical framework support the effective use of digital technologies to achieve values-driven outcomes in adaptive reuse?

The DARBH framework, developed and validated through this research, offers a practical tool for heritage professionals. By organizing digital technologies into functional pillars and linking them directly to adaptive reuse process stages and heritage values, it simplifies complexity and aids informed decision-making. The framework operationalizes values-driven heritage conservation by including cultural, social, ecological, and economic (among others) considerations directly into the selection and application of technology.

It also promotes inclusive multi-stakeholder engagement through communication and collaboration technologies, and it supports consensus and shared ownership. Because of the modular design, the framework can be used in diverse project contexts and resource levels, and it allows for digital adoption to happen gradually while respecting the context.

Main RQ: How can digital technologies be effectively integrated into the adaptive reuse process of built heritage to support values-driven outcomes?

As a result, this research demonstrates that effective integration requires a structured framework that explicitly maps digital technologies to each stage of the adaptive reuse process and aligns their application with the diverse social, cultural, environmental, political, economic and other values that heritage represents. The DARBH framework uses this approach by combining technologies to address specific challenges at different project phases and support collaboration between disciplines.

5.2. DISCUSSION

This research aims to understand how digital technologies can be more effectively integrated into the adaptive reuse of built heritage to achieve values-driven outcomes. The results confirm that digitalization in heritage practice is advancing but remains inconsistent. The DARBH framework developed in this study addresses this gap by connecting technologies to each stage of the reuse process and to the diverse heritage values identified in earlier literature.

Integration and the need for structure

The literature review and case study both showed that digital technologies are often applied in isolation. This fragmented use limits their potential to support broader cultural and social objectives (Plevoets & Van Cleempoel, 2019; Cucco et al., 2023). The DARBH framework addresses this problem by offering a structured approach in which digital tools are not separate interventions but are linked across the adaptive reuse lifecycle. This finding aligns with studies by Arfa et al. (2022) and Bandarin & van Oers (2012), which highlight that heritage transformation requires iterative and multi-layered processes rather than static preservation actions.

The proposed five functional pillars: Capture, Create, Conserve, Communicate, and Control, translate this principle into practice. They provide a simple way for professionals to understand how technologies can work together, from documentation to long-term management. The expert workshop confirmed that this structure makes digital tools easier to navigate and encourages collaboration across disciplines.

Bridging gaps between disciplines

A key insight from both the workshop and the Paradiso case is the communication gap between heritage professionals and digital technology experts. Architects, engineers, and policymakers often work in different technical languages, while technology specialists may not fully understand heritage constraints or values. Similar issues were observed by Jadresin Milic et al. (2022) and Dastgerdi et al. (2024), who emphasized that miscommunication limits innovation.

The study suggests that technologies themselves, particularly collaborative platforms, BIM/HBIM, and immersive tools, can help bridge this divide by providing shared visual and data environments. When used as “common spaces,” these tools enable professionals to exchange ideas more easily and align decisions around shared heritage values. This contributes to the participatory and inclusive processes promoted by the HUL approach (UNESCO, 2011; Ginzarly et al., 2019).

Technology, value, and participation

The results support the shift in heritage theory from object-based preservation to value-based and people-centered conservation (Pereira Roders, 2007; Labadi, 2013). By integrating digital tools into this framework, the DARBH model demonstrates how technologies can help reveal and sustain both tangible and intangible heritage values. For example, VR and AR tools can help communities visualize proposals before construction, creating new ways to engage and take ownership. This confirms the arguments of Spoormans et al. (2024) and Chen (2022), who show that participation is more effective when it uses accessible, interactive methods.

At Paradiso, engagement is still limited, but interviewees recognized the potential of digital technologies to improve transparency and communication. This aligns with broader calls for heritage governance models that link digitalization with inclusivity (Azzopardi et al., 2023; Rosetti et al., 2020).

Practical and ethical dimensions

While digital tools improve efficiency and data accuracy, the study also found ethical and practical constraints. The main challenges revealed in this research: data ownership, interoperability, training gaps, and authenticity concerns, are like those identified in earlier research (Mazzetto, 2024; Ni et al., 2024). For example, AI and IoT systems may optimize monitoring but raise privacy concerns, while BIM models can oversimplify unique heritage attributes.

The DARBH framework recognizes these tensions and encourages application which is sensitive to its context-. “Starting small and scaling fast” helps ensure that technologies are adapted to the available skills, resources, and heritage context. This incremental approach reflects the principle of sustainable innovation within values-driven heritage management (Ginzarly et al., 2019; Pereira Roders, 2018).

Contribution to theory and practice

The framework offers two main contributions. First, it operationalizes the values-driven heritage theory by linking it to tangible digital processes. It shows that values such as authenticity, continuity, and sustainability can be embedded in technical workflows through the structured use of digital technologies. Second, it provides a practical guide for professionals to select and combine technologies based on their purpose, not their complexity.

This synthesis of theoretical and practical dimensions supports both the academic discussion on digital heritage and the professional need for simple, usable guidance. The DARBH framework, therefore, helps bridge the gap between academic models and applied heritage work, advancing the integration of digitalization into sustainable conservation practice.

5.3. RECOMMENDATIONS

To advance the effective integration of digital technologies in heritage adaptive reuse, several key actions are recommended for practitioners, policymakers, and researchers. The guiding formula for success can be summarized as: ***start small, scale fast, think holistically, and take others along.***

The results of this research show that digital adoption in heritage adaptive reuse is growing but remains underused. Professionals are still unsure how to use these technologies in a structured way. To make digital integration more effective, practitioners, policymakers, technology developers, and researchers need practical steps.

For **practitioners** and project teams, the best approach is gradual. Starting small helps to build confidence and demonstrate value before moving to more complex systems. Simple technologies such as 3D scanning, digital archives, or basic sensors can already improve documentation and coordination. Once these early steps show results, teams can expand to more advanced tools. This helps reduce risk and makes learning easier.

Using a structured framework, such as the Digital Adaptive Reuse of Heritage (DARBH), supports this process. The framework connects each technology to a clear stage of the adaptive reuse process and to the heritage values it serves. In this way, digital technologies become part of a wider strategy that balances technical aims with cultural and social goals. Improving digital literacy is equally important. Training for architects, engineers, and heritage managers helps them understand how to manage data, work with digital models, and make ethical decisions about their use.

The study also highlights the importance of collaboration. Shared digital environments, such as Common Data Environments, allow different disciplines to work with the same information and reduce misunderstandings. Interactive tools such as virtual and augmented reality can also be used to engage communities and explain design ideas more clearly. When stakeholders can see and discuss the project visually, it builds trust and makes participation more meaningful.

For **policymakers,** stronger institutional support is needed. Funding training programs and knowledge exchange between heritage and technology sectors would help close the existing skill gap. Clear policies on data ownership, privacy, and long-term storage are also essential for responsible use. Governments can encourage innovation through grants and pilot projects that use digital tools to support adaptive reuse, sustainability, and the circular economy.

Technology developers should design technologies that better fit the needs of built heritage. Many digital systems are made for new construction and are not flexible enough for historic buildings. Simplifying interfaces and making tools easier to use can help heritage professionals work more efficiently. Cooperation with architects, conservators, and policymakers during tool development ensures that digital systems fit existing workflows. Promoting open data standards remains vital so that information can move easily between different systems and project stages.

Researchers can continue to build on this study by testing the DARBH framework in other contexts and more importantly test how it can be best adopted by practitioners. Comparing projects from different countries, building types, and governance systems would help confirm the framework's broader relevance. Further research should also explore the environmental and ethical side of digitalization, such as the energy use of digital storage or the long-term maintenance of models. It would also be valuable to study how digital engagement tools affect participation and inclusiveness in heritage projects.

This research has some limitations. It focused on a single case study and a small expert group, so the findings cannot be fully generalized. Future research should include a broader range of examples to assess how the framework performs in other settings. Because digital technologies evolve quickly, the DARBH framework should remain flexible and be updated regularly, especially updating the list of technologies applicable to each adaptive reuse step.

In summary, digital transformation in heritage reuse should be practical, inclusive, and gradual. Beginning with small, focused applications, sharing knowledge across disciplines, and applying structured frameworks like DARBH can make digital technologies a meaningful support for conserving and adapting built heritage.

5.4. REFLECTION

This thesis set out to build a practical framework for integrating digital technologies into values-driven adaptive reuse of built heritage. In practice, the process was more academic and literature focused than I had initially intended, since this was an important first step to better understand the opportunities and challenges presented by digital technologies before evaluating how they are applied.

A first limitation is the involvement of practitioners and key decision-makers. I aimed to bring together architects, engineers, constructors, digital specialists, and heritage policymakers, but struggled to secure engagement beyond a small group. Many experts did not respond or declined to participate, and the workshop participants who did contribute were mostly early-career. Their input was relevant and thoughtful, but it cannot fully represent more experienced practice or institutional positions. Similarly, policymakers and heritage authorities were underrepresented, which limited the depth of insight into regulatory, governance, and funding conditions. The hesitation some stakeholders showed once digital technologies were mentioned, including reluctance to be interviewed or to discuss tools beyond basic applications, is itself a finding, but it also constrained the empirical strength of the research.

The case study selection reflects the same challenge. The original intention was to compare multiple cases, but the lack of early stakeholder buy-in meant that only Paradiso could be developed in more detail. Even there, access, time, and topic sensitivity restricted how far digital workflows could be traced or tested. As a result, the DARBH framework is only partially validated in a real project context and relies heavily on the literature and a small number of expert perspectives. The late decision to include the SWOT analysis was a direct response to this: it was a way to add structure and critical depth despite limited empirical material. While this addition strengthens the thesis, it would have been more robust if it had been planned and co-developed with a broader group of practitioners.

A second critical reflection concerns the balance between theory and practice. Much of the work focuses on mapping technologies, concepts, and process models from existing research. This was necessary to build an overview in a fragmented field. Still, it also risks an unbalanced view: the technologies identified are not always directly comparable, differ in maturity, and operate at different scales. More practice-based testing would have allowed a more apparent distinction between what is realistically usable now and what remains experimental. The findings also confirm that digital skills, capacity, and cross-domain understanding are significant barriers, including within this research. The limited overlap between heritage experts, digital technologies, and adaptive reuse meant that many conversations stayed either highly technical or highly conceptual. This mirrors one of the thesis's core messages: without cross-expertise, digital tools will not be fully integrated into heritage reuse practice.

A third point is project management. I did not always keep close enough to the initial planning or make full use of review moments to adjust the scope early. Delays in securing participants, confirming the case study, and scheduling feedback directly impacted the depth of the empirical work and the time available to refine the framework. A more proactive approach to locking in stakeholders earlier, defining minimum empirical requirements, and aligning intermediate outputs more closely with the final defense timeline could have reduced the need for late structural changes and strengthened the practical component.

Despite these limitations, the process has been very instructive. It has been shown that there is genuine interest in using digital technologies to support adaptive reuse, especially for long-term maintenance, monitoring, and management, but also clear uncertainty about how, by whom, and with which skills. For future work, I would shift the focus towards more embedded, real-time applications: co-developing and testing a simplified version of the framework within one or two live projects, involving architects, engineers, owners, and policymakers from the start, and evaluating a smaller set of technologies in depth instead of a broad catalogue. In that way, the next step can move beyond describing potential towards demonstrating concrete, context-specific digital workflows that support values-driven heritage transformation.

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APPENDICES

APPENDIX A: DARBH FRAMEWORK DEVELOPMENT

A.1. AR steps to challenges mapping

		ADAPTIVE REUSE PROCESS STEPS*	0. Initiative	1. Analysis of the building	2. Value assessment of the building	3. Mapping level of significance	4. Adaptive reuse potential (function)	5. Defining the design strategy	6. Final decision-making	7. Execution	8. Maintenance	9. Evaluation after years
UNESCO HUL approach	Core challenges (barriers)	Description	Initiate the project by forming ideas, clarifying the design brief, and deciding to begin the AR process.	Analyze the existing condition of the building, including structure, materials, and current use.	Evaluate the cultural, social, economic, and architectural values of the building.	Identify and document the historical and heritage significance of the building components.	Define the possible new uses and functions of the building based on its condition and values.	Develop appropriate design strategies, conservation actions, and functional changes.	Make final decisions, negotiate contracts, and refine plans before implementation.	Implement the reuse project, manage the team, supervise construction, control quality and cost.	Conduct ongoing maintenance and provide long-term support for the reused building.	Perform post occupancy evaluations to assess reuse outcomes and inform future projects.
Mapping resources	Knowledge integration	Siloed or missing information, poor data-sharing	✓			✓	✓			✓	✓	
	Knowledge & capacity	Lack of skills, expertise, and institutional knowledge	✓			✓		✓				✓
Reaching consensus	Participation	Lack of inclusive, effective stakeholder engagement	✓		✓			✓				✓
Assessing vulnerability	Knowledge & capacity	Lack of skills, expertise, and institutional knowledge	✓			✓		✓				✓
	Knowledge integration	Siloed or missing information, poor data-sharing		✓		✓				✓	✓	
Integrating into planning	Regulatory	Legal and policy barriers, or fragmented rules					✓				✓	
	Economic & financial	Funding gaps, weak financial models			✓				✓	✓		✓
Prioritizing actions	Economic & financial	Funding gaps, weak financial models			✓				✓	✓		✓
Establishing partnerships	Participation	Lack of inclusive, effective stakeholder engagement	✓		✓			✓				✓
	Knowledge & capacity	Lack of skills, expertise, and institutional knowledge	✓			✓		✓				✓

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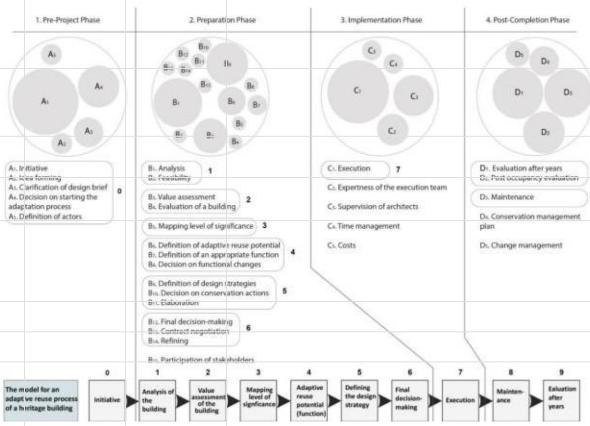
A.2. Proposed Changes to AR process steps

	Step #	Adjusted step description	Roders challenge focus	Practical actions	Justification of suggested adaptations *(if Challenges in column H are not fully addressed in the EARHB, add to framework)*
	1	Map context + identify stakeholders	Participation, Knowledge &capacity	Initial idea forming and decision to start the adaptation, perform site documentation, map key players, including institutions, and missing voices	Focus on inclusion and participation to increase capacity and to understand relevance
	2	Evaluate and assess building and its uses, map level of significance	Knowledge integration	Perform analysis and feasibility, evaluate building, assess value, document physical, cultural, and social values and level of significance	No changes to the actions, but focus on integrating the knowledge resulted from the evaluation and value assessment of the building
	3	Set up engagement process with stakeholders	Participation, Economic & financial	Organize inclusive process of engaging with all stakeholders, including workshops and local forums. Understand needs and analyze conflicts	Combine stakeholder engagement with needs analysis and conflict mapping. Understand economic drivers
	4	Assess knowledge/capacity gaps	Knowledge & capacity, Knowledge integration	Inventory of expertise, skills, and local knowledge	Add knowledge and capacity assessment which is not part of EARHB framework
	5	Analyze legal/policy constraints	Regulatory	Identify conflicts or blockers in laws/regulations	Add legal and policy framework limitations which are not part of the EARHB framework
	6	Co-create reuse goals & values, define potential function and design strategy	Participation, Knowledge & capacity	Co-design with users and owners. Balance values for the adaptive strategy	Map the adaptive reuse potential, adaptive function and decision of functional change with the reuse goals and values
	7	Develop and test design scenarios	Economic & financial, Regulatory	Model options with economic, social, and heritage impact	Add testing to developed design scenarios
	8	Evaluate feasibility + adjust	Economic & financial, Knowledge & capacity	Financial analysis, risk planning, role clarity	Include feasibility analysis from an economic, capacity and other risks perspective
	9	Make final decision and align proposal with policy	Regulatory, Knowledge integration	Review with planning/legal bodies/both authorities and communities, revise based on input	Include alignment with legal framework and policy + community needs
Adaptive Reuse process steps by Arfa et al., 2022	10	Implement, maintain, monitor, and adapt	Knowledge & capacity, Knowledge integration, Economic & financial	Monitoring, long-term support, knowledge-sharing platforms and training	Focus on long term impact assessment of the AR process, the KPIs/AR goals to be monitored and the knowledge to do so effectively



Adaptive Reuse process steps by Arfa et al., 2022

A.3. Adjusted AR steps

ADAPTIVE REUSE PROCESS STEPS*			1.Map context + identify stakeholders	2.Understand existing values & uses	3.Set up engagement process	4.Assess knowledge/capacity city gaps	5.Analyze legal/policy constraints	6.Co-create reuse goals & values	7.Develop and test design scenarios	8.Evaluate feasibility + adjust	9.Align final proposal with policy	10.Implement, monitor, and adapt
UNESCO	**Core challenges (barriers)**	**Description**	Initial idea forming and decision to start the adaptation, perform site documentation, map key players, including institutions, and missing voices	Perform analysis and feasibility, evaluate building, assess value, document physical, cultural, and social values and level of significance	Organize inclusive process of engaging with all stakeholders, including workshops and local forums. Understand needs and analyze conflicts	Inventory of expertise, skills, and local knowledge	Identify conflicts or blockers in laws/regulations	Co-design with users and owners. Balance values for the adaptive strategy	Model options with economic, social, and heritage impact	Financial analysis, risk planning, role clarity	Review with planning/legal bodies/both authorities and communities, revise based on input	Monitoring, long-term support, knowledge-sharing platforms and training
Mapping resources	**Knowledge integration**	**Siloed or missing information, poor data-sharing**										
	Knowledge & capacity	**Lack of skills, expertise, and institutional knowledge**										
Reaching consensus	**Participation**	**Lack of inclusive, effective stakeholder engagement**										
Assessing vulnerability	**Knowledge & capacity**	**Lack of skills, expertise, and institutional knowledge**										
	Knowledge integration	**Siloed or missing information, poor data-sharing**										
Integrating into planning	**Regulatory**	**Legal and policy barriers, or fragmented rules**										
	Economic & financial	**Funding gaps, weak financial models**										
Prioritizing actions	**Economic & financial**	**Funding gaps, weak financial models**										
Establishing partnerships	**Participation**	**Lack of inclusive, effective stakeholder engagement**										
	Knowledge & capacity	**Lack of skills, expertise, and institutional knowledge**										
*Adapted from Arfa et al., 2022												

APPENDIX B: WORKSHOP AND INTERVIEWS

B.1 WORKSHOP

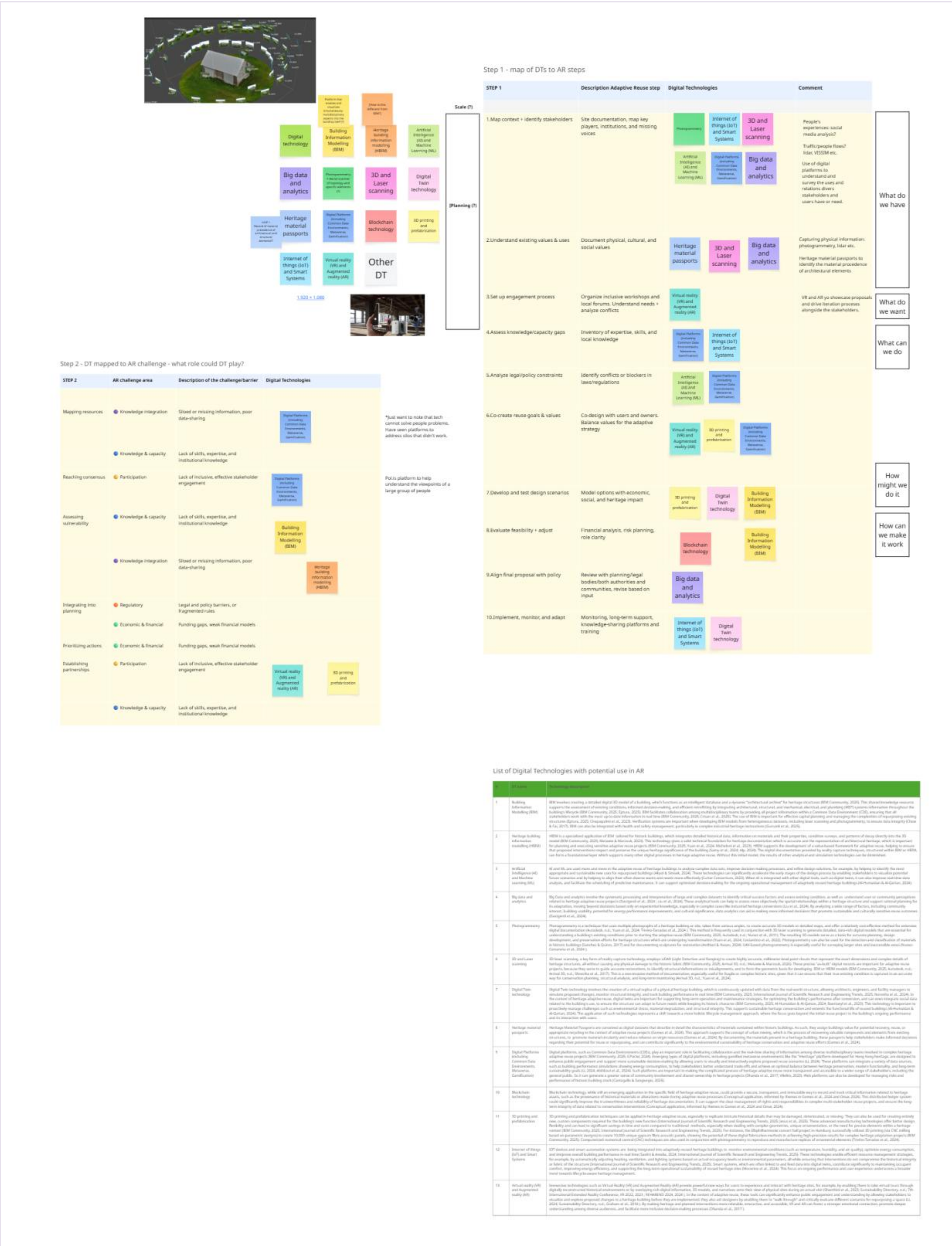
Questions for experts:

Step 1 - only 10 steps and technologies

1. Which digital tools do you know that support adaptive reuse?
2. Where would you map them in the 10-step process?

Step 2 – what could DTs become in the process? How can they help the HUL principles ?

3. Do the six HUL dimensions feel represented?
4. Are the five barriers addressed well with digital support?
5. Is anything missing or unclear in the framework?

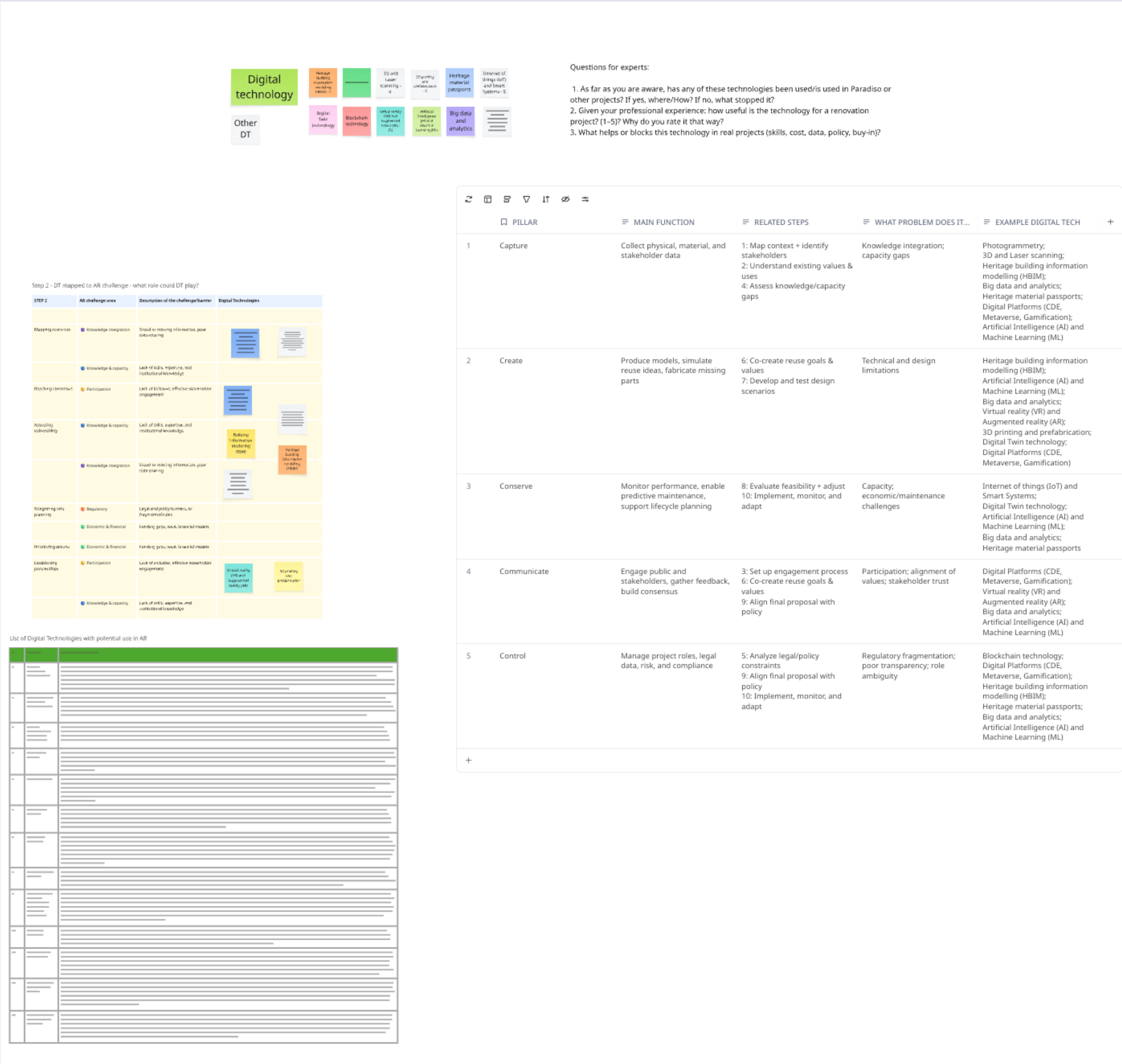


B.2. CASE VALIDATION INTERVIEW – PARADISO (Interview 1)

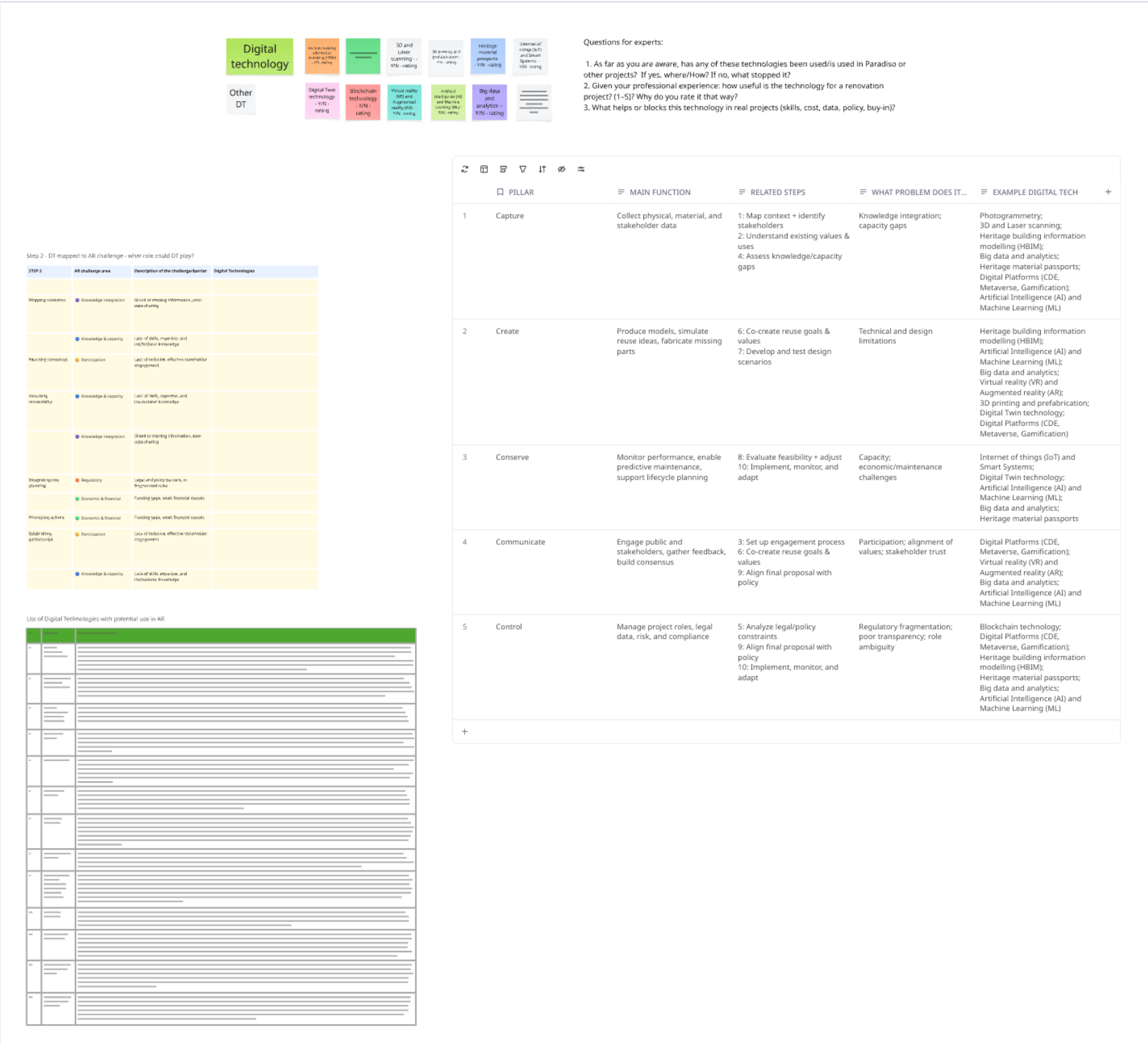
Questions for experts:

1. As far as you are aware, has any of these technologies been used/is used in Paradiso or other projects? If yes, where/How? If no, what stopped it?
2. Given your professional experience: how useful is the technology for a renovation project? (1–5)? Why do

you rate it that way?
3. What helps or blocks this technology in real projects (skills, cost, data, policy, buy-in)?



B.3. CASE VALIDATION INTERVIEW – PARADISO (Interview 2)



	PILLAR	MAIN FUNCTION	RELATED STEPS	WHAT PROBLEM DOES IT...	EXAMPLE DIGITAL TECH
1	Capture	Collect physical, material, and stakeholder data	1: Map context + identify stakeholders 2: Understand existing values & uses 4: Assess knowledge/capacity gaps	Knowledge integration; capacity gaps	Photogrammetry; 3D and Laser scanning; Heritage building information modelling (HBIM); Big data and analytics; Heritage material passports; Digital Platforms (CDE, Metaverse, Gamification); Artificial Intelligence (AI) and Machine Learning (ML)
2	Create	Produce models, simulate reuse ideas, fabricate missing parts	6: Co-create reuse goals & values 7: Develop and test design scenarios	Technical and design limitations	Heritage building information modelling (HBIM); Artificial Intelligence (AI) and Machine Learning (ML); Big data and analytics; Virtual reality (VR) and Augmented reality (AR); 3D printing and prefabrication; Digital Twin technology; Digital Platforms (CDE, Metaverse, Gamification)
3	Conserve	Monitor performance, enable predictive maintenance, support lifecycle planning	8: Evaluate feasibility + adjust 10: Implement, monitor, and adapt	Capacity; economic/maintenance challenges	Internet of things (IoT) and Smart Systems; Digital Twin technology; Artificial Intelligence (AI) and Machine Learning (ML); Big data and analytics; Heritage material passports
4	Communicate	Engage public and stakeholders, gather feedback, build consensus	3: Set up engagement process 6: Co-create reuse goals & values 9: Align final proposal with policy	Participation; alignment of values; stakeholder trust	Digital Platforms (CDE, Metaverse, Gamification); Virtual reality (VR) and Augmented reality (AR); Big data and analytics; Artificial Intelligence (AI) and Machine Learning (ML)
5	Control	Manage project roles, legal data, risk, and compliance	5: Analyze legal/policy constraints 9: Align final proposal with policy 10: Implement, monitor, and adapt	Regulatory fragmentation; poor transparency; role ambiguity	Blockchain technology; Digital Platforms (CDE, Metaverse, Gamification); Heritage building information modelling (HBIM); Heritage material passports; Big data and analytics; Artificial Intelligence (AI) and Machine Learning (ML)

APPENDIX C: SWOT AND DT EVALUATION

C.1. SCORECARD DTs EVALUATION

Technology	Scan to Living Model	Data Driven Decisions	Stakeholder Participation	Collaboration	Circular Economy	Data Acquisition	Interoperability	Costs	Skill Barrier	Obsolescence	Ethics / Authenticity	Average Score -1 to 5
HBIM	4	4	3	4	3	3	2	2	2	2	3	2,91
3D Laser Scanning	4	3	3	3	3	4	3	2	2	2	3	2,91
Photogrammetry	3	3	3	3	3	2	3	4	3	2	3	2,91
AI and ML	3	3	5	5	3	3	2	2	2	2	2	2,91
Big Data Analytics	2	5	3	3	4	2	3	2	2	3	2	2,82
Digital Twins	3	5	3	3	4	3	3	2	2	2	1	2,82
Material Passports	3	5	3	3	3	2	3	2	2	3	1	2,73
Digital Platforms CDEs	5	5	3	4	4	2	2	1	1	1	2	2,73
Blockchain	1	4	3	3	5	1	1	3	3	3	2	2,64
3D Printing Prefab	2	3	2	3	4	3	3	2	2	2	2	2,55

C.2. DIGITAL TECHNOLOGY EVALUATION BASED ON SWOT (DETAILED SCORING)

Digital Technology	Criteria	Score (1-5)	Rationale (sources)
HBIM	Scan to Living Model	4	Integrates capture (laser/photogrammetry) and can evolve into a Digital Twin with IoT feeds (Chow & Fai, 2017; Yuan et al., 2024; Stone, 2019; Noronha et al., 2024).
HBIM	Data Driven Decisions	4	Combines with AI/ML for energy/simulation and coordinated decisions (Akyol & Şimşek, 2024; Crisan et al., 2025; Cinquepalmi et al., 2023).
HBIM	Stakeholder Participation	3	Improves coordination; broader participation usually via CDEs/visualization (Jadresin Milic et al., 2022; Li, 2024; Dhanda et al., 2017; Graham et al., 2018).

HBIM	Collaboration	4	Collaborative, data-rich project backbone (Jadresin Milic et al., 2022; Crisan et al., 2025; Marzouk, 2023).
HBIM	Circular Economy	3	Enables material cataloguing and reuse with passports/blockchain (Rashid et al., 2023; Dos Santos Goncalves et al., 2025).
HBIM	Data Acquisition Accuracy	3	High fidelity if fed by scans; complex geometry demands expert modelling (Metawie & Marzouk, 2020; Tsilimantou et al., 2020; Yuan et al., 2024).
HBIM	Interoperability Integration	2	Challenges and silos risk with proprietary stacks (Chow & Fai, 2017; Jadresin Milic et al., 2022; Tsilimantou et al., 2020).
HBIM	Cost Burden	2	Significant software/hardware and modelling effort (Metawie & Marzouk, 2020; Shrestha et al., 2017).
HBIM	Skill Difficulty	2	Requires substantial HBIM expertise for irregular fabric (Metawie & Marzouk, 2020; Micheloni et al., 2023).
HBIM	Obsolescence Risk	2	Long-term accessibility risks (Vileikis, 2023).
HBIM	Ethics and Authenticity	3	Potential misrepresentation; mitigate via governance and documentation (Vileikis, 2023; Mocerino et al., 2024).
3D_Laser_Scanning	Scan to Living Model	4	Accurate as-built data foundational to HBIM and Twins (Metawie & Marzouk, 2020; Yuan et al., 2024; Noronha et al., 2024; Gómez-Gil et al., 2024).
3D_Laser_Scanning	Data Driven Decisions	3	Objective measurements reduce error (Artopoulos et al., 2024).
3D_Laser_Scanning	Stakeholder Participation	3	Shared records aid understanding though not inherently participatory (documentation role).
3D_Laser_Scanning	Collaboration	3	Common upstream dataset across disciplines (Yuan et al., 2024; Metawie & Marzouk, 2020).
3D_Laser_Scanning	Circular Economy	3	Accurate documentation supports audit/selective reuse (Metawie & Marzouk, 2020; Gómez-Gil et al., 2014).
3D_Laser_Scanning	Data Acquisition Accuracy	4	Very high accuracy for complex/fragile assets (Shrestha et al., 2017; Metawie & Marzouk, 2020).
3D_Laser_Scanning	Interoperability Integration	3	Point clouds exchangeable yet heavy to process (Yuan et al., 2024; Tsilimantou et al., 2020).
3D_Laser_Scanning	Cost Burden	2	Time-consuming/costly at large scale (Shrestha et al., 2017).
3D_Laser_Scanning	Skill Difficulty	2	Expert planning, registration, interpretation needed (Metawie & Marzouk, 2020; Micheloni et al., 2023).
3D_Laser_Scanning	Obsolescence Risk	2	Large datasets require preservation planning (Vileikis, 2023).
3D_Laser_Scanning	Ethics and Authenticity	3	Potential sensitivity/invasiveness in

			heritage contexts (Mocerino et al., 2024).
Photogrammetry	Scan to Living Model	3	Complements LiDAR; cost-effective capture feeding HBIM (Yuan et al., 2024; Triviño-Tarradas et al., 2024; Costantino et al., 2022).
Photogrammetry	Data Driven Decisions	3	Measurable 3D models support analysis (Triviño-Tarradas et al., 2024; Costantino et al., 2022).
Photogrammetry	Stakeholder Participation	3	Enables visuals/tours for engagement (Dhanda et al., 2017; Graham et al., 2018; Vileikis, 2023).
Photogrammetry	Collaboration	3	Standard input to HBIM across teams (Yuan et al., 2024; Machete et al., 2021).
Photogrammetry	Circular Economy	3	Detailed documentation supports reuse planning (Costantino et al., 2022).
Photogrammetry	Data Acquisition Accuracy	2	Accuracy depends on imagery/lighting/calibration; heavy processing (Artopoulos et al., 2024).
Photogrammetry	Interoperability Integration	3	Common formats; well integrated (Yuan et al., 2024).
Photogrammetry	Cost Burden	4	Low-cost vs LiDAR; accessible equipment (Triviño-Tarradas et al., 2024).
Photogrammetry	Skill Difficulty	3	Moderate skills; processing time (Artopoulos et al., 2024).
Photogrammetry	Obsolescence Risk	2	Preservation challenges for models (Vileikis, 2023).
Photogrammetry	Ethics and Authenticity	3	Need context/metadata to avoid misinterpretation (Vileikis, 2023; Mocerino et al., 2024).
AI_ML	Scan to Living Model	3	Operates atop models/data; helps keep 'living' via analytics (Stone, 2019; Savitri & Amalia, 2024; Noronha et al., 2024).
AI_ML	Data Driven Decisions	5	Predictive analytics and multi-criteria optimisation (Akyol & Şimşek, 2024; Cinquepalmi et al., 2023).
AI_ML	Stakeholder Participation	3	Improves insights; participation depends on interfaces (Alshboul et al., 2024).
AI_ML	Collaboration	3	Analysis/service layer across tools.
AI_ML	Circular Economy	3	Optimises energy/maintenance with sustainability co-benefits (Akyol & Şimşek, 2024; Gomes et al., 2024).
AI_ML	Data Acquisition Accuracy	2	Needs large, high-quality datasets (Akyol & Şimşek, 2024).
AI_ML	Interoperability Integration	3	APIs/exports common; stack-dependent.
AI_ML	Cost Burden	2	Compute/licensing/training costs (Alshboul et al., 2024).
AI_ML	Skill Difficulty	2	Specialist skills and governance required (Alshboul et al., 2024).
AI_ML	Obsolescence Risk	3	Fast-evolving; models retrainable.
AI_ML	Ethics and Authenticity	1	Bias/privacy risks; risk of de-humanising interpretation (Mocerino et al., 2024).
Big_Data_Analytics	Scan to Living Model	2	Not a capture tool; supports live status via

			continuous data use.
Big_Data_Analytics	Data Driven Decisions	5	Combines building, community and economic data (Bianchi & De Medici, 2023; Artopoulos et al., 2024).
Big_Data_Analytics	Stakeholder Participation	3	Enables evidence-led engagement if communicated well (Li, 2024).
Big_Data_Analytics	Collaboration	3	Shared analytics in platforms supports alignment (Li, 2024; Artopoulos et al., 2024).
Big_Data_Analytics	Circular Economy	4	Supports reuse, prioritizes by impact (Bianchi & De Medici, 2023; Gomes et al., 2024).
Big_Data_Analytics	Data Acquisition Accuracy	2	Diverse datasets; standardization/quality vary (Artopoulos et al., 2024).
Big_Data_Analytics	Interoperability Integration	3	Integration feasible with data engineering (Artopoulos et al., 2024).
Big_Data_Analytics	Cost Burden	2	Moderate tools but engineering effort.
Big_Data_Analytics	Skill Difficulty	2	Advanced analytics skills required.
Big_Data_Analytics	Obsolescence Risk	3	Methods evolve; governed data persists.
Big_Data_Analytics	Ethics and Authenticity	2	Privacy/consent and representativeness concerns (Mocerino et al., 2024; Vileikis, 2023).
Digital_Twins	Scan to Living Model	5	Real-time virtual replica (Stone, 2019; Noronha et al., 2024).
Digital_Twins	Data Driven Decisions	5	Integrates with AI for predictive analytics (Akyol & Şimşek, 2024; Cinquepalmi et al., 2023).
Digital_Twins	Stakeholder Participation	3	Specialist dashboards inform multiple groups (Baeriswyl et al., 2023).
Digital_Twins	Collaboration	4	Shared operational model (Noronha et al., 2024; Baeriswyl et al., 2023).
Digital_Twins	Circular Economy	4	Optimises lifecycle performance (Noronha et al., 2024; Marzouk, 2023).
Digital_Twins	Data Acquisition Accuracy	2	Requires robust HBIM+IoT; high setup effort (Metawie & Marzouk, 2020; Shrestha et al., 2017).
Digital_Twins	Interoperability Integration	2	Integration complexity across sensors/platforms (Alshboul et al., 2024).
Digital_Twins	Cost Burden	1	High initial/operational investment (Shrestha et al., 2017).
Digital_Twins	Skill Difficulty	1	High digital literacy/specialist skills (Alshboul et al., 2024).
Digital_Twins	Obsolescence Risk	1	Platform/toolchain longevity risk (Vileikis, 2023).
Digital_Twins	Ethics and Authenticity	2	Security/integrity of live data (Vileikis, 2023).
Material_Passports	Scan to Living Model	1	Catalogues materials; not live (Gómez-Gil et al., 2024).
Material_Passports	Data Driven Decisions	4	Guides reuse/eco-design (Gomez-Gil et al., 2024; Dos Santos Goncalves et al., 2025).
Material_Passports	Stakeholder Participation	3	Shared reference improves coordination (Gomes et al., 2024).

Material_Passports	Collaboration	3	Works with HBIM/blockchain (Gómez-Gil et al., 2024; Rashid et al., 2023).
Material_Passports	Circular Economy	5	Core to reuse/recycling transparency (Gómez-Gil et al., 2024; Dos Santos Goncalves et al., 2025).
Material_Passports	Data Acquisition Accuracy	1	High survey effort; quality risk (Gómez-Gil et al., 2024).
Material_Passports	Interoperability Integration	1	Standards vary regionally (Gómez-Gil et al., 2024).
Material_Passports	Cost Burden	3	Moderate: labor-intensive capture (Gómez-Gil et al., 2024).
Material_Passports	Skill Difficulty	3	Moderate assessment/documentation skills (Gómez-Gil et al., 2024).
Material_Passports	Obsolescence Risk	3	Manage via governance/legal frameworks (Rashid et al., 2023).
Material_Passports	Ethics and Authenticity	2	Trust depends on data quality (Gómez-Gil et al., 2024).
Digital_Platforms_CDEs	Scan to Living Model	3	Enable integrated workflows; not model creators (Jadresin Milic et al., 2022).
Digital_Platforms_CDEs	Data Driven Decisions	3	Better information flow supports decisions (Li, 2024; Artopoulos et al., 2024).
Digital_Platforms_CDEs	Stakeholder Participation	5	Strong enabler for inclusive participation (Li, 2024; Dhanda et al., 2017; Graham et al., 2018).
Digital_Platforms_CDEs	Collaboration	5	Central backbone for multi-disciplinary teams (Jadresin Milic et al., 2022; Balocco et al., 2020).
Digital_Platforms_CDEs	Circular Economy	3	Coordinate material/data flows (Gomes et al., 2024).
Digital_Platforms_CDEs	Data Acquisition Accuracy	3	Depends on upstream; governance helps (Jadresin Milic et al., 2022).
Digital_Platforms_CDEs	Interoperability Integration	2	Need robust standards to avoid silos/vendor lock-in (Jadresin Milic et al., 2022; Tsilimantou et al., 2020).
Digital_Platforms_CDEs	Cost Burden	2	Moderate licensing/implementation/training (Alshboul et al., 2024).
Digital_Platforms_CDEs	Skill Difficulty	2	Organization change and training required (Alshboul et al., 2024).
Digital_Platforms_CDEs	Obsolescence Risk	2	Migration risk with centralized data (Vileikis, 2023).
Digital_Platforms_CDEs	Ethics and Authenticity	2	Access control/security concerns (Vileikis, 2023).
Blockchain	Scan_to_LivingModel	1	Ledger for provenance; not capture/modelling (Omar, 2024; Rashid et al., 2023).
Blockchain	Data_Driven_Decisions	3	Immutable provenance supports decisions (Rashid et al., 2023; Gomes et al., 2024).
Blockchain	Stakeholder_Participation	3	Shared ledger builds trust; participation via governance (Omar, 2024).

Blockchain	Collaboration	3	Accountable exchanges across stakeholders (Gomes et al., 2024; Rashid et al., 2023).
Blockchain	Circular_Economy	4	Traceability with passports/HBIM (Dos Santos Goncalves et al., 2025).
Blockchain	Data_Acquisition_Accuracy	3	Integrity strong; input acquisition external (Omar, 2024).
Blockchain	Interoperability_Integration	2	Integration non-trivial; stack choices matter (Rashid et al., 2023).
Blockchain	Cost_Burden_higher_is_better	1	High energy/transaction costs on some chains (Rashid et al., 2023).
Blockchain	Skill_Difficulty_easier_is_better	2	Moderate-specialist skills; tooling improving (Gomes et al., 2024).
Blockchain	Obsolescence_Risk_lower_is_better	2	Regulatory/legal uncertainty; irreversible entries (Rashid et al., 2023).
Blockchain	Ethics_Authenticity_lower_is_better	3	Integrity supports authenticity; irreversible mistakes risky (Omar, 2024).
3D_Printing_Prefab	Scan to Living Model	2	Depends on accurate upstream models; not live (Triviño-Tarradas et al., 2024).
3D_Printing_Prefab	Data Driven Decisions	3	Prototypes/fit checks inform decisions (Jesus et al., 2025).
3D_Printing_Prefab	Stakeholder Participation	2	Limited beyond demos (Triviño-Tarradas et al., 2024).
3D_Printing_Prefab	Collaboration	3	Bridges design-fabrication (Núñez-Camarena et al., 2011; Triviño-Tarradas et al., 2024).
3D_Printing_Prefab	Circular Economy	4	Precise repair/replication reduces waste (Jesus et al., 2025; Parracho et al., 2025).
3D_Printing_Prefab	Data Acquisition Accuracy	3	Requires robust scans/HBIM (Metawie & Marzouk, 2020).
3D_Printing_Prefab	Interoperability Integration	3	CAM/CNC toolchains align with BIM/scan (Triviño-Tarradas et al., 2024).
3D_Printing_Prefab	Cost Burden	2	Capital equipment and specialist processes (Parracho et al., 2025).
3D_Printing_Prefab	Skill Difficulty	2	Specialist fabrication/material validation (Jesus et al., 2025).
3D_Printing_Prefab	Obsolescence Risk	2	File formats/toolchains evolve (Vileikis, 2023).
3D_Printing_Prefab	Ethics and Authenticity	2	Authenticity debates on replicas (Triviño-Tarradas et al., 2024).
IoT_Smart_Systems	Scan to Living Model	3	Feeds Digital Twins with real-time data (Noronha et al., 2024; Xiao et al., 2025).
IoT_Smart_Systems	Data Driven Decisions	5	Enables proactive O&M optimisation (Noronha et al., 2024; Xiao et al., 2025).
IoT_Smart_Systems	Stakeholder Participation	3	Dashboards inform multiple parties (Mocerino et al., 2024).
IoT_Smart_Systems	Collaboration	3	Shared streams across platforms/teams (Noronha et al., 2024).
IoT_Smart_Systems	Circular Economy	4	Extends life; reduces energy/waste via predictive maintenance (Xiao et al., 2025).
IoT_Smart_Systems	Data Acquisition Accuracy	3	Continuous data; installation in heritage fabric is challenging (Mocerino et al., 2024).

IoT_Smart_Systems	Interoperability Integration	3	Standards and integration effort required (Noronha et al., 2024).
IoT_Smart_Systems	Cost Burden	2	Hardware/network/maintenance costs (Mocerino et al., 2024).
IoT_Smart_Systems	Skill Difficulty	2	Ongoing operational skills required (Mocerino et al., 2024).
IoT_Smart_Systems	Obsolescence Risk	2	Hardware lifecycle refresh (Vileikis, 2023).
IoT_Smart_Systems	Ethics and Authenticity	1	Privacy/security sensitivity of real-time data (Vileikis, 2023).
VR_AR	Scan to Living Model	1	Visualization/overlay; not live models (Li, 2024).
VR_AR	Data Driven Decisions	3	Improves understanding via immersive review (Graham et al., 2018; Li, 2024).
VR_AR	Stakeholder Participation	5	Inclusive engagement and education (Graham et al., 2018; Dhanda et al., 2017; Jadresin Milic et al., 2022).
VR_AR	Collaboration	3	Supports cross-disciplinary reviews (Li, 2024; Balocco et al., 2020).
VR_AR	Circular Economy	1	No direct circular impact; indirect via better design.
VR_AR	Data Acquisition Accuracy	2	Relies on high-quality 3D assets; rendering realism (Li, 2024).
VR_AR	Interoperability Integration	3	Consumes BIM/HBIM outputs; compatibility varies (Li, 2024; Jadresin Milic et al., 2022).
VR_AR	Cost Burden	1	Bespoke content/hardware costs (Shrestha et al., 2017).
VR_AR	Skill Difficulty	3	Authoring skills; low end-user barrier (Li, 2024).
VR_AR	Obsolescence Risk	2	Toolset/content refresh cycles (Vileikis, 2023).
VR_AR	Ethics and Authenticity	1	Risk of misleading/decontextualized representation (Vileikis, 2023; Mocerino et al., 2024).

SCORING: The scoring was based on a review of current literature, supported by insights gathered during the workshop and interviews. Each digital technology was evaluated against specific criteria using a 1–5 scale, where 1 indicates very limited evidence or weak practical support, and 5 reflects strong, consistent validation and adoption across sources and expert opinions. The scores represent how convincingly the literature and discussions demonstrated each technology's maturity, effectiveness, and relevance for heritage and built environment applications.

C.3. DECISION MATRIX – DTs EVALUATED AGAINTS THE INITIAL QUESTIONS OF THE SWOT

Technology	Scan to Living Model	Data Driven Decisions	Stakeholder Participation	Collaboration	Circular Economy	Data Acquisition	Interoperability	Costs	Skill Barrier	Obsolescence	Ethics / Authenticity
HBIM	Strong (foundational)	Strong (with AI)	Neutral - Supportive processes available	Strong, if configured appropriately	Neutral - Supportive processes to be configured	Good if quality inputs	Challenged by proprietary formats	High initial cost	High specialist skill	Moderate risk	Manage authenticity risks

3D Laser Scanning	Strong (capture)	Good (quantitative)	Neutral - Supportive	Neutral - Supportive	Supports material audit	Very high accuracy	Common formats but heavy processing	High (site/scale)	Moderate skill	Moderate risk	Low direct risk but invasive capture concerns
Photogrammetry	Good (cost-effective capture)	Good	Enables engagement	Supportive	Supports reuse planning	Accuracy sensitive to conditions	Good as common input	Low cost	Moderate skill	Moderate risk	Watch contextual accuracy
AI and ML	Supportive (analysis layer)	Very strong	Supportive (if presented well)	Supportive (integration)	Supports optimisation	Requires extensive data	Integrates via APIs	Moderate-high compute cost	High expertise needed	Evolving tech risk	High bias/privacy risk
Big Data Analytics	Limited as capture	Very strong	Supportive	Supportive	Strong (policy & market)	Requires broad datasets	Integration required	Moderate cost	High skill for analytics	Evolving standards risk	Privacy/liability concerns
Digital Twins	Very strong (living model)	Very strong	Supportive (specialist)	Strong (central model)	Supports lifecycle optimisation	Needs HBIM+IoT	Integration complex	Very high cost	Very high skill	High security concerns	Data obsolescence risk
Material Passport s	Not a live model	Strong (materials decisions)	Supportive	Supportive	Very strong (circularity)	Labor-intensive capture	Standards lacking (regionally)	Moderate cost	Moderate skill	Moderate legal/record risk	Trust depends on survey quality
Digital Platforms CDEs	Supportive (integration)	Supportive	Very strong	Very strong	Supportive	Depends on input governance	Depends on standards	Moderate cost	Organization change required	Moderate migration risk	Centralization raises access concerns
Blockchain	Not a capture tool	Supportive (provenance)	Supportive (trust-building)	Supportive (framework)	Strong (traceability)	Input quality external	Integration non-trivial	High (some chains)	High skills to implement	Regulatory/legal risk	Irreversibility and legal uncertainty
3D Printing Prefab	Limited for living model	Supportive (replication)	Limited	Supportive	Supports reuse (replacements)	Requires good scans	Works with modelling	Capital equipment cost	Specialist fabrication skills	File/toolchain obsolescence	Authenticity debates
IoT Smart Systems	Supportive (feeds living model)	Very strong	Supportive	Supportive	Supports maintenance & circularity	Requires sensor deployment	Standards exist but varied	Moderate hardware/networ k rk cost	Moderate operational skills	Hardware lifecycle risk	Privacy/security high concern
VR and AR	Not a living model	Supportive (visual decisions)	Very strong (engagement)	Supportive	Little direct circular impact	Requires	Limited integration	Moderate costs depending on scope	High skills required	Evolving tech risk	Privacy/security high concern

C.4. DTs MAPPED TO THE ADAPTIVE REUSE PILLARS

AR Pillar	Rank	Digital technology	Supporting AR steps	Integrated score (all Qs)	Rationale (summary
Capture	1	Photogrammetry	High	47.7	Low-cost capture; complements LiDAR; accuracy sensitive to conditions (Triviño-Tarradas 2024; Yuan 2024)
Capture	2	3D_Laser_Scanning	High	47.7	Gold-standard accuracy; heavier cost/processing (Shrestha 2017; Metawie & Marzouk 2020)
Capture	3	HBIM	Supportive	47.7	Consumes capture data; basis for downstream modelling (Chow & Fai 2017; Yuan 2024)
Create	1	HBIM	High	47.7	Authoritative model for reuse design (Crisan 2025; Cinquepalmi 2023)
Create	2	AI_ML	Supportive	43.2	Analysis/generative layer for options and optimisation (Akyol & Şimşek 2024)
Create	3	Digital_Twins	Supportive	43.2	Scenario testing before intervention (Stone 2017; Noronha 2024)
Create	4	3D_Printing_Prefab	High (niche)	38.6	Replicates elements; verify materials/compatibility (Jesus 2025; Triviño-Tarradas 2024)
Conserve	1	IoT_Smart_Systems	High	45.5	Monitoring for predictive maintenance (Xiao 2025; Stone 2017)
Conserve	2	Big_Data_Analytics	Supportive	45.5	Portfolio-level insights; prioritization (Bianchi & De Medici 2023; Dastgerdi 2024)
Conserve	3	Digital_Twins	High	43.2	Continuous optimisation and risk simulation (Noronha 2024; Baeriswyl 2023)
Conserve	4	Material_Passports	Supportive	40.9	Track condition/material reuse potential (Gomez-Gil et al., 2024)
Communicate	1	Digital_Platforms_CDEs	High	47.7	Backbone for engagement and collaboration (Li 2024; Jadresin Milic 2022)
Commu	2	Photogramme	Suppor	47.7	Feeds high-fidelity visuals/tours (Vileikis 2023)

nicate		try	tive		
Communicate	3	VR_AR	High	31.8	Immersive consultation/education (Graham 2018; Dhanda 2017)
Control	1	HBIM	High	47.7	Project/asset information backbone (Machete 2021)
Control	2	Digital_Platforms_CDEs	High	47.7	Governance, permissions, single source of truth (Jadresin Milic 2022)
Control	3	Big_Data_Analytics	Supportive	45.5	Evidence-led policy/portfolio control (Artopoulos 2023; Cantagallo & Sangiorgio 2025)
Control	4	Material_Passports	High	40.9	Material accountability and circularity tracking (Gomes 2024)
Control	5	Blockchain	Supportive	36.4	Immutable provenance and responsibility sharing (Omar 2024; Rashid 2023/24)

SCORING: The pillar rankings were developed by aggregating the previous scores of each digital technology across the eleven evaluation criteria. Each technology was then mapped to one or more of the five AR pillars: Capture, Create, Conserve, Communicate, and Control, based on how strongly the evidence from literature, workshop discussions, and interviews indicated its contribution to that stage of the adaptive reuse process. The integrated scores reflect the overall strength and consistency of support across all criteria, and the rank within each pillar shows the relative maturity, relevance, and impact of each technology in achieving that specific function.