FROM PHYSICAL TO VIRTUAL

Developing a Framework for Sustainable Historic Building Management and Preservation utilising LiDAR and Virtual Modelling

Arkwright Building at Nottingham Trent University - As Found Cover Figure 1 (top) and As Virtual Cover Figure 2 (bottom)

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Note: This work has benefitted from the use of ChatGPT, an AI language model, which assisted in refining sentence structure and enhancing the clarity of the text.

In memory of my father Alf, who exemplified the value of hard work; I was truly fortunate to receive his encouragement, support and generosity.

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Abstract

Heritage serves as the foundation of contemporary life, intertwining cultural, historical, intangible and tangible elements that define societal identities. Effective management of historic assets demands proactive strategies to preserve their authenticity and significance within urban context. As outlined by the UK National Planning Policy Framework (NPPF), heritage significance lies in its value to present and future generations. Heritage conservation operates within a complex framework of laws, principles, and ethics, requiring strategic planning, stakeholder engagement, and interdisciplinary collaboration to ensure assets are preserved for future generations.

Managing heritage assets, which are complex, multifunctional, and diverse, presents significant challenges and requires an understanding of their form, materials, history, and archaeological context. Preserving authenticity and cultural significance while planning for sustainable futures requires informed interventions. Understanding the asset's lifecycle, investigative methodologies, and stakeholder engagement is crucial. Effective management strategies must navigate constraints, including the asset's characteristics, ethical and political imperatives, and stakeholder interests.

The aim of the research is to develop a framework for utilising LiDAR and virtual modelling technologies in the management of historic building data to support the sustainable preservation and management of heritage assets. Three case studies were identified and secured to iteratively explore the objectives.

The methodology evolved from practical advancements to a more analytical application of theoretical frameworks. Grounded in a subjectivist inductive approach, theory emerged directly from the research data, enabling a nuanced understanding of heritage asset management. Despite challenges, this approach fostered a systematic, replicable method, ultimately enhancing sustainable heritage management through the integration of LiDAR and virtual modelling technology, thereby advancing both theoretical and practical knowledge in the field.

Empirical research and case studies have shifted the digital model’s role from supportive to central, emphasising its dynamic nature. The model captures

data at all project stages and adapts to changes, aligning with guidelines from the Construction Leadership Council (2024). This approach enhances the accuracy, accessibility, and relevance of the model enhancing understanding, planning, and preservation efforts. Active stakeholder engagement in data retrieval and contribution links cultural significance to management strategies, fostering mutual understanding and informed decision-making. Case studies demonstrate its application in capturing and disseminating significant information, guiding interventions, and fostering sustainable practices.

The framework provides a robust, ethical approach to heritage conservation, supporting informed decision-making and preserving the socio-economic benefits of heritage assets. The flexibility and comprehensive data support make the framework a valuable tool for maintaining the significance and sustainability of cultural heritage assets. It introduces a novel, data-driven method, emphasising asset significance and proactive management. The research demonstrates that the dynamic digital model effectively supports heritage management by clarifying information flow. Testing digital outputs with stakeholders underscores the importance of engagement and knowledge dissemination in enhancing both the management and appreciation of heritage assets.

The research effectively achieved its primary objectives, yet there are several areas where further exploration could add depth to specific elements. These include testing the framework in live projects, refining data collection methods, and incorporating a broader range of stakeholder feedback. Addressing these areas would enhance the robustness and applicability of the digital models in heritage management, ensuring that they continue to evolve in line with industry needs and technological advancements.

ETHICAL APPROVALS

This work was approved by the Nottingham Trent University Joint Inter College Ethics Committee with confirmation received 17 July 2017.

The Hawara Pyramid Project was conducted in line with the guidelines set by the University's Code of Good Conduct in Research and its Policy on the Ethical Approval of Research as well as taking account of Egyptian and International regulations regarding the intellectual copyrights and access to historic artifacts in virtual environments. This was verified, justified and approved in advance of commencing any fieldwork with both local authorities and the Research Ethics Committee at Nottingham Trent University.

The Nottingham Castle Ducal Palace project was conducted in line with the guidelines set by the University's Code of Good Conduct in Research and its Policy on the Ethical Approval of Research as well as taking account of regulations regarding the intellectual copyrights and access to historic artifacts in virtual environments. This was verified, justified and approved in advance of commencing any fieldwork with both local authorities and the Research Ethics Committee at Nottingham Trent University.

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
AIM	Asset Information Model
AR	Augmented Reality
BGS	British Geological Survey
BIM	Building Information Model
BISRA	Building Services Research and Information Association
BS	British Standard
BSI	British Standards Institute
CAFM	Computer Aided Facilities Management
CAUGH	Centre for Architecture, Urbanism and Global Heritage
CDE	Common Data Environment
CIOB	Chartered Institute of Building
CLC	Construction Leadership Council
CLEAR	Contract, Listen, Explore, Action, Review
COTAC	Council on Training in Architectural Conservation
CRM	Cultural Resource Management
DOM	Digital Outcrop Model
DSS	Decision Support System
DSM	Digital Surface Model
DTM	Digital Terrain Model
EH	English Heritage
EIR	Employers Information Requirements
FISH	Forum on Information Standards in Heritage
GCP	Ground Control Points
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPR	Ground penetrating Radar

HBIM	Heritage Building Information Model
HDD	Hard Disk Drive
HDR	High Dynamic Range
HE	Historic England
HER	Heritage Environment Record
HES	Historic Environment Scotland
HIA	Heritage Impact Assessment
ICCROM	International Centre for the Study of the Preservation and Restoration of Cultural Property
ICOMOS	International Council on Monuments and Sites
ICT	Information and Communication Technology
IFC	Industry Foundation Classes
IMU	Inertial Measurement Unit
IP (54)	Ingress Protection
LED	Light Emitting Diode
LiDAR	Light Detection and Ranging
LOA	Level of Accuracy
LOD	Level of Detail/Development
LOI	Level of Information
MBM	Master Benchmark
MCI	Monument Condition Indicator
NHPP	National Heritage Protection Plan
NPPF	National Planning Policy Framework
NRIAG	National Research Institute of Astronomy and Geophysics
NT	National Trust
NTU	Nottingham Trent University
^{o}C	Degrees Centigrade
OIR	Organisational Information Requirement
OSCE	Organisation for Security and Co-operation in Europe

OUV	Outstanding Universal Value
PAS	Publicly Accessible Standard
PAM	Property Asset Management
PIC	Property in Care
PIM	Project Information Model
PPE	Personal Protective Equipment
RGB	Red Green Blue
RIBA	Royal Institute of British Architects
RICS	Royal Institute of Chartered Surveyors
SDG	Sustainable Development Goal
SLAM	Simultaneous Localisation and Mapping
SMART	Specific, Measurable, Achievable, Relevant, Timely
SSD	Solid State Drive
SSoT	Single Source of Truth
TLS	Terrestrial Laser Scanner
ToC	Theory of Change
UAS	Unmanned Aerial System
UK	United Kingdom
UK HM Gov	United Kingdom His Majesties Government
UNESCO	United Nations Educational, Scientific and Cultural Organisation
VR	Virtual Reality
WWII	World War Two

PUBLICATIONS

PIDDUCK, A., 2017 Capturing Heritage Data with 3D Laser Scanners. In: Arayici, Y., Counsell, J., Mahdjoubi, L., Nagy, G., Hawas, S., and Dewidar, K., eds. *Heritage Building Information Modelling*. Oxon: Routledge, Chapter 7. pp.61-74

PRESENTATIONS

November 2020 The Virtual Reconstruction for Historic Sites: Laser Scanning and Digital Modelling – Data Capture and Modelling of Nottingham Castle. Research Workshop 1: The Old Summer Palace – History, Archaeology and Creative Practices. On Line

13 February 2019. The Virtual Reconstruction for Nottingham Castle. Workshop - Engaging with Nottingham Castle Future: Virtual Platforms and Public Engagement with Nottingham Castle User Groups. Nottingham Trent University, UK

18-28 October 2018 Nottingham Castle Heritage - Digital Archive for Sustainable Management and Planning in Heritage Conservation. Digital Heritage 2018 3rd International Congress and Exposition. San Francisco, USA

11-12 September 2018. Data Capture and Modelling of Nottingham Castle: Digital Archive for Sustainable Management and Planning in Heritage Buildings with Community Access. The City (Re) Shaped: Exploring the Nexus Between Politics, Memory and Urbanism in the Built Environment. University of Leeds, UK

05-12 May 2018. Digital Data Acquisition for Heritage Sites – Terrestrial Laser Scanning. Virtual Heritage Environments: Principles and Purpose Workshop. Fayoum Egypt

05-12 May 2018. Fieldwork at Hawara Pyramid. Virtual Heritage Environments: Principles and Purpose Workshop. Fayoum Egypt

05-12 May 2018. Demonstration of Excellence in 3D Laser Scanning and Modelling: Nottingham Castle. Virtual Heritage Environments: Principles and Purpose Workshop. Fayoum Egypt

08 November 2016. Surveying the City. Nottingham Civic Society Lecture Series at Nottingham Trent University, UK

04 March 2016. Recording Techniques. IHBC East Midlands Understanding Buildings – Structure and Condition Nottingham Trent University, UK

12-15 March 2015. Researcher Links Workshop HBIM. Luxor, Egypt

Chapter 1.0 Introduction

1.0 Introduction

The introduction chapter explains the research problem and defines heritage management, identifies the stakeholders and introduces the framework concept including that specific to heritage. Aims and objectives, and the research questions will outline the conceptual framework. The contribution to knowledge is articulated annunciating how this research can guide and bring benefit to the heritage community and more specifically the stakeholders. Bruno, De Fino and Fatiguso in the conclusion of their paper state "…. *despite some recognised advantages of (heritage digital models and management) … its potential should be further investigated and exploited.*" Bruno, De Fino and Fatiguso (2018, p.273). The holistic knowledge pertaining to the heritage asset, a single source of truth, stored, maintained and retrieved efficiently and effectively would support the retention of the significance in the inevitable evolutionary process.

1.1 Research Background

Heritage as the bedrock on which contemporary life is built, embodies a tapestry of cultural, historical, and tangible elements that shape societal identities and values. As the reservoir of collective memory, heritage encapsulates the essence of past civilisations, traditions, and achievements, providing valuable insights into the evolution of human endeavour. Moreover, it serves as a repository of knowledge and inspiration, fostering a sense of belonging and continuity across generations. However, the preservation and management of heritage pose multifaceted challenges in the face of rapid urbanisation, globalisation, and environmental pressures. Thus, understanding and effective stewarding of heritage assets is paramount for ensuring their endurance, relevance, and contribution to contemporary society.

Effective management of historic assets requires careful and proactive strategies to safeguard the building's authenticity and its significance in the urban landscape. According to the National Planning Policy Framework this significance is defined as *"the value of a heritage asset to this and future*

generations because of its heritage interest." (NPPF, 2023 p. 75). Management involves understanding the form, materials, history, and significance of the asset, as well as the nature and extent of any archaeological deposits.

Heritage conservation practice operates within a complex landscape of established laws, principles, and ethical guidelines, requiring careful alignment to address contemporary issues effectively. A framework must balance compatibility, adaptability, and effectiveness, navigating the interdisciplinary nature of heritage preservation to maintain conservation equilibrium and narrative coherence. Success hinges on strategic planning, stakeholder engagement, and a refined understanding of the operational context.

The primary goal of the heritage sector is to preserve assets for future generations, ensuring consistent management practices, informing ideologies, and building on international heritage management foundations. In the UK, the Secretary of State, advised by Historic England and similar bodies in Wales, Scotland, and Northern Ireland, oversees heritage conservation. The National Planning Policy Framework governs built heritage in England, with comparable provisions in other UK regions. Internationally, UNESCO, through ICOMOS, integrates heritage preservation into its seventeen Sustainable Development Goals (SDGs), linking heritage management to broader sustainability issues.

Embedded within this discourse is the sustainability challenge, compounded by the influence of external, often unknown future factors that introduce additional layers of complexity. In pursuit of a sustainable heritage asset, the significance must be understood through analysis of the four factors, archaeological, architectural, artistic or historic.

Heritage asset weathering, or erosion, refers to the gradual loss of fabric, which can diminish the significance of the resource over time, and is used as a definition for this research. Weathering can include loss due to interaction with the elements or erosion (temperature, water, wind, sun), biological organisms, chemical interaction, local conflict, vandalism, poor maintenance and repair, and use attrition, all effectively wearing away the material. This phenomenon accentuates challenges that threaten to dilute the asset's

significance attributed by the stakeholders, highlighting the importance of addressing the problem. Moreover, these stakeholders, some of whom possess concealed connections to the edifice, yet through this relationship wield substantial influence over interventions. To effectively attain sustainability, it is imperative to contemplate the future trajectory of the edifice today. This entails grappling with inquiries regarding the forthcoming challenges, the extent to which preservation efforts can mitigate risks, and diverse desires and priorities of stakeholders invested in the endeavour.

A critical component requiring precise delineation within this research is the terminology associated with digital modelling. Despite the nuanced conceptual distinctions among various terms, they are frequently employed interchangeably, which can obscure analytical clarity. The term digital model typically denotes a temporally fixed, computer-generated geometric representation, originating either from data acquisition techniques or digitally drafted within modelling software. In this context, such models generally comprise exclusively geometric data, devoid of interpretive or semantic enhancement. Nevertheless, the term is also commonly utilised as a generic descriptor encompassing all computerised representations of components integrated within the construction process, culminating in the production of a physical structure.

The notion of a virtual model builds upon the digital model's foundational framework, introducing elements of interactivity and dynamic engagement. Precision in the representation of extant structures necessitates that such models be grounded in the object's point cloud - a dense aggregation of spatial data points that enables measurement with a high degree of fidelity. Although a point cloud may underpin either a digital or virtual model, it generally embodies purely geometric data, often supplemented with surface textures to simulate visual realism.

Moreover, the concept of (Heritage) Building Information Modelling ((H)BIM), predicated upon an accurate digital model, is broadly acknowledged within the field. However, (H)BIM systems frequently exhibit incompleteness due to limitations in access to specific elements or datasets. Even when founded upon robust and precise modelling methodologies, the omission of critical components often results in partial representation. Consequently, whilst

(H)BIM serves as a pivotal framework for heritage documentation and analysis, its application warrants scrutiny in light of its inherent constraints.

Reconsidering the digital model, it may incorporate attributes aligned with (H)BIM - extending beyond geometric fidelity to encompass enriched data - yet it may also function as the precursor upon which an (H)BIM is developed. The deliberate adoption of the term digital model within this research seeks to clarify that it does not necessarily constitute a Building Information Model embedded with semantic depth; nor does it represent a virtual model with immersive textures, or a simulation model characterised by defined material properties. The digital model, thus, may be understood both as a simplified geometric abstraction and, in certain instances, as a comprehensive BIM. It is this conceptual flexibility that underpins the choice to employ the term digital model throughout the study.

Detailed documentation with access for all stakeholders whether decision makers, influencers, consultants, or workforce, directly or indirectly employed by the asset management organisation for any site is the support required for the decision-making process. This documentation comprising a current dimensionally accurate geolocated three-dimensional geometric model, and the historic records could uphold a thorough understanding of the historic asset leading to informed decision-making in support of significance retention and augmentation. Acquiring this extensive dataset involves non-destructive techniques; however, comprehending the next stage, i.e. artifact materials, necessitates invasive procedures, contravening policy and ethical standards. Consequently, such methods have been excluded from this study.

Multiple methods for 3D data capture of historic sites exist including passive photogrammetry and active LiDAR technology, Historic England (2011). Photogrammetry employs sensors to capture overlapping images, converted into a 3D model through specialist software, necessitating precise control points for scaling yet may encounter inaccuracies in the shadow areas where data is unavailable Remondino et al, (2011). Conversely, LiDAR technology, utilising the speed of light for precise distance measurement, presents challenges such as inherent tool inaccuracies and limitations of data gaps due to line-of-sight information ‘shadows’, Barber, Mills & Bryan (2003) and Historic England (2018). Ground-based, tripod-mounted instruments are

slower yet mobile using Simultaneous Localisation and Mapping (SLAM), offer flexibility but may compromise accuracy, Mora et al (2021). The research adopts data precision crucial for discerning the condition and changes in the structures moving forward hence the use of a tripod-based instrument in the research. As Tang et al (2010) advise the extract of a digital model from LiDAR data is the smartest accurate method for large assets.

In both instances, the acquired data undergoes post-processing to generate a comprehensive model documenting its contemporary state Bryan (2009), Historic England 2020. The model is then juxtaposed with archival photographic and historic records to discern features revealed through the overlay Chiabrando et al, (2016), Munster et al (2024). By leveraging accurate three-dimensional data, this approach facilitates the examination and exploration of theories relating to the asset, Russhakim et al (2019). Such a novel framework, underpinned by precise data, could inform decision-making processes aimed at preserving the significance and ensuring the sustainable management of heritage assets.

Employing a grounded qualitative methodology, this study utilises action research coupled with case studies to iteratively scrutinise and understand geometric data capture within a pragmatic, experiential learning framework. Action research is rooted in construction practice and renowned for fostering improvement and sustainability, involves reflective engagement with practice. The investigation anticipates a non-binary outcome, potentially favouring qualitative techniques derived from empirical research. This research endeavours to delineate existing conventional challenges through process analysis, emphasising the imperative of stakeholder input via workshops to ascertain best practices before theorising a revised framework. Accessible, consistent, and accurate data significantly enhance heritage management by enabling timely, robust, and sustainable decisions.

Investigating the theoretical framework improves understanding of prominence and provenance, supporting the structured argument for its benefit in sustainable asset management through a conservation lens. As the heritage industry shifts from "preservation at any cost" to "evolution" for sustainability, the management of heritage assets becomes more complex. Sustainable management necessitates ethically justifiable actions such as

maintenance, preservation, and repair while acknowledging the intangible meanings that heritage sites embody for individuals and collectives. The changes over time are exemplified by weathering effects on carvings depicted in Figure 1, where exposed carvings show significant weathering compared to those in sheltered locations. This loss of physical integrity diminishes the asset's significance for stakeholders, erodes esteem, reduces protection, and limits future potential, impacting the overall perceived value and sustainability of the heritage asset.

However, the necessary deep knowledge for managing assets is often dispersed across various physical repositories, ex-owners, caretakers, specialists, or managers, making it inaccessible to stakeholders. This fragmentation affects sustainability, as the time required for knowledge gathering allows for further deterioration of the asset. A Single Source of Truth (SSoT) model, originating from information systems theory, can

Figure 1 Stone details Arkwright Building Nottingham Trent University (By author)

centralise accurate and relevant data, ensuring all stakeholders use the same information for decision-making, thereby enhancing management effectiveness.

Stakeholders in heritage asset management include a wide range of parties, such as private and public property owners, regulatory bodies, private sector support systems, employees, volunteers, consultants, contractors, and the general public. These stakeholders are divided into two groups: 'involved' stakeholders, who are directly engaged in the asset's management and operations (e.g., owners, occupiers, employees, contractors, surveyors), and 'peripheral' stakeholders, who interact with the asset more passively (e.g., visitors, local community, interested parties). This categorisation is fluid, allowing stakeholders to transition between roles based on their evolving interactions and interests.

The dynamic nature of stakeholder involvement requires a nuanced approach to engagement and management, recognising the shifting roles and intentions of stakeholders. Effective heritage asset management must adopt adaptive and inclusive strategies to accommodate these changes, ensuring sustainable conservation efforts that consider the diverse and evolving interests of all stakeholders.

The conceptual framework which, in this research, sets parameters for the investigation giving focus and direction, proposes the key pillars and interdependencies. This framework affords critical support for the study including clarification of the context especially for the reader. A conceptual framework in qualitative research should focus on identifying and defining the variables to become the invisible theory at the beginning of the investigation reinforcing the interconnected nature of the terms. Noted at this juncture in the thesis, a framework is the justification, the review and the outcome of the research. The aim and the research questions serve as the foundation for both the conceptual framework, and with this framework established, the development of the theoretical framework. The literature review encompasses a broad range of topics to contextualise and substantiate the problem, facilitating the identification of knowledge contributions and the formation of the conceptual framework, which in turn supports the research methodology. Existing knowledge informs the empirical research, guiding the answers to the research questions and contributing to the theoretical framework.

The conceptual framework's foundational features must be meticulously captured to define its key components, aiming to enhance heritage asset management. These assets, characterised by their complex amalgamation of materials, forms, locations, and environmental interactions, justify their inclusion. Additionally, the framework incorporates two other critical elements: the stakeholders, both 'involved' and 'peripheral', and the guiding principles of policy and ethics. Integrating these components, the conceptual framework comprehensively addresses the multifaceted nature of heritage management, ensuring a robust, ethical, and inclusive approach to the preservation and sustainability of heritage assets. Constructing any framework can be laborious, hindered by details and starting points. However, clarity arises from historical significance and available resources. These two determinants form the foundation for building the digital model. Consequently, the conceptual framework's development will evolve into the theoretical framework, culminating in this thesis.

The primary requirement for data collection is to define its purpose and the intended outcomes. The data in the digital model should align with the asset's importance, as determined by policy (NPPF, 2023). A project's prerequisite is the asset's historical value, defined by its evidential, historical, aesthetic, and communal significance, not monetary worth, and sometimes recognised by statutory designation, Historic England (2008). Most heritage assets are cash-poor, relying on grants and donations, necessitating strategic data acquisition based on the asset's significance, condition, and intervention needs (Morris, Hargreaves & Mcintyre, 2023).

Heritage forms the foundation of contemporary society, encompassing cultural, historical, and tangible elements that shape identities and values. As a collective memory reservoir, it captures past civilisations and traditions, fostering belonging and continuity. Preserving heritage amidst urbanisation, globalisation, and environmental pressures requires understanding and effective management. The National Planning Policy Framework (NPPF) underscores the value of heritage for current and future generations, emphasising the significance of careful management to maintain authenticity and significance. Heritage conservation involves complex legal, ethical, and practical considerations, demanding strategic planning, stakeholder engagement, and precise data collection. Techniques like 3D

photogrammetry and LiDAR facilitate detailed documentation, aiding in informed decision-making. Stakeholder involvement is crucial, necessitating adaptive and inclusive management strategies to ensure significance is respected in a sustainable practice.

1.2 Research Problem

The challenge is to manage heritage assets—complex, multifaceted, multifunctional, multilocational, and technologically varied—effectively and ethically. It is essential to preserve their authenticity and cultural significance while planning for sustainable futures. Interventions can be ill-informed (Fidler, 2002); thus, understanding the artefact, lifecycle dynamics, investigative methodologies, and stakeholder engagement is crucial. These fields must be accessible, modifiable, and controllable to integrate historical insights, current realities, and future projections. Effective management strategies depend on navigating diverse constraints, including the asset's characteristics, ethical and political imperatives, and stakeholder interests.

Earlier survey methodologies used basic tools - rulers, black-and-white photographs, and sketches, - leading to laborious processes involving scaffolding, working at height, environmental sensitivity, and long durations. This oft-compromised data integrity, making it subjective and outdated when contractors are engaged. While close proximity to the fabric allowed detailed observation of material condition, compromised the apparent eminence of the digital survey.

Effective management requires understanding the asset's historical evolution, technological solutions, and local environmental influences. Despite the benefits of propinquity for contextual understanding, modern practices are challenged by a transient workforce of consultants, surveyors, contractors, and managers. This threatens the continuity of knowledge acquisition and poses challenges related to time constraints, environmental conditions, data precision, asset vulnerability, and surveyor safety.

Digital solutions offer a centralised repository which, with cloud storage, is accessible to stakeholders globally. This consolidation allows managers to achieve consensus, provides authorities with insights for political and ethical decisions, and gives educators access to previously hidden materials.

Construction professionals gain immediate heritage knowledge, enhancing comprehension and reducing risks to significance, thus promoting sustainability. Disseminating data ensures transparency and equity, mitigating risks as professionals transition to new roles. While elements of digital models are being researched, there is a push towards automating data models, though their management use remains less understood.

A modern solution could replace traditional survey methods, offering superior accuracy, comprehensiveness, expedited processes, and reduced risks for both surveyors and assets. Data quality depends on the instrument, environment, scanned material, and instrument location. Commissioning these data capture campaigns is challenging; although English Heritage and the Royal Institute of Chartered Surveyors (RICS) provide specifications, they focus on technical outputs rather than practical solutions. This creates a knowledge gap in planning campaigns. The output data must be relevant, accurate, accessible, repeatable, measurable, and support asset management (English Heritage, 2009).

In summary, heritage conservation is paramount, underpinning our present and shaping our future. Effective management of historic assets demands a nuanced approach that integrates an understanding of the artefact's significance, lifecycle dynamics, historic narrative and stakeholder engagement, Cadw (2011). Traditional survey methods, whilst foundational, face challenges of subjectivity and data degradation, Bosche, Forster & Valero (2015). Conversely, digital solutions, such as LiDAR and 3D laser scanning, offer precise comprehensive data and streamlined processes, enhancing sustainability and risk mitigation. However, these technologies must be adeptly managed to ensure thorough observation and quality data capture. Standardised protocols, like those from Historic England and the RICS, provide guidelines but require practical enhancements for optimal implementation. Ultimately, the synergy of historic insight, modern technology, and stakeholder collaboration is essential for preserving cultural heritage with integrity and foresight. This necessitates a flexible, knowledge-driven methodology, the framework provides structure yet allows for adaptable strategies focused on the sustainability of heritage assets and the development of a model that facilitates stakeholder interaction with the data. For both immediate and long-term management decisions, aligned with the

ICOMOS Burra Charter, the model's dynamic nature enables consumption, action, and outcome recording.

1.3 Aim and Objectives

The aim and objectives are set out below.

Aim

To develop a framework for utilising LiDAR and virtual modelling technologies in the management of historic building data to support the sustainable preservation and management of heritage assets

Objectives

1. Critically analyse the methods, methodologies and practices involved in recording, retrieving and updating information for a heritage asset, focused on aligning these processes with contemporary conservation practice

2. Evaluate the existing systems and processes in heritage asset management for administering information identifying best practices and limitations within the current frameworks

3. Analyse the benefits and challenges of adopting digital models in the management of historic buildings

4. Develop a comprehensive framework for the integration of digital models in heritage asset data management

5. To continuously evaluate, through action research, the proposed framework's impact on stakeholder engagement and the effective management of heritage assets

1.4 Research Questions

This project is designed to answer the key research questions:

How can a digital model based on precise LiDAR data, serve as an effective

tool for sustainably managing and future evolution of built heritage?

What are the essential components of a framework that ensures all stakeholders can effectively contribute to and access data from a digital model, thereby supporting the sustainable management and preservation of heritage assets?

1.5 Outline Methodology

The methodology underwent a transformative evolution, transitioning from an initial emphasis on practical advancements and strategy testing in tangible projects to a more sophisticated and analytically driven application of theoretical frameworks in concluded case study projects. In an iterative action research process, three case studies were utilised, and historic records were probed to draw together a picture of the building development to prepare a timeline for the project. The records and representations were overlaid with the geometric data to understand and explain the features being observed, this was tested in two stakeholder workshops. Within this progression towards heightened academic rigour, characterised by a subtle distinct exploration of theoretical foundations and their practical implications emerges a refined comprehension. Such an approach enhances the depth of academic understanding whilst fostering a wide-ranging integration of theory and practice to enrich the discourse around strategic decision-making in sustainable heritage management.

The methodology is grounded using the literature review. The subjectivist inductive approach as found in this research utilises the gathered data to develop and process the theory from that data in constructing the framework. Furthermore, the theory should be considered flexible undergoing refinement, the shift taking place in the researcher and/or the research. In this situation, the theory can develop out of the research, be a major component in forming the research or be exploited in interpreting/analysing the data to conclude.

Case studies as defined is a pragmatic study of a current phenomenon existing in an everyday setting, especially powerful where there is congruence between the situation and the context. The strategy involving three sites provides elements of similarity and dissimilarity as the basis for robust investigation. The workflow for the repeat operations seeks to eliminate

variables to focus on elements which are most likely to provide the solution, for example, using the same density of stations and instrument settings as the previous campaign. The inductive, bottom-up approach allows the exploration of the assembled data from the scanning campaigns be it RGB, intensity or metric within a media.

A 'goal-free' evaluation allows the description of the actual effect rather than pre-proposing a theoretical stance liberating the research to explore a range of possibilities within the collected data. Furthermore, in this situation, without goals or specific outcomes, the research is freed to examine the data content for actual change and attribute the variation to specific weathering typologies. There is a counterargument advocating without clear goals, organisation and invention are challenging yet without this freedom the most appropriate methodology may remain concealed, and tunnel-vision will be less evident.

In the empirical research, one case study embraces four campaigns, this is suggestive of a longitudinal method however as there is only a beginning and an end point this would suggest a linear weathering process whereas the events can be anything but. The importance is to reduce the number of limitations to bring forward a replicable method in pursuit of the significance imbued in the asset and the management of this.

Synthesis of the empirical workflow, the data capture and the quality of the output provides the opportunity to design a theoretical framework to answer the aim of the research in the use of LiDAR and virtual modelling technology for the management of historic building data in sustainable preservation and management of heritage assets to support informed decision-making to retain significance by all stakeholders.

The methodology evolved significantly, progressing from practical advancements to a more analytical application of theoretical frameworks. Three case studies were conducted iteratively, utilising historic records and geometric data overlaid to understand building development. This approach, grounded in the literature review, employed a subjectivist inductive approach, allowing theory to develop from the research data. The 'goal-free' evaluation facilitated the exploration of data content, attributing variation to specific weathering typologies. Despite challenges, this approach enables a nuanced

understanding of heritage asset management, fostering a systematic and replicable method to preserve significance. Through the synthesis of empirical findings, a theoretical framework emerged, addressing the research aim to enhance sustainable heritage management through LiDAR and virtual modelling technology. Thus, the evolved methodology fosters a systematic, replicable approach to heritage asset management, enhancing both theoretical and practical understanding in the field.

1.6 Contribution to Knowledge

The transition from static to dynamic digital heritage model marks a pivotal shift in the preservation and management of heritage assets. This research introduces a conceptual framework, developed through empirically grounded case studies, which evolves into a robust theoretical model. The framework facilitates comprehensive knowledge acquisition, enabling informed decision-making and promoting sustainable heritage management practices. Rigorous heritage management protocols featuring stakeholder engagement transforms the approach to optimise the asset lifecycle, curtail expense and fortify significance.

Central to this advancement is the seamless integration of historical and geometric data, which provides critical insights into asset weathering and ethical conservation. Stakeholder engagement plays a pivotal role, ensuring that sustainable practices are embedded within the management lifecycle. This participatory approach not only preserves the physical integrity of heritage assets but also enriches their cultural significance, fostering a collective sense of stewardship. The proposed dynamic framework represents a significant advancement in the conservation field, fostering a sustainable and informed methodology for heritage management.

The framework accounts for the diversity of heritage assets, necessitating a universally applicable model. This model should encompass artefacts, lifecycle stages, investigative practices, and stakeholder interactions, ensuring accessibility, editability, and manageability throughout the conservation process. Presently, public engagement with digital models is minimal; the lack of an ‘aura’ restricts their use to professionals, thereby limiting decision-making capacity, the framework reverses that detachment.

Embracing dynamic models, this research pioneers a proactive approach, steering away from reactive management practices that dominate the current landscape. In the realm of heritage preservation, the norm often involves haphazard maintenance efforts lacking strategic foresight and deep-rooted knowledge. Determining the threshold between maintenance and replacement poses a formidable challenge, yet policy mandates retention of materials to safeguard significance.

This research champions a proactive stance, moving away from reactive and fragmented maintenance practices that lack strategic foresight. Determining the threshold between maintenance and replacement remains a complex challenge, particularly under policy constraints that mandate material retention to preserve significance. The framework addresses this by proposing the amalgamation of diverse datasets—maps, images, reports, texts, and archival records—into a unified digital repository. These resources, often dispersed across institutions and private collections, are rendered accessible, thereby supporting precise and sustainable management decisions.

Current digital models are predominantly technical and fail to adequately support the narrative and significance of heritage assets. The future lies in integrating extensive, heterogeneous datasets ranging from archival records to contemporary social data. Despite this potential, few monuments have been accurately recorded in either 2D or 3D. The contrast between ancient rural and modern urban heritage, between external and internal elements, and between worn and renewed states. The absence of a current digital record to underpin future development or understanding of asset weathering.

Incorporating layers of historical information and ongoing data capture, the model at the centre of the framework gains a temporal dimension, transforming it into a digitally agile tool. This transformation creates a real-time digital resource that supports strategic and planned interventions. Building an accessible framework on high-quality data substantially enhances the robustness and efficacy of management decisions, both real-time decision-making and strategic planning.

In conservation management, while technology is available, the challenge lies in navigating the plethora of software, technologies, and approaches, Bosche,

Forster & Valero (2015). The ambition is to construct records that are linked, accessible, live, updatable, and searchable, McKeague et al (2019). The framework addresses these challenges, integrating diverse datasets preserving the significance of each heritage asset and enhancing the decision-making process, thus fostering a more informed, connected, and sustainable approach to heritage conservation, Charalambous & Artopoulos (2018).

For both spontaneous and long-term management decisions that align with policy and ethics, the model should be dynamically consumed, modified, and updated. Real-time data integration allows changes to be actioned, and outcomes recorded, making the model a dynamic tool that evolves with each interaction. This approach ensures that conservation practices remain robust, adaptive, and responsive to the needs of heritage management.

Despite its potential, research in this domain remains limited, particularly in relation to strategic and functional decision-making. The currency and quality of data should be critically assessed, with new campaigns initiated as required. Reapplying the theoretical framework periodically, tailored to specific output, will reinforce its dynamic nature. When additional historical records and documents, emerge, the model must validate their quality during the evaluation phase before inclusion. Maintaining a high-quality digital facsimile necessitates thorough data evaluation at each iteration.

Ultimately, this proposed framework, serving as a principal force, represents a synthesised, flexible, and dynamic core, providing a novel contribution to knowledge in heritage conservation. It provides a sustainable, participatory, and data-driven methodology that enhances the preservation of cultural assets and ensures their enduring legacy for future generations.

1.7 Thesis Structure

The next chapter develops the literature review required for grounded research. The appreciation of frameworks in particular heritage contextualises the research yet there is change and this is expounded to determine the need for digitalisation. The complexity of managing a heritage asset is explored, the myriad of periods, technologies, constituent parts, uses and required skills are the starting point, and the issues of weathering of

natural materials, maintenance regimes, local climate and past incidents all contribute. The binary of digital would appear to be the antithesis of the sinuous, organic nature of the heritage asset yet in synthesis the two become one. The benefit of the digital model leads to the development of the conceptual model as the basis for the empirical investigation.

The methodology employed in this study effectively aligns with its objectives in Chapter 3 by establishing the ethical framework guiding the empirical investigation. The rationale for selecting a case study approach is clearly articulated within the research strategy, emphasizing its suitability. Detailed elucidation of digital data capture processes, presented in a diagrammatic format accompanied by comprehensive explanations, enhances clarity. Through iterative cycles of action research, the efficacy of geometric data capture methods is continuously refined, demonstrating the relevance of the approach. The chapter concludes with research diagrams encapsulating key findings and methodologies employed, consolidating the study's contributions.

Chapter 4 delves deeply into the intricacies of workflows and meticulously details the case studies. It comprehensively covers survey methods, data capture and data security protocols annunciating the challenges encountered in the following sections. Pragmatic obstacles are explored particularly in regions at the edge of instrument capabilities. Comprehensive post-processing is imperative for managing data prior to utilising it in applications. The three distinct case studies are the Arkwright Building in Nottingham, Ducal Palace within the Nottingham Castle walls and Hawara Pyramid in Fayoum, Egypt. Each case study undergoes detailed analysis before being summarised and the synthesis of the findings to inform the design of a theoretical framework.

Progression from Conceptual to the Theoretical framework marks a critical juncture in Framework Development, representing the culmination of research outcomes. Chapter 5 initiates an exploration into the nature of frameworks, scrutinising their constituent content and development paths before delving into the conceptual framework as the research cornerstone. Subsequently, the theoretical framework emerges as the output synthesising the empirical that amalgamates geographic and historic data to enrich the content. Following refinement, the application of the framework is debated to conclude

the chapter with a comprehensive overview of its implications and potential applications.

Chapter 6 culminates the research journey by outlining how the objectives were met, thereby bolstering the overarching aim. This entailed synthesising a theoretical framework that delineates a cohesive and lucid direction for establishing a digital repository, fostering connectivity among pivotal elements. Such a framework necessitates flexibility to encompass diverse heritage assets, accommodate technical details, materials, and depth of historical documentation. This chapter illuminates limitations whilst shedding light on opportunities for an extended research program aimed at refining the framework. Ultimately, it expounds the contribution this research has made to advancing scholarly understanding.

Chapter 2 Theory and Literature Review

2.0 Introduction

The section moves to encapsulate a critical examination of the intersection between heritage preservation and the adoption of digital tools and methodologies. Furthermore, it will consider the notion of frameworks, specifically those which shape the understanding of heritage asset preservation. These frameworks will demarcate the conceptual and contextual parameters of the research and emerge as theoretical constructs resulting from the investigation.

Philosophies regarding the preservation of tangible heritage assets are dynamic and evolving, ICOMOS (1964). For instance, within the conservation community, there is increasing recognition of the potential benefits of adaptive reuse, wherein the modification of a small portion of the physical fabric may enhance the overall utility of the site through occupation, ICOMOS (2010). This acknowledgement does not detract from the idea of preserving historic sites for their original purposes; however, it acknowledges the evolving needs of contemporary society. For instance, traditional village retail outlets, whilst historically significant, may no longer serve their original function in modern life and could be repurposed into spacious family accommodation, thus ensuring their continued relevance and utilisation, adding life to the settlement.

The complexity inherent in traditional assets, reflected in the diverse materials and technologies developed over millennia and often specific to their locations, presents contemporary practitioners with challenging and often costly decisions. Effective heritage asset management, guided by the three pillars of policy/ethics, stakeholders, and the monument significance itself, must integrate multifaceted requirements with core management practices at strategic and operational levels, Green Balance and Grover Lewis (2012). This comprehensive approach ensures that preservation efforts are not only ethically sound and stakeholder-inclusive but also strategically aligned and operationally efficient, thereby balancing the intricate needs of heritage conservation with modern practicalities.

This review delves into a multidisciplinary discourse, drawing from fields such as heritage studies, archaeology, cultural anthropology, humanities, and

information technology. It explores the evolving role of digital technologies in heritage documentation, conservation, interpretation, and dissemination, elucidating their impact on scholarly research, public engagement, and policymaking. Moreover, this review scrutinises the theoretical frameworks, methodological approaches, and practical applications underpinning the integration of digital tools into heritage practices. It analyses key themes including digital documentation techniques (e.g. LiDAR, 3D scanning), virtual reconstructions, augmented reality, digital archives, stakeholder heritage initiatives and the ethical considerations inherent in digital practices. Crisan et al. (2024) ascertain that the integration of historical data with digital models produces dynamic representations that elucidate the development of sites over time. Nevertheless, capacity building is essential to cultivate the requisite skills among heritage professionals. By synthesising and critically evaluating existing literature in this grounded approach the review aims to provide a comprehensive understanding of the opportunities, challenges, and implications associated with the digital transformation of heritage management in contemporary contexts.

Throughout the world, a wealth of aging urban development has limited inventory and no repository to capitalise on opportunities for proactive management. It is widely recognised heritage assets are more difficult to manage with additional philosophical, regulatory, and community requirements and are unique in many ways, simplistically for example, in materials, technology, construction methods or in repair, maintenance, refurbishment obligations, Roy and Kalidind (2017) and Historic England (2017). Only with a profound understanding of the heritage asset and stakeholder involvement can the most appropriate action be envisaged, planned and enacted to ensure sustainability. Consolidating information in a single repository establishes a foundation for sound decision-making, ensuring accurate, efficiently maintained, and effectively retrievable knowledge regarding heritage assets. This supports the preservation of their significance amidst inevitable evolutionary processes (Saygi et al., 2013). Precise, focused information underpins a wide array of decisions impacting both the asset and its operational environment, facilitating informed and strategic heritage management.

Proactive management maintains the significance of the asset by defending against prospective loss and managing risk, recording the change acts as a

feedback loop thereby ensuring planned rather than reactive interventions. As heritage assets embody complexity and uniqueness, an effective repository must possess flexibility, and a robust foundation to formulate a strategic and collaborative heritage management plan, Landorf (2009). While this plan serves the objective, its sustainability hinges on dynamic adaptability to internal and external pressures, the evolving nature of assets, and shifts in partnerships. Hence, a framework is an exemplary solution to offer a structured basis for the conservation and management of heritage assets where complexity exists, shaping without constraining. The systematic approach to the organisation and dissemination of conservation information facilitates effective stewardship of the asset (Historic England 2015) yet allows for engagement and interdisciplinary collaboration within the field of heritage management, Magar et al. (2022). In similar circumstance where digital models to enhance building management, utilising a digital platform will bring about a model to nurture collaboration, support discovery and ensure retention of significance Palomar et al. (2020), in the face of extant weathering of the asset.

With any part of the built environment evolution is a necessity, redundancy threatens disposal, future sustainability is a planning mantra, NPPF (2021). Therefore, to retain and maintain heritage assets, continued use is paramount yet there is often a tension with significance, accessible data in a repository would enable the management of that tension. Furthermore, most owners, occupiers and users are unsure of the attributes of the asset which combine to determine the significance, and therefore heritage value, such that there is grave risk of forfeiture or disfigurement. Accurate knowledge pertaining to the heritage asset stored, maintained and retrieved efficiently and effectively will support the retention of the significance in the inevitable evolutionary process, Historic England (2015c). A simple method to check and determine the significance of an element would reduce this risk, support the statutory requirement and maintain the significance of the asset, in all aspects supporting sustainability.

The literature review starts by examining heritage, critically analysing the current regulatory drivers and principles. Digital is evident in every aspect of contemporary existence. From communication and commerce to education and entertainment, digital permeates the fabric of modern life, profoundly shaping shared dynamics and individual experiences. This is explored in

depth; whilst heritage is considerably analogue, the opportunities offered by the digital construct are unlimited yet often constricted by skills and vision. The conceptual framework as an output of this section is the starting point for the research, this literature review embarks on an academic inquiry of existing knowledge, insight to determine new conduits of understanding and providing the shape. None of this sits in isolation, existing frameworks from the macro to the micro detailed in the following section form a rich background for the research to contextualise and advance within the dynamic landscape of heritage management. The research output, a theoretical framework springs forth, reliant on the conceptual for shape and the existing heritage landscape to ground its theoretical underpinnings, thus fostering a comprehensive understanding and offering actionable insights for effective heritage management practices.

2.1 Heritage

Our heritage is essential to the individual and collective being the foundation on which we shape our life in the present and plan our future. The built environment, the stage on which we exist creating memories, supplementing, and extending that heritage, the significance concurrently tangible and intangible therefore of immense importance. Space mediated by custom, memory, myth, and narrative becomes place, uniqueness, a relationship to the past, Ashworth et al (2007).

The International Council on Monuments and Sites (ICOMOS) Venice Charter adopted in 1965, acknowledges the past for the future when stating "*The common responsibility to safeguard [historic monuments] for future generations is recognized. It is our duty to hand them on in the full richness of their authenticity*." (ICOMOS 1964, p. 1). Di Guiseppantonio Di Franco refers to the inclusion of digital models in this practice "*… potential revolution of safekeeping of cultural objects and heritage sites, afforded by high-quality digital facsimiles."* Di Guiseppantonio Di Franco (2018, p.xii), as a political and security decree, beyond which there is climate and natural disasters, and obliteration through conflict and mass tourism. However, it is considered there are issues with digital representation insofar as the lack of physicality and context, duplicability, inability to weather and ownership issues. Generally, engagement by the public with the digital model is absent, the lack of 'aura' related to creativity, aesthetics and construction limits use to

professional actors thereby inhibiting the decision-making capacity, Jeffrey (2015).

The building façade, the public face of heritage, is often the meaningful component in our collective memory, to be retained at all costs, the first interactive element in use and arguably the most important. Alishah et al (2016) provide an insight into this understanding, expounding the view the composition of the urban provides everyday awareness and belonging. This understanding of heritage and urban design is repeated in Moughtin et al (1995) where the face of the building engages the collective providing additionality in their experience of the public environment.

Heritage management is a complex activity requiring carefully planned interventions to retain and augment significance without removing the legacy patina. The extensive range of materials, techniques, methodologies, composites, mutations mediated through the construct of time adds layers of difficulty in the design of any invention. Repair/replace too soon removes material or units with residual life, wait too long and the damage extends to areas beyond that originally affected. Fidler supports the view of English Heritage that "*… too much building work takes place that is either unnecessary or inappropriate*." Fidler (2002, p.vii). These interventions by purported professionals can be ill-informed, the sustainable historic fabric is being lost or inappropriate treatments applied resulting in rework. Acierno et al (2016) point to a lack of synergy in the information available for a heritage asset which reduces the effectiveness of the outcome.

Heritage is crucial to individual and collective identity, shaping our present and future. The built environment, intertwined with custom, memory, and narrative, is of immense importance. The ICOMOS Venice Charter (1964) emphasises the duty to preserve historic monuments' authenticity for future generations. Digital models offer potential for cultural preservation but face challenges like lack of physicality and limited public engagement. Heritage façades are significant in collective memory and urban experience. Effective heritage management requires careful interventions to maintain significance, avoiding unnecessary or inappropriate work.

2.2 Heritage Weathering

Change in Heritage fabric over time is exemplified by the images seen in Figure 1, the eroded version of the frog and the turtle sit on top of the stone plinth on either side of the main north-facing entrance of the Nottingham Trent University Arkwright Building. Hidden in the recess to the rear of the same plinth feature is a virtually complete version displaying the detail that the mason would have incorporated in those facing north. Close inspection shows some distinctions for example the frog's front legs are in an alternate location however the care taken by the mason would be indiscriminate. The loss of material over time expounds the significance flaw where weathering, like memory, clouds detail to diminish the ability to revitalise the experience. Sufficient change deletes heritage, especially long term, and in the collective memory, reduces congruence in the comparative narrative.

John Ruskin as the founder of critical thinking on heritage through his writing in the Seven Lamps of Architecture was an exponent of recording and preserving. His philosophy underpins SPAB, Society for the Preservation of Ancient Buildings, especially the materiality, their coherence with local vernacular and most appropriately in this context the care of the monuments. He was especially dismissive of restoration suggesting it removed layers of previous history; buildings should be tended for future generations. The passage of time is bound in the surface, exposed for the 'stakeholder' to view and be in awe of, the scourge of Victorian life, soot, trapped in the pores of the material. Along with William Morris, Ruskin leant their weight to SPAB developing into the approach to protect ancient buildings against destructive work thereby destroying the character of the monument. This philosophy survives today, 'Wear and tear adds beautiful patination that new work can only acquire through the slow process of aging.' Slocombe, (2017, p.9).

The term "weathering" or "erosion" of fabric encompasses various aspects of material degradation, appreciably impacting heritage asset's significance, Pappalardo et al., (2022). While the influence of climate change theories on these processes is noteworthy, it represents only a fraction of the broader issue. General weathering caused by precipitation, sunlight, and wind, exacerbated by current climatic changes, operates at a fundamental level, Phillipson et al. (2016). Additionally, catastrophic events such as floods, earthquakes, landslides, theft, and fires contribute to material loss.

Furthermore, degradation can arise from conflict, vandalism, or accidental damage, Pedersoli et al., (2016). The lack of maintenance, substandard repairs, unforeseen outcomes from interventions, and the actions of uninformed or inconsiderate workers can also be deemed forms of vandalism. These various elements collectively erode the physical integrity of heritage monuments, thereby compromising their longevity and significance. Despite these challenges, heritage assets often retain their importance to stakeholders, even when marred by such blemishes. The most profound impact of weathering or erosion is not typically attributable to catastrophic events; rather, it lies in the gradual degradation resulting from maintenance and repairs conducted by purportedly experienced experts or specialists who lack a comprehensive understanding of the full implications of their actions. This stealthy form of deterioration, often overlooked, poses a greater threat to the integrity of heritage assets than sudden, dramatic occurrences.

There is a need to carefully and proactively manage the historic asset, paramount to safeguarding the authenticity of the building and its standing in the urban scene. This authenticity supports the significance defined by the NPPF as "… *the value of a heritage asset to this and future generations because of its heritage interest*." NPPF, (2023, p.75). There are two stages in this endeavour as highlighted in the Historic England document, "*… understand the form, materials and history of the heritage asset and/or nature and extent of archaeological deposits, and understand the significance of the asset(s)."* Historic England (2019b, p.3). The statement of significance is objective, describes the heritage, specifically what matters and why, and is used in the management of the asset. ICOMOS imbues cultural significance with status in one or more of the following categories, aesthetic, historic, scientific, social, and spiritual.

Conservation may be achieved by no action in difference to the habitual process of preservation or reestablishment, where preservation leads to maintenance, repair, adaptation and even restoration or reconstruction, Historic England (2008). Historic England (2008) deem new work, for example, additions, can only be exonerated when it does not deform or make opaque the significance of the heritage asset, or impede appreciation of either the fabric or cultural heritage. The Burra Charter under Article 27 states "*Existing fabric, use, associations and meanings should be adequately recorded before any changes are made to the place*." ICOMOS (1999, p.8).

Therefore, in change management, the statement of significance is the starting point where extreme proposals may need to be tempered especially to ensure retention of meaning in the original asset. The recording proposed here is part of the solution in heritage management Dallas (2003), especially when there are additional layers of importance, the captured data is multifunctional having the ability to be used for general record, analysis within the auspice of the building narrative or for information dissemination for example in touristic endeavours.

Buildings in use are the best conserved according to the Advice Note 2 Historic England (2015), as supported by the NPPF (2021), generally leading to ongoing maintenance which retains the fabric in a useful condition. *"Good conservation of heritage assets is founded on appropriate routine management and maintenance."* Historic England (2015, p.3). Acierno (2016) states conservation requires intense comprehension of the fabric and edifying identity to robustly design the intervention including realising the constraints. Repair as the next level is considered as an intervention yet in most cases there is no need for authority consent. Care is required in all repair interventions to maintain the meaning of the asset requiring the highest integrity in the conservation consultant and the craftsperson. The introduction of an extraneous material especially where it contests significance would need clear justification, robustly argued and consent unless it replaced an existing inappropriate, non-original material.

An accurate survey is considered the essential first step in the process of decision-making making Mezzino (2017), Historic England (2016a) to inform the management and use of buildings. However, this needs context and time to become the basis on which to determine the extent and subsequent schedule for any work. Furthermore, upon completion of the work, there is a need to monitor and review the impact of the solution on the remaining fabric and if necessary, reverse the intervention.

In summary, the evolution of heritage fabric over time, as illustrated by the images in Figure 1 (Page 6) underscores the complex nature of material degradation. This material loss exemplifies a significant flaw: like memory, weathering obscures detail, reducing its congruence and significance. While climate change exacerbates these processes, it is only a part of the broader issue. General weathering from natural elements and catastrophic events,

alongside human actions such as conflict, vandalism, and poor maintenance, collectively erode the physical integrity of heritage monuments. Surprisingly, the most profound impact often stems from gradual degradation caused by maintenance and repairs by experts who lack a comprehensive understanding of their actions' full implications.

To safeguard the authenticity and significance of heritage buildings, proactive management is essential, this involves understanding the form, materials, history, and significance of heritage assets. Conservation strategies range from preservation and restoration to recording existing fabric before any changes. Effective heritage management includes routine maintenance, accurate surveys, and context-informed decision-making.

2.3 Heritage Management

Managing historic assets is a complex task; notwithstanding the monument itself, there is a myriad of stakeholders, legislation and systems. The asset significance, conservation philosophy and practice extend this difficulty in support of sustainability. The management approach to the necessary maintenance, repair, retrofit and refurbishment of building fabric, systems and setting is made difficult by the need to minimise the risk to the significance of the building. However, in heritage assets, the greatest impact on significance is not wholesale destruction but slow erosion caused by weathering or human forces, with or without malice.

Building conservation, according to BS 7913:1998 The Principles of the Conservation of Historic Buildings is, "… *to secure the preservation of the nation's stock of buildings and in particular its historic buildings and fine architecture, in the long-term interest of society*." BS (1998, p.5). In this document, the term 'heritage asset' is used to refer to historic buildings and their immediate setting but not, as in the normal use of the term, memorials, archaeological remains and designated landscapes, which are held to have cultural value.

In the UK there is an extensive range of heritage assets, most of which are in a serviceable condition, upholding the notion of architecture as cultural expression. These start with the artisan tradition through to the conservation movement of today with all stages in between and using a myriad of skills, materials and techniques which enrich our lives. Where is the information for

these sites held, is it robust and who are the gatekeepers? If the heritage asset is to be resilient now and, in the future, there is a need for efficient, effective and robust management with an economic focus upholding a sociocultural underpinning. Immediate access to data in support of this management is an imperative, Saygi et al state "*.. for better comprehension a crucial point in a database system is the possibility to integrate and manage heterogeneous data that will be linked to a multi-layered 3D model.*" Saygi et al (2013, p.284).

At this juncture, sustainable heritage management necessitates a meticulous selection of definitions of sustainability and the incorporation of key principles that underpin a long-term, holistic development approach, emphasising the active participation of all stakeholders involved (Landorf, 2009). This concept of sustainability extends beyond the mere preservation of physical heritage; it encompasses intangible elements, to address all pillars of sustainability—environmental, social, and economic. The integration of these pillars ensures a comprehensive strategy that respects and enhances cultural heritage while promoting sustainable development. Consequently, sustainable heritage management has evolved into a critical and practical focal point within the heritage sector, reflecting its growing importance in policy and practice (Tu, 2022). This approach underscores the interconnectedness of heritage conservation and broader sustainability goals, emphasising collaborative efforts and inclusive governance.

Sustainability within physical asset heritage management should be contextualised within the framework of the fundamental SDGs and the NPPF as implemented by the UK Government. These frameworks, widely endorsed across the sophisticated domain of heritage conservation, serve to shape and refine the notion of sustainability. ICCROM highlights SDG 11, which focuses on making cities and human settlements inclusive, safe, resilient, and sustainable, and Target 11.4, which mandates strengthening efforts to protect and safeguard the world's cultural and natural heritage. Other SDGs are equally pertinent, including ensuring healthy lives and well-being (SDG 3), providing quality education and lifelong learning opportunities (SDG 4), promoting gender equality and diversity (SDG 5), fostering inclusive economic growth (SDG 8), reducing inequalities (SDG 10), and addressing climate change and its impacts (SDG 13). As previously determined the goals applied to heritage conservation, are grounded in the five foundational principles

known as the 'five Ps': People, Planet, Prosperity, Peace, and Partnerships. This comprehensive approach ensures that heritage management not only preserves cultural and natural assets but also promotes broader sustainable development objectives.

The heritage values focus on the tangible fabric of the site rather than the outwardly looking sustainable values; to achieve this the stakeholders should be more engaged individuals and groups supporting the socio-economic elements. Some key issues in heritage fabric are climate change and environmental degradation bringing about unplanned loss and whilst slow undermining of heritage value through inappropriate interventions is considered a risk, the latter can be managed whereas the former remains without redress.

The heritage asset must be authentic to be valued intrinsically, less so when it is monetarily as a physical object. This monetary value may have a negative aspect if it has a maintenance deficit which is likely larger due to the heritage complications. Authenticity has not only the physical manifestation but will comprise the building methodology, function, embedded history, and setting. This multiplicity must be accounted for in any conservation or future development and maintenance to retain authenticity under the lens of "*… design and form, usage and function, traditions and techniques, location and settings, materials and substance, etc."* Lopez (2018, p.26). The digital twin should be precise in identifying "*… genuine values of architecture (form, space, structural system, materials, textures, etc.) that have been accredited by scientific research as originals, deserve to be preserved (or recovered, if lost), and transmitted to future generations*." Lopez (2018, p.26). Data acquisition technology for the base 3D digital model should be complete and accurate, and augmented with simultaneously accessible material, analysed and integrated into the model to inform the conservation process. Lopez further promotes the architectural term Anastylosis, "*… a reconstruction technique whereby a damaged building or monument is restored using the original architectural elements to the greatest degree possible while new parts are made visible through the use of distinct material*." Lopez (2018, p.27). Whilst this aligns with best practice to the untrained eye it can bring reservations, the perspective coloured and the asset criticised or underutilised. "*Virtual conservation can be applied to knowledge about purpose and use, as well to the representation of the object, but not to the*

object itself." Lopez (2018, p.27). The removal of setting, realism, and the loss of complete sensory contribution diminishes the experiential effect, therefore, the authentic nature.

The management plan as proposed by UK government brings a proactive approach based on objective survey and research documentation, robust strategic organisation supported and determined by multiple stakeholders is extensively considered necessary in achieving sustainable development. The requirement to provide consistency between local and international value will produce tension especially as management plans tend to be underpinned by the expert direction utilising the statutory instruments. The strategic objective to ensure endurance through use thereby satisfying local socioeconomic need may require intervention at the expense of elements of significance. As stated in Landorf "*… greater community participation and sustainable development lies in the connection between authenticity, outstanding universal value, and the tangible manifestation of that value.*" Landorf (2009, p.499), as pervaded in the Western heritage practice. Therefore, a consolidative site management plan is the most important strategic framework in the armoury of heritage management.

As management plans are based on a raft of data, accurate robust surveys and comprehensive research, the proposed solution as presented here is a sound basis for the plan. The output as presented (See Figure 2) is based on the aspiration for a holistic planning framework employing the participation of a diverse group of stakeholders essential in a sustainable development process. This framework identifies the complexity of the management of heritage and the requirement at the inception of the plan at a strategic level. This framework arguably precedes the Chartered Institute of Building (CIOB) (2020) conservation process however analysis will require data. The case for cyclical data capture and the inclusion of newly acquired research material can be determined as moving from the plan into the execution stage will require current unyielding knowledge and understanding of the asset. The plan should also be dynamic and progressive in response to internal and external forces including fluctuating stakeholder requirements, the research by Landorf concludes that the framework '*… is reliant on heritage managers having complementary conservation, management and negotiation skills, in addition to access to the data to support the decision-making process*.' Landorf (2009, p.508).

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Figure 2: A Comparative Framework for Sustainable Heritage Management Landorf (2009)

A decision support system (DSS) provides a method enhanced by information technology to assist managers in making evaluations in a complex environment such as heritage for example when programming, communicating, controlling finance etc. This approach does not supplant the managerial role; rather, it facilitates the evaluation of proposed solutions, enabling their acceptance, revision, and re-evaluation. The paramount requirement is that the information contained within the system must be comprehensive, relevant, and current, thereby addressing the complexities of unstructured or semi-structured multifaceted issues. Given that such assessments frequently involve multiple decision-makers, the platform must also enhance clarity, particularly in communication and collaboration, to

achieve the optimal outcome. Effective communication and collaborative mechanisms are essential for ensuring that all stakeholders are aligned and can contribute to well-informed, consensus-driven decisions. This enhances the robustness of the decision-making process and ensures that diverse perspectives are integrated into the final solutions. The improved outcomes will limit the heritage assets deterioration assisting the conservation strategies, reduces cost and contributes to proactive management. Experience plays a large part in the final evaluation and action, with digital data and platforms at the core of the process these solutions can be shared with those less skilled to bring forward a more robust conclusion.

Mustafa et al (2019) propose that Building Information Model (BIM) is a DSS as it can provide comparative evaluation across time in asset development, the software can store, retrieve and analyse plans, models and research data. There is apprehension generally as the lack of documentation or outdated information is leading to poor decisions impacting negatively on the asset thereby losing Outstanding Universal Value (OUV). Custodians and/or managers need to effectively evaluate, design, and apply management plans to stabilise and improve the heritage site. For sustainable situations the DSS encompasses the wider implementation of knowledge distribution to proactively include stakeholders and facilitate. Stakeholder involvement in DSS development has been pursued though a mismatch between expectancies and actuality continues to limit application.

The introduction of Heritage Partnership Agreements under the Enterprise and Regulatory Reform Act 2013 between the Local Authorities and any one owner of the building has opened an opportunity for change in the management of heritage. English Heritage in their Good Practice Advice Note states "*The main focus of the document is likely to be details of the consented works to the listed building, which may be specified works of alteration or extension but not demolition, that may normally be granted listed building consent.*" English Heritage (2013, p.1). It goes on to suggest that records for benchmarking, the record of previous consents, categories of permitted work and recording of work "*may … be appropriate … to assist parties in monitoring the agreement.*" English Heritage (2013, p.5). The agreement, whilst not explicitly suggesting an information model, would benefit at all stages in having such a model available to support it. Further still, the government, in managing their historic estate within the High Performing Property document, requires each

department to prepare a Property Asset Management (PAM) Plan hoping it will support an economic advantage and a heritage information model would provide a sound basis for such a plan.

Quattrini, Pierdicca, & Morbidoni, (2017) paper is an example of this covering the workflow for the building of a model in four stages, providing a data structure, data enrichment, conversion to a machine-readable format and demonstrating a data exploration web-based application. The issues were a lack of complex components in the modelling software, modelling of irregular shapes and data enrichment and 3D interoperability. It has been suggested that the primary function of the digital model is to delineate the state of conservation and to strategize future interventions. However, the paper begins to diverge from the core objectives of this thesis in two significant aspects. First, the intricate components necessary for planned interventions entail a costly modelling exercise that, when implemented, may result in compromises and potential inaccuracies. Secondly, the sustainable management of the asset should encompass the enhancement of data within the live model as it evolves. Planning future operations necessitates the inclusion of community needs, the pressures exerted by stakeholders, and, most importantly, the asset's significance in determining the level of acceptable intervention. This holistic approach ensures that the asset's preservation is aligned with both contemporary and future requirements.

Managing historic assets involves balancing numerous stakeholders, legislation, and systems, emphasising the asset's significance and sustainability. Effective heritage management includes maintenance, repair, retrofit, and refurbishment while minimising risks to the building's significance. Conservation, as per BS 7913:1998, aims to preserve historic buildings and their architecture for societal benefit. In the UK, heritage assets are generally in good condition, reflecting architecture as cultural expression. Efficient management requires robust data integration and stakeholder involvement, essential for sustainable heritage management. This approach aligns with SDGs and the NPPF, emphasising cultural and natural heritage protection. Authenticity, encompassing physical manifestation and historical context, is crucial for heritage value. Digital solutions like BIM facilitate decision-making and data management, enhancing conservation strategies. Heritage Partnership Agreements and Property Asset Management Plans further support systematic heritage management. Sustainable management

includes continuous data enrichment and stakeholder engagement, ensuring heritage preservation aligns with current and future needs.

2.4 Heritage Data for Management

The management framework as proposed by Budiman et al (2019) utilises the 5R concept of timing, site, interface, consumer and content in the cultural heritage field. This sits towards the dissemination phase of heritage management, that is not to say it has no value in the management of the asset, it will support many stages of the process through efficient distribution of the information underpinning the OUV. The effective management, storage, and dissemination of heritage data has recently been significantly enhanced by advancements in information and communication technology (ICT). The emergence of e-Culture, which facilitates the storage, preservation, and utilisation of heritage data, is evolving rapidly. This technological progress allows for more efficient and sophisticated methods of handling heritage information, thereby improving accessibility, accuracy, and long-term preservation. The integration of ICT in heritage management not only streamlines processes but also supports innovative approaches to conservation and dissemination, fostering a more dynamic and interactive engagement with cultural heritage. This advancement encompasses new tools, hardware, and workflows but risks immediate obsolescence therefore losing the advantage ICT affords.

Knowledge management improves performance in the creation, sharing and use of information in decision-making. However, access to all can impact the OUV diminishing preservation though conversely it can intensify and develop identity. The classification can be difficult due to the nuances of the asset, and owing to this complexity, how the content can be developed to be accessible. The content will originate in repositories or specific campaigns, reports, and collections, and be brought together in the virtual world, the important elements are the creation and delivery. Integration is central relating to site, time, user, interface and content Budiman et al (2019) to make it appropriate.

The generation and presentation of data derived from pragmatic exploration constitute a crucial connection between the heritage value maintenance and enhancement frameworks proposed by institutions such as Historic England,

Council on Training in Architectural Conservation (COTAC), and UNESCO, and the theoretical framework for managing cultural heritage information. This linkage underscores a key element in the effective management of cultural heritage, ensuring that the methodologies and best practices advocated are seamlessly integrated into the practical management of heritage data. By aligning empirical data with these established frameworks, the proposed management approach enhances the preservation, interpretation, and dissemination of cultural heritage, thereby reinforcing the principles of sustainable maintenance and enhancement within the sector.

The current trend in building management emphasises the accessibility of information within the information model via mobile technology, allowing any object within the built environment to be identified, along with all associated attributes and data, by any authorised user to enhance maintenance, repair, performance, or refurbishment. These interfaces empower the stakeholders to higher levels of efficiency and effectiveness and reduce the need to seek specialist advice when the object for review is defined as having little or no impact on the significance of the heritage asset. With this information to hand any project would proceed unencumbered by obligations to the heritage of the asset, where an impending impact may result there is the opportunity to seek alternative solutions before engaging with the conservation authority. Where an impact on the significance of the heritage asset is unavoidable, the possibility of quantifying the loss of significance and extracting data for assessment from the model will quicken the process and ensure a robust decision. Finally, any changes to the asset can be recorded in the digital model along with the pertinent information leading to the decision and resulting from the revision. This data improves the understanding of the heritage asset creating historic records and informs the decision-making process to advance the efficiency and effectiveness of the decision.

The incorporation of a data repository necessitates thorough evaluation, particularly within the context of digital practice. Although the current model offers a fine-grained solution, historical data often remains coarse, pertaining to the entire asset rather than its individual components. Within this context a digital model, integrating Geographic Information Systems (GIS) and information modelling, provides a suitable platform for capturing data at all levels. For instance, Google Maps showcases the Nottingham Trent University

Newton Building as an architect's drawing, detailing the building layout including furniture. However, the coarse nature of historical data poses limitations, preventing specific details from being preserved especially during interventions. This lack of detail can hinder both current and future uses of the data, elements such as in repairs. To maintain the significance of historical assets, a highly detailed, fine-grained model emerges as the most appropriate solution. Such a model ensures precise documentation and facilitates effective maintenance, repair, and preservation activities.

Returning to the paper by Quattrini, Pierdicca & Morbidoni, (2017) three levels of information, global, macro and elemental which can be grouped as the need requires, elements become macro become global. An issue with placing all data in a single repository is the time required to attach the links/upload the data currently a manual activity and the computer requirement that may preclude this. Furthermore, there are more fundamental issues such as the terminology and the definitions including geometric location tag, all necessary for data inclusion, search functionality and interoperability between platforms. Finally, several critical factors must be addressed, including data security, the potential for lost links, data corruption, infrastructure scale, accessibility, and compatibility.

The paper published by Acierno, Cursi, Simeone & Fiorani identify the investigation and design phases, the model being built in the design phase to '..*provide and manage investigation results that can be used for conservation planning and to act as support for design decision-making*.' Acierno, Cursi, Simeone & Fiorani, (2016, p.124). The investigation revolves around two elements - examination and analysis - the output being an assessment considering each piece of evidence avoiding ambiguities to merge the parts into a coherent framework from which decisions can be made. However, once a project transitions to the design phase, significant overarching management decisions have already been made. Proceeding without comprehensive investigatory data risks suboptimal decision-making, particularly if stakeholder engagement has been inadequate, potentially compromising the asset's importance. The need is to ensure all stakeholders have access to the data to focus on collaboration leading to consensus, a requirement of sustainability in the management of a heritage asset.

Building an accurate model with comprehensive data is very difficult without infinite records, intrusive surveys and capable infrastructure notwithstanding the current basic inabilities of consistent terminology and definition but also the output required to link seamlessly into any software platform. Limitations in any solution proposed require a certain flexibility with a resultant risk to the conservation, project success and ultimately the significance of the asset. However, the concept cannot be dismissed, the current situation is equally untenable risking the sustainability of the heritage asset due to the lack of cohesive accessible data therefore, even embracing these limitations, the need is indisputable.

The model will contain both the objective and subjective, the dimensional and the contextual information, described as "*… an appropriate concept-logic network …. further enriched by the description of the entities and of the relationships that occur between them."* Acierno, Cursi, Simeone, & Fiorani, (2016, p.126). The paper aimed to "*… develop a knowledge-based model for the representation of architectural heritage, in order to support both the investigation and design phases of the conservation process*." Acierno, Cursi, Simeone, & Fiorani, (2016, p.124). A limiting factor in this intention is any model should be the stepping stone to the future of the asset, models are ultimately able to support maintenance, operation and education from the single source of truth. It could be perceived that any editing embraces the addition of data through the inclusion of discoveries, events, actions and outcomes undeniably enhancing the model. There is an acknowledgement that the model with *"meanings, description, and the relationships between them [should offer] a formalisation of contents within a logical network that can be managed by all the experts who are involved."* Acierno, Cursi, Simeone, & Fiorani, (2016, p.125).

A certain component of the requirement for flexibility could be mitigated in the model if new evidence were to become available during the design, planning or execution stage inclusion could rapidly lead to a robust solution which minimises further threats to the asset or in an ideal situation removes previously accepted risk. Management will need to acknowledge the interpretations of the discoveries which include the '*indirect knowledge … heterogeneous and critical assumptions provided by the studies that are carried out in a conservation project*.' Acierno, Cursi, Simeone, & Fiorani,

(2016, p.125). The paper delves into the nuances of each element for example how it is represented in the model using web-based languages; lifecycle is one area where the authors state "*Only profound comprehension of the material and cultural aspects of its historical architecture identity can properly address the design of the conservation, by highlighting critical issues, constraints and values. … (lifecycle gathers) all activities … involving the transformations of the building or influenced architectural configuration, use, or even identity itself: therefore, all other domains in the ontology must be involved.*" Acierno, Cursi, Simeone, & Fiorani, (2016, p.130). The proposition being the timeline is the key factor in the data by which all other elements can be defined. A timeline starting in context; location, site, external pressures (political, social, economic, environmental) prior to inception through to the moment when the model is being enhanced, part of which will be the development of the model either running concurrently or intertwined with the asset.

The principal framework elements proposed in the ontology by Acierno, Cursi, Simeone, and Fiorani (2016) encompass the artefact, investigation process, lifecycle, and actors. These elements interrelate and within each sub-domain, they delve into specific sub-links operating at various domain levels. The synthesis of parametric, material, technological, and historical data enhances the understanding of the artefact lifecycle, elucidating transformations and informing conservation or evolutionary design. This comprehension "…*can properly address the design of the conservation (or evolution), by highlighting critical issues, constraints, and values*" (Acierno, Cursi, Simeone, & Fiorani, 2016, p.130). However, the less-than-objective nature of historic information can lead to errors in the narrative, notwithstanding this, importance must be placed on the model being the best fit and, therefore, the most appropriate basis for the conservation or evolution of an artefact.

A further mitigating aspect is that any conservation measure, or evolution, applied to the artefact should be reversible if the principles are followed as considered by Petzet (n.d.) on the ICOMOS Venice Charter forty years on. The model used as the basis for any transformative intervention will not be in a steady state, the process will provide additional evidence which upholds or contradicts the knowledge, this flux leaves the project on an intermediate foundation. With this comes a necessity for malleable solutions, therefore,

the model is the flexible best-fit decision-making tool. The proposition in the paper is that the knowledge base will remain a constant throughout the process, only the 3D model will be adjusted however, the interdependency between the two suggests otherwise. The flexibility will need to be built in to allow the flow of information in and out of the model as any project progresses and for the lifetime of the artefact. The paper does propose the model has a conceivable contribution in the planning of maintenance, a component often overlooked in artefact lifecycle yet plausibly the most important. The other element not covered is the link to other similar artefacts, models are the median and contain the micro but where is the macro in the equation? There is a high-level link missing in drawing into the model data from sources not directly related to the artefact, this may enhance the status or identify other fonts of information to verify or adjust the comprehension. In summary, the paper upholds the notion a knowledge model is centred on the investigation process whether objective or subjective and the synthesised combination. There is a proposal the model should be available to all stakeholders, yet this is not explored at any level, the output is a digital model, yet stakeholders are not always able to engage on this platform type.

Duality can be identified in the artefact, the aesthetic and the historic dimension, perception is in the eye of the observer, irrepressible due to external influence however it is only the fabric that can be conserved as the fourth dimension can only be developed. This is where the digital model can help the process of understanding, melding the four dimensions to ease access and analysis. *"The virtual model allows us to explore interactively and in real-time the architectural space, including the access to different information levels. This helps understanding the building and allows us to integrate various levels of information."* Lopez (2018, p.28). Furthermore, with the inclusion of all known information, "*Virtual models enable the representation of different parts of the building or heritage site and at different historical moments."* Lopez (2018, p.28) a clear benefit to the dissemination of knowledge.

The lifecycle of the building is linear from the original construction, and modification and may include revision, pauses, conservation intervention that may include loss of historical fabric or architectural form, consolidation of existing and introduction of new elements all of which will direct any new phases in the building's history. In parallel the 4D model is constructed, the

three dimensions are validated or challenged in the narrative or layered or determined exploiting typology yet constantly ignoring the architectonic theme. The virtual can and often does include the imaginary however to be authentic the conservation of any artefact must stop before conjecture commences.

A potential limitation would be consideration of the aim of any intervention, the model should be universally applied to the whole including the setting to ensure a full understanding is used in the decision-making process. If the aim focuses on a single element there may be an appetite to expend all the necessary resources to capture the whole. This could lead to a poor decision affecting the whole asset therefore it is necessary to provide sufficient data at all levels, world, local and micro, with micro being focused on the area of concern. The London Charter published in 2006 sets the principles for the application of digital visualisation in research and communication of heritage specifically cultural.

Reverting to the DSS in supporting the management of the heritage asset, Allen et al (2017) suggest an open cloud-based interactive tool regularly updated with access to information, analysis and decision guidance would bring DSS in the form of an information model. Utilising LiDAR is easier, more effective, quicker and safer than data collected utilising conventional methods, Ali et al (2018). It is imperative to cultivate specific personal attributes, essential core competencies, and process-oriented skills to effectively implement information models within a heritage context. To initiate efficiency utilising DSS requires proficiency in collecting, handling, refining, consistency and accuracy of data, thereby allowing more effective decisions to be made and executed based on an organised approach. Allen et al. (2017) propose that the DSS should be augmented by incorporating the Theory of Change (ToC) approach. This approach involves the professional team managing the heritage asset and the stakeholders engaging in a collaborative process of analysis and reflection, rather than merely designing a linear solution. The ToC methodology envisions an iterative refinement process that extends throughout the asset's lifecycle. This adaptive framework allows for continuous revision and improvement, accommodating changes in team composition and stakeholder involvement, thereby enabling new members to review outcomes and influence interventions. Furthermore, the cyclical nature

of this process ensures that any alterations in policy or contextual factors are systematically integrated, maintaining the relevance and effectiveness of the management strategy.

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Figure 3: Theory of Change approach for key project elements in a logic model Allen et al. (2017)

As identified in Figure 3 the inputs are resources, activities are interventions, and outputs are Specific, Measurable, Achievable, Relevant, Timely (SMART) results split into short, medium and long-term, or utilisation/operational, intermediate and strategic. Tables can be nested to account for the complexities in the logic model and sufficient detail should ensure all elements can be explained especially to the non-specialist. Having elucidated the situation these same models can be used in the monitoring and evaluation stages; this reflection identifies the effectiveness of any action and contributes to the sustainability of the asset. A deep understanding of the context is required and conversely, this will identify the risk afforded by the external forces to be accounted for in the model. Required understanding may come from prioritising, identifying technical and environmental possibilities, demonstrating sustainable benefits, and identify best practice locally and for the wider conservation community. Adaptive modus as identified also upholds the research methodology of active methods.

As the ToC is a method in which the DSS will be implemented, the requirement is for clear boundaries to be developed and appreciation of the desired outcome will evolve the understanding of the activities to achieve these. Although simplistic in this discussion, as the logic models grow the full complexity of the issues will become apparent allowing the stakeholders to have a deeper understanding of the direction of travel, a systematic

assessment of the progress and guarantees coherency across a range of management activities. The requirement for implementation is an effective process, excellent communication, and time to allow development through to outcome appraisal. Stakeholders, encompassing professionals integrated across all disciplines as well as amateur and peripheral interested parties, are required to contribute a diverse array of complementary skills that extend beyond mere technical expertise. This holistic skill set is essential for the formulation and implementation of an ethical, effective, and efficient heritage management plan. The inclusion of varied perspectives and expertise ensures that the social dimensions of sustainable management are comprehensively addressed. By fostering collaborative and interdisciplinary engagement, the management plan not only adheres to best practices in heritage conservation but also fulfils the broader social objectives intrinsic to sustainable heritage management. This inclusive approach underscores the importance of stakeholder diversity in achieving long-term sustainability and cultural preservation.

In summary, advancements in ICT have greatly improved the management, storage, and dissemination of heritage data, thereby improving accessibility, accuracy, and long-term preservation. Integrating ICT into heritage management not only streamlines processes but also supports innovative conservation and dissemination approaches, fostering dynamic and interactive engagement with cultural heritage.

Effective knowledge management boosts performance by enhancing information creation, sharing, and use in decision-making. Generally, universal access to information can positively impact the OUV through collaborative working. However, the nuanced nature of heritage assets poses classification challenges, affecting content development and accessibility. A detailed, fine-grained model ensures precise documentation, facilitating maintenance, repair, and preservation activities. Ensuring stakeholder access to data fosters collaboration and consensus, essential for sustainable heritage asset management. The model should encompass both objective and subjective information, serving as a robust decision-making tool. Flexibility is crucial, allowing for new evidence and iterative refinement throughout the asset's lifecycle.

Organising information at global, macro, and elemental levels is essential, despite challenges in data attachment and terminology consistency. Critical issues such as data security, lost links, corruption, infrastructure scale, accessibility, and compatibility must be addressed. Combining artefact, investigation process, lifecycle, and actors with parametric, material, technological, and historical data informs conservation or evolutionary design by highlighting critical issues, constraints, and values.

A Decision Support System enhanced by the Theory of Change approach promotes continuous revision and improvement, integrating policy changes and contextual factors to maintain strategy relevance and effectiveness. Aligning empirical data with established frameworks reinforces sustainable maintenance and enhancement principles. Diverse perspectives and expertise ensure a comprehensive heritage management approach, addressing technical, environmental, and social dimensions for long-term sustainability and cultural preservation.

2.5 Digital Practice

Digital technology is permeating every facet of contemporary society, profoundly influencing and enhancing daily activities. Data, whether stored on small implanted solid-state devices or in vast remote data centres, is meticulously captured in both structured and unstructured forms. This data is then rendered accessible for diverse sophisticated processes such as mining, interrogation, integration, analysis, and reporting. Consequently, digital information serves as a foundational element, driving informed decision-making and enabling proactive actions across diverse domains. This pervasive digital integration underscores the transformative power of technology in shaping modern life and underscores the critical importance of data management and analysis in harnessing its full potential.

The construction industry is increasingly recognising the transformative potential of digital technology across an assortment of domains, including sustainability, health and safety, record-keeping, clash detection, material management, modelling, and building management. BIM, an innovation inspired by the manufacturing sector, serves as a powerful tool for managing and sharing vast amounts of interconnected data via a graphical interface. BIM facilitates efficient data sharing, retrieval and location during critical

events, revolutionising project management and operational workflows in the construction industry. This digital evolution underscores a significant shift towards more integrated, intelligent, and sustainable building practices. Barnes and Davis advise "*Information is at the heart of BIM, and standardised, well-structured information will enable enormous efficiencies in the construction and civil engineering industries."* Barnes and Davis (2014, p.129). There is a UK government mandate specifying the use of BIM in all new centrally procured construction ventures however the industry is waking up to the opportunity to this benefit on all projects. This does not stop at handover, it extends through the operation and maintenance of an asset before feeding into the renovation or demolition/recycling stages.

To further this initiative the UK HM Government are striving to adopt Level 3 BIM as the document Digital Built Britain Level 3 Building Information Modelling – Strategic Plan sets out. BIM Level 3 is the holy grail in building management manifesting itself in a Facilities Management Information Model which it is perceived will add value throughout the whole lifecycle of the building supporting sustainability at all junctures. Irizarry, Gheisari, Williams and Roper state *"BIM not only provides the 3D visualisation of all objects in the facility but also plays the role of a data repository in which required information is tied to each object and can be used for maintenance and operation purposes."* Irizarry, Gheisari, Williams and Roper (2014, p.135).

Poirier, Staub-French & Forgues (2014) provides two implications of digital models, clear industry policy which is there for standard application but not heritage, and a strategic adoption and implementation process at the stakeholder level. That is not to say without inclusion this will not benefit the management of the asset but that there are areas ripe for improvement. Digital models are intricate, multifaceted constructs designed to facilitate the formation, aggregation, and dissemination of relevant data, emphasising both quantity and quality, thereby enhancing effective communication and ensuring the integrity of complex data-centric interactions. The groundwork of such a model lies in accessible digital content and heritage assets, evolving from their inception to the present iteration. To achieve comprehensive understanding in heritage, the foundational data must encompass the current 3D form and the historical events that have shaped the monument's structure and importance. This integrative approach allows for a thorough appreciation of both the physical and historical contexts, enhancing the cultural and

academic value of the heritage assets, yet this solution is not common practice, Isa, Zin, Rosdi and Sarim (2018). Formalising this in a digital facsimile constitutes the initial phase of an evolving model, which preserves values, underscores importance, and, when intervention is necessary, ensures the retention of significance, thereby facilitating informed decision-making and safeguarding heritage integrity for the future.

Throughout the world, we have a wealth of urban development for which there is limited data and no model to capitalise on these opportunities. Several research projects and SMEs are looking at the asset digital model to contain the assembled data and aid retrieval during an event. The gathering of the data needs managing, from the outset of an information model clear understanding is required of the intended use; that is not to preclude future development of the model but to ensure data is not captured for capturing's sake. The digital twin is becoming a reality with embedded sensors collecting and relaying data to the model for analysis using algorithmic functions' intelligent control, Al-Ali et al (2020). This will work within the Internet of Things to instigate adjustments where outside parameters or flag for intervention in more extreme cases ensuring timely involvement of the support staff to provide effective and efficient building management.

The opportunity exists to draw together information in an accessible knowledge model borne out of the Light Detection and Ranging (LiDAR) data to support the decision-making process. There are four areas of knowledge which should form the backbone of a model - artefact, lifecycle, investigation practice and stakeholders which should be accessible, editable and manageable in the conservation process. *"The challenge is to synthesise our knowledge of past, present and what we can predict of [the asset's] future."* Janvier-Badosa (2016, p681). The proposed model is intricately positioned within both micro and macro frameworks, as well as the overarching policy context, which collectively inform and shape the conservation response. Crisan et al. (2024) concur, asserting that 3D LiDAR scanning is a groundbreaking tool that provides numerous benefits for the preservation, research, and accessibility of cultural heritage sites through meticulous documentation, recovery, and conservation efforts. This technology integrates seamlessly with historical records and discovered artefacts, culminating in a comprehensive understanding of a site's historical and contemporary contexts.

The management of a heritage asset, which may or may not be listed, includes the evolution of the building, Historic England observes *"Change in the historical environment is inevitable, whether caused by natural process, through use, or by people responding to social, economic or technical advances"* Historic England (2008, p.22), they then propose historic values and networks should be exposed and understood to assist in current and future decision-taking to make robust any benefit to the community. The maintenance, repair, retrofit and refurbishment of building fabric, systems and setting is made difficult by the need to minimise the risk to the significance of the building, and this determines the ethical management approach. It is well recorded that to maintain our heritage continued use is paramount yet there is often a tension between exploitation and the impact on significance. By having digital data accessible in one location, it would enable the management of that tension. The knowledge pertaining to the heritage asset stored, maintained and retrieved efficiently and effectively will support the retention of the significance in that inevitable evolutionary process.

Most owners, occupiers and users are unsure of the attributes of the asset which combine to determine the significance, and therefore value - social, environmental and economic - such that there is a grave risk of forfeiture or disfigurement. An information model as 3D graphic data, metric, explanative and illustrative coexisting, an ideal media in which to identify the levels of significance, and therefore value, to clarify the areas for protection, their vulnerabilities, the risks to weathering, erosion and loss, and opportunities to protect which would feed into the management of the asset supporting all pillars of sustainability. Historic England in the document Conservation Principles, Policies and Guidance for the Sustainable Management of the Historic Environment stated the following, "*Sustainable management of a place begins with understanding and defining how, why, and to what extent it has cultural and natural heritage values: in sum, its significance. Communicating that significance to everyone concerned with a place, particularly those whose actions may affect it, is then essential if all are to act in awareness of its heritage values. Only through understanding the significance of a place is it possible to assess how the qualities that people value are vulnerable to harm or loss. That understanding should provide the basis for developing and implementing management strategies (including*

maintenance, cyclical renewal and repair) that will best sustain the heritage values of the place in its setting. Every conservation decision should be based on an understanding of its likely impact on the significance of the fabric and other aspects of the place concerned." Historic England (2008, p.14).

A simple method to check and determine the significance of an element would reduce this risk, support the statutory requirements, maintain the significance of the asset, in all aspects support sustainability. Access to the data through a graphic interface would simplify the process therefore an information model should be the starting point, the fact that the data is shared with all stakeholders improves the robustness of the decision-making upholding the unifying principle of a common data environment and a single source of truth. Furthermore, the data can be extracted to extend community knowledge to grow understanding and extend the reach of the asset beyond the local populous to grow links with similar throughout the globe.

Digital technology has become integral to contemporary society, significantly enhancing daily activities across various domains. The construction industry is recognising the transformative potential of digital advancements, especially through elements such as digital models. BIM facilitates the efficient management and sharing of vast amounts of interconnected data via a graphical interface. This innovation is revolutionising project management, procurement, construction and operational workflows, promoting more integrated, intelligent, and sustainable building practices. In this process the requirement is heterogeneity of data, the dimension of time, track changes for reversibility/authenticity and community engagement, Crisan et al (2024).

The UK government mandates BIM usage in all new centrally procured construction projects, aiming to leverage its benefits across all ventures. Moving towards Level 3 BIM, as outlined in the document 'Digital Built Britain Level 3 Building Information Modelling – Strategic Plan,' UK Gov (2015), promises to add value throughout a building's lifecycle. This approach supports sustainability by ensuring efficient data management, from construction to operation, maintenance, and eventual renovation or demolition.

Integrating heritage data within these information models enhances the management and conservation of heritage assets. By providing comprehensive, accessible digital records, digital models support informed

decision-making and preserves the significance of historical structures. This integrative approach fosters sustainable management practices, ensuring that the cultural and academic value of heritage assets is maintained and appreciated.

Digital technology profoundly influences contemporary society, enhancing daily activities and driving informed decision-making through sophisticated data processes. The construction industry increasingly adopts digital tools, in particular BIM, which manages and shares interconnected data efficiently, revolutionising project management, collaboration, and fostering sustainable building practices. Crisan et al. (2024) reinforce the manner in which BIM models are tailored to address the unique requirements of cultural heritage sites throughout all stages of their management. The incorporation of material properties, historical data, and decay analysis within these models establishes a digital framework that not only aligns with sustainability objectives but also upholds the historical significance essential for the preservation of cultural heritage.

In heritage conservation, integrating digital models preserves the significance of historical structures, facilitating informed decisions and sustainable management. These models provide comprehensive digital records, aiding in the maintenance, repair, and refurbishment of heritage assets while ensuring cultural and academic value. Access to such data supports stakeholders in managing heritage assets effectively, balancing utilisation and preservation. Thus, digital technology not only transforms modern construction practices but also enhances the conservation and appreciation of historical assets thereby contributing to the retention of significance.

2.6 Frameworks

Primarily this section will explore the heritage framework in presenting the overarching thread in the initial stages. The intent is to add structure to the research without undue procedure as adding this relinquishes the opportunity to explore and discover elements to enhance the outcome. The chapter will contextualise the conceptual framework which, in this research, sets parameters for the investigation Ngulube (2018) gives focus and direction, proposing the key pillars and interdependencies as identified when determining the contribution to knowledge.

Exploration of the literature provides an understanding of frameworks defending the decision to diverge the contextual and the theoretical, thus the distinction promotes the development of the framework from the initial stages to the final iteration. Once agreed, a thorough examination of the conceptual framework draws out the elements to be contained. Providing a robust relationship between the macro and the micro perspectives, contextualising the theoretical framework enhances comprehension of both prominence and providence, thereby enriching the discourse on heritage management with nuanced insights and comprehensive perspectives.

The first requirement of the approach is to establish the context and identify the risks, hence the record, to fully understand the asset, the constituent parts, the setting and their contribution to the significance, and to recognise stakeholder's edicts in a participatory manner to the direct management. Magar, Thompson and Wijesuriya (2022), elucidates that heritage assets are increasingly subjected to pressures, thereby jeopardising their conservation and intrinsic value. The greatest risk arguably lies in the absence of decisive action, as safeguarding heritage is essential to preserving its significance for future generations. Meticulous and robust decision-making processes are necessary to ensure their preservation and continued significance. This exercise is designed to account for the management of sites in terms of conservation, presentation, and education. Given the multifaceted nature of heritage assets, a nuanced, 'no one size fits all' approach is essential.

Merriam (2001) proposes the structure, scaffolding, and frame of the research emanating from the subject, the literature and the theory. This could be realigned to critique concepts, terms, definitions, models and theories through the lens of the subject, in this case, the management of heritage assets. This research uses this key notion in development beyond the conceptual framework where the theoretical framework is founded. The outcome will aid direction to establish a comprehensive platform designed to store and manage precise data, identify critical information required for achieving desired outcomes, delineate the methodologies for data collection and collation, specify the necessary instruments and support systems, and allocate resources to ensure the successful completion of the project.

The key to the research framework is accuracy, especially in heritage data, as

the golden thread bound in a single location. Utilising an accessible tool, this data contributes to the sustainable preservation and management of heritage assets supporting informed decision-making by all stakeholders to retain, if not enhance, significance. Secondary requirements are presentation and education, although poor quality assets could have a negative impact on both, furthermore, it can be argued that the data will be used in the education of the stakeholders in managing the asset.

Accessible data will support the decision-making process, in defining significance for development the NPPF specifically indicates, '*The level of detail should be proportionate to the assets' importance and no more than is sufficient to understand the potential impact of the proposal on their significance.*' GB NPPF (2021 para.194). The framework, as a versatile, multifaceted, and multifunctional apparatus, can serve as a robust mechanism for determining, managing, and disseminating data. Historic England (2019) repeats and extends the statement to include those needing to recognise the issues when undertaking the work. A challenge is not to generalise the objects in an endeavour to reduce the work as this would devalue the resultant model owing to the diminished accuracy of data, Quattrini, Clini, Nespeca and Ruggeri (2016). The visual quality and richness of representation are essential for a management strategy, facilitating appreciation of the accuracy in the model and building confidence in the data within. For a virtual copy of the asset to be resolute and accepted as accurate, spatial precision and meticulousness in digitalisation are important.

When making decisions Historic England refers to Significance Statements, Heritage Impact Assessments and Conservation Management Plans, the latter is detailed and prominent as a driver for this research. The Significance Statements and Heritage Impact Assessments have currency when decisions have been revealed and the effect on the asset determined. In all instances, the data needs to be regularly updated to support effective day-to-day management, Historic England (2016c), dynamic as proposed in the contribution to knowledge. Any plans, maps, images or local data should extend to the whole site, furthermore, the Heritage Fund identifies conservation planning is best completed without a project vision to be objective and impartial, the owner and/or occupier can bring forward the requirement for the data.

However, at this stage, there is no notion as to the data requirement without referring to the sustainable development plan where it is to be proportionate. Landorf (2009) argues inclusion of data should be a partnership agreement yet is underutilised and a lack of universal definitions impacts negatively. Williams (2006) postulates a strong strategic plan defines accountability and evaluation in sustainable development and Wilson and Boyle (2006) deem a heritage site management plan to be most important at a strategic level. A reliable foundation to determine a strategic and collaborative approach should be adopted, the heritage management plan achieves this objective, Landorf (2009) however, it needs to be dynamic to withstand internal and external pressures, evolving and weathering of assets and changes in partnership measures. This is reinforced in English Heritage's (2023) Sustainable Conservation Principles where the planned inspections, appraisals and routine conditioned surveys ensure the effective quick reaction to evolving problems defending fabric failure in the asset.

This section explored the heritage framework, adding structure to the investigation while allowing for discovery. It contextualises the conceptual framework, setting investigation parameters to guide focus and direction, enhancing understanding of heritage management. Establishing context and identifying risks are essential to understanding assets, their significance, and stakeholder involvement. Meticulous decision-making is crucial to preserving heritage amidst increasing pressures.

The framework emphasises accurate data management for sustainable heritage preservation. Accessible data aids in decision-making, education, and stakeholder engagement. A framework, detailed and dynamic, supports effective day-to-day management and strategic planning, ensuring resilience against evolving challenges and maintaining asset significance.

2.7 Understanding frameworks

Ngulube (2018) links the management of heritage assets and the need for a deeper understanding and explanation of methods, activities, proceedings, and structures utilising frameworks with practice fundamental to theories. Frameworks, according to Miles, Huberman, and Saldana, can be "… *simple or elaborate, common-sensical or theory-driven, descriptive or causal.*" Miles, Huberman, and Saldana (2014, p20). Simply defined in the Collins online

dictionary "… *is a particular set of rules, ideas or beliefs which you use in order to deal with problems or to decide what to do.*" Colins (n.d.). A definition of theory as proposed by Varpio, Paradis et al. "… *is an abstract description of the relationships between concepts that help us to understand the world.*" Varpio, Paradis et al. (2020 p.990), and has characteristics such as explanatory, descriptive, disruptive for example, and progress along a continuum of macro to micro phenomena. Ngulube (2018) postulates researchers use theory to examine their role in valuable knowledge generation. Whetten (1989) states a theory must include the following important components:

- What? Which variables, constructs and concepts are considered explanatory of the phenomena (Descriptive)
- How? Relationships and causality between these factors (Descriptive)
- Why? Justification for the choice of factors and their relationships (Explanative)
- Who/Where/When? Contextual, used for setting the boundaries (Identifies limitations)

A simplified version is Krausz and Miller (1974) asserting concepts are segments of theories as abstract ideas used in the classification of items with mutual properties for explaining and understanding phenomena. Theory development provides an explanation of observed regularities as defined by Bryman and Bell (2007), and they suggest literature demarcates the focus and performs as an equivalent to theory. It can be argued all research starts from a theory whether implied or defined of the phenomenon to be examined, Merriam (2001). In an alternate position, theory develops from the collection and analysis of data Bryman and Bell (2007). These theories can lead to alternate lenses to view a particular problem Koskela (2008). The research employs conservation as the primary philosophical lens for examining heritage assets. While other perspectives such as surveying, materiality, and technology are considered, the paramount importance of the monument lies in its classification of significance. This classification integrates policy and ethics, and stakeholder roles within the management framework, ensuring a comprehensive approach to heritage preservation.

These are multifaceted with countless layers; they may be a small part of a larger organism or the overarching support for many smaller detailed factions as in this research. Moving on the conceptual framework can evolve Varpio, Paradis et al. provide a definition of a theoretical framework as a "… *logically developed and connected set of concepts and premises … to scaffold study.*" Varpio, Paradis et al. (2020 p.990). Thus, the theoretical framework to be presented has the same content except underpins the conclusion. A theoretical framework is conceived as a production or assessment of theory according to Crawford (2020).

Generally, the research community has a narrow idea of a theoretical framework being a supposition at the beginning of any research, often confused with a conceptual framework as defined by Crawford (2020) although Lederman and Lederman (2015) would appear to differ over the nuances. Ngulube (2018), proposes the differentiation as concepts are the ingredients of theories with the latter containing the relationship between concepts and the variables in explanation, description, prediction or control. Maxwell (2013) is congruent with the theoretical and conceptual frameworks being synonymous, where the latter emanates from tacit knowledge, previous research, and published theory. They adhere to the notion research frameworks should precede the exploration when proposing two basic questions the answers to which should be found in the literature review, i.e. What is the problem? and, Why is the approach to solving the problem feasible? The nuances in theoretical and conceptual are to be embraced for distinction between the initial and final stages of the research. Notwithstanding this, an issue to be drawn out at this stage is the conceptual framework should not contain facts, to do so might constrain the research thereby restricting the extent of influence, and the exploration of the subject and subsequently limit the theoretical framework. Maintaining flexible elements ensures the study can thoroughly explore the potential of the research proposition without bounds.

A contrary argument postulates that without some confines the research spirals beyond the aim becoming unwieldy without a depth of enquiry. The methodology affirms delimitation thereby allowing a description of the actual effect rather than pre-proposing a theoretical stance liberating the research to explore a range of possibilities within the collected data. Furthermore,

without goals or specific outcomes, the research is freed to examine the data for actual change and attribute the variations to specific typologies. That is not to say there are no set outcomes in the research, the objectives proposition the use of LiDAR data to proactively manage the heritage asset however the approach as to how this may be accomplished is ambiguous. Additionally, there is a counterargument advocating without clear goals, organisation and invention are challenging yet without this freedom the most appropriate methodology may remain concealed, and akin to tunnel vision, will be less evident.

Research papers document the opportunity brought to the management of heritage assets using digital models, when unified with the research empirical data advances knowledge to provide understanding viewed through the conservation lens. As Ngulube (2023) suggests grounded theory determines links between concepts in data produced from research to build or uncover theory. This theory continues to be developed, appraised, composed, and recomposed, therefore not fixed, i.e. representations of fact, abduction between the theory and data. Considering this stance, the theory will only be resolute at the analysis stage, shaping the context for the research, the interactions with study participants, defining the collected data and may act as a translator for insights from theory to contributions into aspects of the theoretical framework.

This section has dissected terms to solidify an understanding of frameworks and their application in this research. The thesis embraces nuances in theoretical and conceptual frameworks, differentiating between the initial conceptual framework guiding research and the output framework being theoretical. The literature emphasises the necessity of frameworks in heritage asset management, advocating for a deeper understanding of methods and activities grounded in theory. Furthermore, frameworks are fundamental to structuring research, serving as either simple or elaborate constructs guiding problem-solving and decision-making processes. Theory, elucidates relationships between concepts, explaining phenomena. Whetten (1989) outlines a theory's components: variables (descriptive), relationships (causal), justification (explanative), and context (limitations). Conceptual frameworks will evolve with research, incorporating insights to support data collection and analysis. This research employs conservation as a primary lens,

integrating diverse perspectives to manage heritage assets effectively. The dynamic nature of frameworks ensures comprehensive exploration and robust theoretical development, ultimately guiding sustainable heritage asset management.

2.8 Conceptual Frameworks

The conceptual framework's argument exerts a pervasive influence on the entirety of the research endeavour, shaping its path and guiding methodology. Building on this notion Crawford (2020) is specific in the definition of the conceptual framework as incredibly important for study orientation, identifying the contribution to knowledge, aligning the elements studied, and how the design of the study shows rigour. In defence of this stance, Ravitch and Riggan (2017) state conceptual framework contains the theoretical framework in that the latter additionally includes the relationships. The conceptual framework identifies the intellectual bins, and the theoretical framework fills them or even recognises new bins using terminology from Miles, Huberman and Saldana (2014). In agreement, Varpio, Paradis et al. simplify the problem, *"… a theoretical framework articulates the logic of why we are using a particular theory; a conceptual framework justifies why this problem/context/phenomenon is relevant to the field."* Varpio, Paradis et al. (2020 p.993). Moving forward they reinforce the logic of the conceptual framework as a discrete entity to the theoretical framework, it defines the identified knowledge, elucidates the gaps in understanding and outlines the methodology suitable for the investigation, i.e. the first sections of a research thesis. To be specific, Merriam and Simpson (2000) propose the following function of the conceptual framework;

a) Constructs a foundation
b) Establishes advancement in the study
c) Conceptualises the research
d) Considers research methodology
e) Identifies control for findings interpretation

The conceptual framework should not be static, Maxwell (2012) promotes the perception that as the research progresses the framework will evolve, the 'bins' and links too, hence the advancement of the theory to benefit the research conclusion. In action research when completing the empirical work,

the tacit knowledge builds to develop the theoretical framework. The subjectivist inductive approach as found in this research utilises the gathered data to develop and process the theory from that data in constructing the framework. The theory should be considered flexible undergoing refinement, the shift taking place in the researcher and/or the research. In this situation, the theory can develop out of the research, be a major component in forming the research or be exploited in interpreting/analysing the data to conclude.

In this research, as advocated by Crawford (2020), the framework affords critical support for the study including clarification of the context especially for the reader. The endpoint is to classify and describe the principles of the study and their relationships, Rocco and Plakhotnik (2009). Consistent with this idea, a framework in qualitative research should focus on identifying and defining the variables to become the invisible theory at the beginning of the investigation reinforcing the interconnected nature of the terms.

At this stage, it is imperative to emphasise that within the thesis, a framework serves as the justification, comprehensive review, and ultimate outcome of the research. Using the argument *"A conceptual framework consists of concepts that inform a research project."* Ngulube (2023, p.11), and Lederman (2015), proposed research questions are the initial conceptual framework as sufficient to define the stance. Underpinning the research questions are the aim and objectives of the research as found in the introduction chapter. These have been reviewed as applicable to the production of the final iteration of the conceptual framework and, therefore, have been met within the initial research. On this basis, development of the theoretical framework can proceed unhindered. The initial literature review served as a foundational element, encompassing a broad spectrum of topics to define the research problem, identify contribution to knowledge, establish the conceptual framework, and underpin the methodology. This process builds on existing tacit knowledge, shaping and informing the empirical research to address the research questions and ultimately contributing to the development of the theoretical framework.

In support of the term heritage management van Vollenhoven proposes "*... the application of management techniques to conserve and develop cultural resources so that they remain part of a cultural heritage with long-term value*

and benefit for the general public." van Vollenhoven (2018, p.342). The framework for managing heritage assets Historic England (2017) takes this to include 'Identify', to comprehend the asset, with deficient information a barrier to effective management recognising that gathering and maintaining data is resource intensive. It is important to note that many of the existing frameworks, particularly those at the macro level, have a global scope and influence and have been adopted by the UK agencies.

The legal entities in the UK are generally government-driven in Planning, Listing, Conservation and specific environmental requirements, Conventions, World Heritage Site, Archaeological, etc. The ethical policy is for example dictated by the ICOMOS Ethical Principles for members as adopted promoting conservation, respect, sustainability, inclusivity, professionalism, collaboration, and objectivity ICOMOS (2014). These principles are upheld by all professional bodies and are further bolstered by societal expectations for those not formally affiliated with a professional organisation. All members are required to be transparent, honourable, inclusive, independent, unprejudiced, and accountable and disclose any conflict of interest. In contributing to the conservation of heritage assets those involved are expected to adhere to these principles especially as the historic bodies in the United Kingdom (UK) observe the UNESCO principles hence inclusion.

In summary, the conceptual framework exerts a profound influence on the research, guiding its trajectory and methodology. Moreover, the conceptual framework sets intellectual boundaries, while the theoretical framework fills these with detailed constructs. Differentiation occurs emphasising that the theoretical framework explains the rationale for using specific theories, while the conceptual framework justifies the relevance of the research problem. Furthermore, the conceptual framework has a foundational role in advancing the study, shaping the research, and ensuring methodological integrity. The framework evolves with the research, ensuring flexibility and refinement. The initial literature review anchors this process, defining the research problem and shaping the empirical investigation. The resultant model integrates heritage management within a UK context, addressing assets, stakeholders, and legal and ethical policies, thus supporting comprehensive heritage conservation.

2.9 Heritage Frameworks and Models

This section delves into a comprehensive examination of existing frameworks and models to elucidate the context within which this research is positioned and to ascertain how the findings will integrate with and enhance current industry practices. While these frameworks predominantly originate within the heritage sector, this research emphasises a digitisation process poised to generate substantial data volumes. Consequently, the discussion will extend to downstream repositories, highlighting their critical role in managing and leveraging this data within the broader conservation framework. Beyond this application, frameworks are identified that are specific to location, category or relate to different stages in the management process. Frameworks can be elucidated through text, diagrams or tables however their purpose is to standardise a process without prescribing solutions to problems. These will draw together multiple interacting factors and direct the most appropriate action.

The framework will operate with external environmental pressures and internal risks which will require assumptions to be clarified. The requirement for a framework is to identify the components which will be brought to bear on the problem including purpose, context, all resources, interventions, outputs and effects. Whilst the framework will have flexibility built in, especially at the strategic level, the pressure from a changing policy and technological landscape will require regular reassessment to ensure validity.

The lens describing the topic for this research has a conservation core, and the global heritage manifesto focuses on futureproofing through preservation. In doing so, the historic fraternity prioritises sustainability. The management of heritage assets via a conservation lens in compliance with the manifesto, particularly the specific sustainability requirement, is a difficult undertaking. The management of historic places now goes beyond the technical requirements by incorporating sustainability, the three pillars of environmental, economic, and social well-being. According to UNESCO (2021), the issues for heritage management include typologies, stages of dilapidation/ruin, climate change, conflict, vandalism, and so on. This framework maintains a distinct focus on asset conservation and management, but once articulated, it will be found to flow into strategic and 'day-to-day'

components, such as education/training, planning, social currency, recognition/tourism, digital content, policy, etc. United Nations 2030 Agenda (2015). In particular, the goals as applied to heritage are grounded in the five 'Ps' being people, planet, prosperity, peace and partnerships being, "*… areas of critical importance for humanity and the planet."* UNESCO (2015, p.1).

UNESCO (2021) guidelines identify in their World Heritage Convention that heritage is a priceless and irreplaceable asset for humanity as a whole and embraces the concept of sustainable development. The governments of countries are required to provide records of property for inscription based on objective and scientific considerations evaluated methodically and reliably. The Convention defines the stakeholders as "*… local communities, indigenous peoples, governmental, non-governmental and private organisations and owners …"* UNESCO (2021, p.19).

Outstanding Universal Value UNESCO (2021) criteria for heritage assets have to be one of the following;

- A masterpiece of human creative genius
- Exhibit an important interchange of human values
- An exceptional testimony to a cultural tradition or civilisation
- An outstanding example of a type of building
- An outstanding example of traditional human settlement, land-use or sea-use etc.

In extension of this there is the understanding of authenticity honestly and plausibly articulated through;

- Form and design
- Materials and substance
- Use and function
- Traditions, techniques and management systems
- Location and setting
- Language and other intangible heritage
- Spirit and feeling
- Other internal and external factors

The guidelines delve into protection and management using a regular review of the general state of conservation which leads to the OUV. The asset should be supported with a management plan outlining how OUV will be maintained. The management system ensures effective protection for current and future generations. As per this research, effectual management includes an unending sequence of preparation, enactment, monitoring, appraisal and feedback. Pressures and changes may contribute to the susceptibilities of the property to sustainability issues in the environmental, social and economic elements. Monitoring needs to include the trends of the wider heritage backdrop and any projected intervention. Maintenance of the OUV through time is critical not only for the asset but also for the context, this integrated approach to planning and management guides the evolution of asset(s). As the guide states, '*Effective management involves a cycle of short, medium, and long-term actions to protect, conserve and present the nominated property*.' UNESCO (2021, p.35).

To promote this, an appropriate management plan is required referencing the OUV and specifying how it will be preserved utilising the participation of the stakeholders effectively protecting for present and future generations. The operational guidelines identify that "*Environmental Impact Assessments, Heritage Impact Assessments, and/or Strategic Environmental Assessments be carried out as a pre-requisite for development projects and activities that are planned for implementation within or around a World Heritage property.*" UNESCO (2021, p.36). These should be based on a full and accurate assessment of the significance and condition of the asset and not promote a single intent but elucidate alternatives, clearly showing the impact on the OUV and any mitigation for potential negative consequences. Asset's OUV requires safeguarding for the long-term especially to augment resilience to disaster and climate change. Preparatory work should gather all available material to demonstrate the OUV set in the context of national and international comparable sites or assets. These should form the basis for any protected status and future protection of the asset consideration being given to identification, description, justification, condition, management procedures, monitoring, documentation, accountable authorities etc. As part of the documents, the management plan is considered vital to maintain the OUV and within this plan, the proposal for monitoring the asset is intrinsic to maintain current documentation, record change and the state of conservation.

The competencies framework guide written by UNESCO published in 2021 identifies essential skills and knowledge for heritage practitioners covering four levels from skilled worker to executive. The users of the framework include organisations, individuals and educators to benchmark, motivate, upskill, review, recruit etc. staff to make them effective in their roles and drive efficiencies. In Figure 4 extracted from the UNESCO guide 2021, competencies relate to management, specifically information management and administration covering implementation of procedures at the most basic records through to comprehensive systems to monitor, report and document. Within the sector there is a general disparity between the education providers and the competencies required by the industry, the focus of this element is to develop a capacity-building strategy.

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Figure 4 Competencies specific for information management and administration UNESCO (2021)

Competences were suggested as being required for all heritage-related jobs regardless of the context, and include the ability to undertake research, documentation, and values assessment, among other key skills. When considering the management proficiencies, it can be seen from the extract above that at each level there is a need to manage and administer information encompassing that necessary for the management of the site. Within this category are the more specific technical and strategic elements which contribute to sustainability. The general understanding of the local situation is that the skills and knowledge required for the management of complex systems as found in the heritage sector are not available leaving the assets vulnerable to erosion of the OUV.

In summary, the UNESCO framework lucidly sets out to promote skills in the heritage industry as opposed to educational achievements recognising the

complexity of the sector and the need to utilise experiential learning to further protection of the heritage asset in an efficient and effective approach.

At the highest level in the UK, the framework is bordered by Historic England (HE), Cadw, Historic Environment Scotland (HES) and Historic Environment Division Northern Ireland conservation principles for the sustainable management of the historic environment. The primary provision is to sustain an asset for future generations, ensure consistency in approach, inform management ideologies, and build on the international foundations for heritage management. Although the principal heritage bodies in the UK exhibit some variance, their core principles remain largely congruent. Addressing each individually would be superfluous; therefore, this study will predominantly focus on the framework and perspectives provided by Historic England.

The principles of Historic England (previously English Heritage) (2008) start with the following which inform this research;

Principle 1: The historic environment is a shared resource

Principle 2: Everyone should be able to participate in sustaining the historic environment

Principle 3: Understanding the significance of places is vital

Principle 4: Significant Places should be managed to sustain their value

Principle 5: Decisions about change must be reasonable, transparent and consistent

Principle 6: Documenting and learning from decisions is essential

Furthermore, the Historic England document covers the assessment of heritage significance through eight key ideologies setting out a process. Notably, these relate the identified heritage values to the fabric of the place, one of the key elements here. In alignment with this research, change management directs the question of sufficient information to understand impact, sustainability, effect on authenticity and integrity, reversibility, comparing options, mitigation and monitoring and evaluating outcomes.

Thus, the framework promotes an ideal solution to provide a basis for conservation information to manage assets. In Principle 6 the underlying requirement is for managers to monitor, evaluate and use the results, investigate and analyse loss to record and circulate the results. To appreciate the value, an understanding of the structure, especially in progression to that currently observed, principally when set in the perspective of communal and cultural circumstances determining the local influence. As stated in paragraph 71, *"It will normally best be illustrated by maps or plans showing the age and relative significance of the components or character areas of a place. … addressed at an appropriate level of detail … always in relation to the place as a whole."* Historic England (2015 p.37).

A conservation requirement considered as a framework for heritage assets is to manage all physical aspects starting with maintenance and following up in the specific order repair, renew, restore, replace. In planning terms, alteration and new work will be approved if there is no or limited impact on significance, the intervention is reversible, there is no other solution for example. A historic asset that is occupied or used viably *"… is likely to lead to investment in their maintenance necessary for their long-term conservation."* UK Government (2019 Para.15). These principles provide a basis for the fabric conservation of an asset however the complexity of the materials, technologies, development and the historic narrative bring a complexity requiring careful management strategies and their application.

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Figure 5. Historic England Managing heritage assets simple framework Historic England (2016)

Historic England's guidance proposes a simple framework for managing historic assets, which serves as an overarching policy for this research (see Figure 5). The framework begins with the identification stage and progresses through a five-stage cyclical system. It includes best practices for categorisation, significance clarification, obligations, applicable policies, and crucially, data gathering and recording.

Data collected from various sources, include images, reports, texts, accounts, research papers, local records, newsprint, drawings, planning applications, census data, maps, and other records. This data will provide robust evidence during the planning stage, supporting strategic solutions for impactful results. Real-time data will inform decision-making, ensuring minimal negative impact on the asset's fabric.

In the closeout stage, data will benchmark success, lessons learned, and potential improvements. Ongoing records of implementation and intervention impacts will be considered. Finally, the model with embedded data will initiate the framework's identification stage, ensuring continued benefits to the asset.

The framework for heritage conservation in the UK is governed by principles set forth by Historic England, Cadw, Historic Environment Scotland, and the Historic Environment Division Northern Ireland. These principles emphasise the sustainable management of heritage assets, ensuring their preservation for future generations. While each body may have its nuances, their core values remain consistent. This research primarily focuses on Historic England's guidelines, which align with global standards such as those from ICOMOS, supporting the SDGs. The research underscores the significance of a robust conceptual framework that evolves with the study, ensuring comprehensive management of heritage assets through a detailed, cyclical approach. This includes the stages of identifying, categorising, and managing data to inform strategic decisions, ultimately aiming to sustain the historical, cultural, and material integrity of heritage sites in line with international conservation principles.

In England and Wales, the NPPF, is an overarching governmental policy applied to the development of buildings throughout England. When considering the potential impact of development either to the heritage building or the setting, the developer must "… *record and advance understanding of the significance of any heritage assets to be lost (wholly or in part) in a manner proportionate to their importance and the impact,* …" NPPF (2021, p.58) and equally important to make publicly accessible the archival material. The local authority contributes to the Historic Environment Record however not all the records are online, and even when they are, the depth of information is limited which is not conducive to inclusivity. The policy

governing the sharing of any collected data being made accessible is clear, it should be digitally presented and in a format that can be 'read' by the public. The conclusion of the paper by Hafez (2019) suggests due to the cyclical nature of building occupation in use, maintenance, repair and refurbishment, a knowledge base of historic information must support the conservation process without which inaccuracy and restorative destruction occur de-signifying the site.

The National Heritage Protection Plan (NHPP) (2012) see Figure 6, a framework for heritage protection has a set of priorities, the environment should not be a risk of damage, erosion, or loss, is experienced, understood and enjoyed, contributes to sustainable places, and helps deliver positive economic growth. The definition of protection is diverse based on a robust evidence foundation having four measures Foresight, Strategic Threat Assessment and Response, Recognition and Identification of the Potential Resource, and Assessment of Character and Significance. As a National Framework it covers a large range of assets, sites, and locations, and is not limited to specific issues therefore has less focus. The framework equally does not allude to the changing requirements or cyclical nature of the situation. Furthermore, the NHPP has no action plan as to how evidence is being integrated or how the asset is to be managed etc.

Action should be based on a framework to determine and deliver priorities to support the protection defined as conservation and management to safeguard significance. Mediated by the NPPF and other policy, intervention in pursuit of this aim will require identification, assessment and recording, qualified by research knowledge and sustained by the stakeholders as a key element in the plan. The concern will be ascertaining priorities, not all would be achieved due to the limited resources, but these will focus the action and ensure opportunities will not be missed. The founding dialogue referring to key supporting actions states, '*Ensuring that information management and knowledge transfer is as good as it can be so that it can be used to its greatest benefit …*' NHPP (2012, p.12). NHPP as part of Management Frameworks, the section including Model Management Plans states, '*It is essential that management activities …… are based on a clear understanding of significance. … identification of need and delivery of information to the relevant stakeholders in a timely manner and to the appropriate format*.' NHPP (2012,

p.22). The requirement for accurate, relevant, accessible and timely data for the stakeholders is succinctly enunciated in this section.

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Figure 6: Summary of the NHPP structure (NHPP 2012)

Part of the management plan in the NHPP (2012) is the requirement to manage change, planned or impromptu. Strategic Condition Monitoring is identified demanding a well-defined understanding of the state of the assets and sites. Furthermore, these will feed into future priorities, planning and action to support significance. In change management, the impact can be determined and the action creating the least pressure on significance can be adopted. Finally, the archives can elucidate the significance, support analysis and promote understanding of the heritage, and as identified, can have importance as a result of their distinctive value. This protection plan,

therefore, is an overarching framework for heritage at the strategic level in parallel with the NPPF discussed earlier.

HES asset management plan published in 2016 sets out to the Scottish Government the requirement for process, accountability and reporting. Considerable infancy is found in the development of heritage management plans, especially involving a large portfolio of assets, and the diversity in the stock precludes standardisation. HES workflow is a cyclical approach of inspect, understand, prioritise, plan, deliver and improve, whereas to just maintain leaves the asset stagnant if not drifting into irrelevance. This knowledge-based approach based on sound policy capitalises on research, understanding and experience. A Property in Care (PIC) is subject to the Asset Management Policy and the Asset Management Delivery which includes regular condition surveys using the Monument Condition Indicator (MCI). These have been digitised which in addition to a simple site layout or plan and a bar chart showing critical elements for work give immediate visual understanding of the areas requiring intervention and the total resource requirement. The report expounds accurate monitoring through timely regular surveys and linking this with other datasets, especially in GIS systems creating synergy in the scope and utility of the arrangement.

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Figure 7: Historic Environment Scotland - PICAMS interface for Properties in Care HES (2018)

The PIC Asset Management Tool stores and presents the conservation situation overlaid with the maintenance data to provide a current condition, see Figure 7. If, in real-time, this was sown with the accurate survey data efficiencies and consistencies would ensue especially if it capitalised on the 3D expertise in Historic Environment Scotland. The addition of photographic records, sketches and digitised documents all linked to the elements enhance the usability and effectiveness of the system. HES's long-term goal "*… is for a fully integrated 3d asset management system specifically designed for heritage assets.*" Historic Environment Scotland (2018, p.16).

The HES Asset Management System is based on consistent data acquired for each site which builds on through regular surveys depending on the site content. The digital record sitting at the heart of the system is available at each location via a mobile device and the asset condition can be monitored against the significant data on the system. The collection and exchange of highly accurate survey data form the core of a record but can be developed as a pillar in proactive asset management. In simple terms "*… the creation of high-quality spatial data is an important output in itself, … Accurate survey and modelling from physical and archival evidence can provide new perspectives*." HES (2018, p.20). The report goes on to state that the use of digital information management in the heritage sector is immature. This requires flexibility as the system matures to allow for integration of future technology especially around the use of 3D models for user interfaces for example. Here, this research framework meshes to provide the solution for the systematic rigorous effective collection and presentation of 3D data for inclusion in proactive Asset Management.

CIOB (2020) Fundamental Understanding of Conservation includes both listed and non-listed traditionally constructed buildings, appearing somewhat at odds with the listing of modern buildings such as the Lloyds of London building. The principal focus is a conservation approach which considers the construction technology, the heritage significance and the processes which require deeper understanding than the modern equivalents which tend to be, in technical terms, vapour impermeable. This additional layer requires a specialist approach where the competencies exceed those in modern construction techniques, and beyond this for requirements under the climate

change issues and retrofit. Edwards, the author of the guidance proposes the following illustration Figure 8 for the conservation process.

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Figure 8 – The building conservation process - proposed by Edwards Hart CIOB (2020)

The inspection for construction and condition precedes a similar requirement for significance yet this data should also include the historic, artistic, evidential and/or communal value which builds to the overall historic importance Cadw (2017). The document strengthens the link to the categories as guiding principles to identify significance as defined in the Burra Charter. The suggestion is all conservation starts with the asset fabric (as shown in Figure 8), yet it should be more than this as elements such as intangible heritage should inform the eminence. This argument is reinforced as the golden thread running through conservation because understanding and ethically respecting the importance of an asset is managing significance.

As technical issues are a major part of retaining the fabric on which the significance is imbued then the two are inextricably linked and dealing with these must be achieved at the highest level. The conservation principle of underpinning knowledge encompassing history and current order leads to strong understanding of the asset as the basis for planning and any subsequent interventions. Feilden and Jokilehto (1998), reinforce this by recommending evaluating value should first document its history and existing

condition before proposing intervention, and any valuation should include the intangible elements. However, this understanding appears secondary in the building conservation process. Furthermore, the process appears not to take account the cyclical nature of the conservation practice, or repair/catastrophic event which often requires immediate intervention and, in this situation, a current thorough understanding of the asset including its significance is of primary importance.

The knowledge gleaned through the process of assessment and recording of the asset, and the subsequent understanding revealed in analysis of the data contributes to the appreciation of significance. This goes beyond the asset itself at a macro view to include setting, the proximity of other structures, landscape etc. and micro, the use, progression of the rooms, details, decoration, etc. Heritage value must include comparison with other heritage of similar disposition and acknowledge this sometimes extends beyond the fabric. Objective judgement needs to be expressed through analysis levels of significance using criteria differentiating the elements of the structure, colour coding plans or models would promote this visually however, the narrative needs to detail why to ensure credibility. When this is current and complete, the decision-making process around interventions for repair and catastrophic event can adhere to the international and local policy with the conservation principles leading the solution. Decisions made without the assessment of heritage value could negatively affect or eradicate the significance however once this value is understood informed management can proceed.

The CIOB (2020) document places the three elements core to conservation as technical, significance and process but this should be supported by the understanding extending out of the research and record. The planned elements provide sufficient time to enact the development of the knowledge however this is not accessible in the repair/catastrophic event. Therefore, the focus on contemporary recorded data to drive the process of conservation management is established and the proposal should merge stages 1 and 2 of the conservation process and a more cyclical process which may or may not include intervention. This documentation would morph into, or be subsumed by, the conservation plan providing the supporting understanding for proactive and reactive management, and in doing this the vulnerability of the asset would be managed thereby ensuring retention of significance.

Furthermore, best practice is enacted through periodic surveys to identify changes to be integrated into a management plan for the asset and in devising plans. This would not preclude further intensive surveys to assist in the development of interventions. Within this initial stage, the development can be established which will determine the history to contribute to the heritage assessment and the appreciation of the significance. Furthermore, this knowledge of development will provide some insight into the technical element as not every detail will be apparent without physical intervention contrary to conservation principles.

The CIOB document moves into the next stage, developing the proposals, which should account for significance where understanding the technical implications over time may also impact the value. The discourse has a very technical bias beyond the scope of the research here. However, in the production of accurate survey data revelations during the construction phase should be recorded thus building on the argument for the cyclical data capture hence updating the model to ensure currency. It is at this juncture that the Heritage Impact Assessment (HIA) is undertaken before the decision-making to elucidate the effect on heritage value for each proposal. Cadw (2017) defines the HIA as a structured process used in a proposal for change to test appropriateness by weighting the risk and benefit. The impacts can be simply valued as positive, neutral and negative, the latter may be mitigated by the positive aspects however one which did include negative value the overarching view would be an unacceptable intervention.

The theme throughout being expounded by the CIOB is the heritage value, i.e. significance, however, the included conservation process appears to set asset condition as the initial input. Significance research follows and whilst these precede 'plan for action' it would appear to be at odds with the industry policy, a simple merging of the two themes in a single action of research and survey would amend the execution of the process aligning it with best practice. The narrative suggests that the two elements are intertwined whereby one informs the other therefore this action is appropriate.

The refurbishment of Nottingham Trent University's Grade II listed Arkwright Building illustrates nuanced heritage conservation. Permission to demolish the central lecture theatre, part of the original structure, was granted due to the

minimal remaining original fabric. This strategic move created a courtyard, improving visibility and appreciation of the historic structure, including the science laboratory, and providing a vital communal space for events. Historic England praised the project, upgrading the building to Grade II*, highlighting how sensitive interventions can enhance heritage appreciation and meet contemporary needs.

There is a general misconception, especially outside the conservation community that the HIA comes after the decision-making process to identify and propose mitigation of the impact however this would not place significance at the centre. Furthermore, whilst proformas are a way to ensure consistency in the HIA process, they should not be a tick-box exercise but illustrate the decision development. To ensure effectiveness the asset should be understood, without copious accurate data the knowledge to generate the understanding is unidentified and the decision weak with high risk of failure at best or loss of significant fabric at worst. As the four heritage values contribute to the significance it would be implicit these are considered individually when determining the impact. The developing record of the site is of paramount importance to manage the risk of any intervention, a subsequent update of the record can provide insight to the quality of the solution and act as the base point for future monitoring in the management of the asset. The document also covers maintenance and management of the buildings stating that the process and understanding of heritage value applies to this activity where a conservation plan should be referred to or an HIA invoked for each situation. The strategy should be one of proactive preventative rather than reactive corrective action and repair over replacement.

The RICS Historic Building Conservation – Guidance Note (1st ed., 2009) addresses heritage projects for surveyors, outlining relevant guidelines and policies. It references the Burra Charter, emphasising the importance of cultural significance as a basis for informed actions. The document discusses conservation philosophy from the surveyor's perspective rather than the asset's, advocating for a holistic approach before focusing on specific issues and emphasising the need for familiarity with official protection measures. While stakeholder inclusion is not discussed, the responsibility of custodianship beyond the owner’s interests is highlighted.

The guidance stresses that conservation is not about merely applying rules but understanding the building through detailed knowledge and research, supporting intervention decisions. A Conservation Management Plan as previously highlighted, prepared and adopted by stakeholders, is crucial for the asset's future. Discoveries during a project should be made accessible to interested parties.

The note acknowledges the importance of understanding significance and preparing detailed studies for intervention. It includes definitions like vulnerability and outlines that there is no set methodology for producing Conservation or Management Plans, referencing Heritage Lottery guidelines. Minimal intervention is the guiding principle, reinforced by the plan, which should consolidate research, set policies through formal consultation, and rank interventions.

Surveys and inspections are fundamental, involving detailed appraisals and photographic records, with a hierarchical structure for recording. Any survey should be objective, and analysis should follow later. Maintenance is seen as the optimal intervention, with significance assessment and risk determination as starting points. The guidance underscores the need for robust inspection regimes, excellent information management, and a planned preventative approach, aligning with Historic England's conservation principles.

Routine prioritised assessments contextualising heritage significance and addressing vulnerabilities are essential. The cycle of inspections should be frequent in vulnerable areas, considering local observations and the effectiveness of previous interventions. Comprehensive, continuously updated records are vital for effective, sustainable management.

Summarising the RICS document, it can be determined the stance of the surveyor is based on the role, the standard performance criteria and ethical conduct, the heritage dimension appears to be contributary rather than centralised. The discourse does move forward to embrace the ideals of significance retention and contributory value in the management of heritage assets, and inclusion in the decision-making process. Finally, a comprehensive, current and accessible database is fundamental to the management of significance however, the inclusion of the stakeholder to support sustainability is not developed in this guidance.

COTAC advise the repair and management of heritage assets is generally more ad hoc than other construction projects especially managing the process. The difficulty is the unknown when instigating a project due to the individualist nature of the building at construction and subsequent interventions during the lifetime be they extension, refurbishment, repair etc. most of which there is no record data. At the instigation of a project the survey data can be as simple as an Ordinance Survey (OS) map of the site, or if a measured survey has been enacted, a set of basic plan drawings as a paper copy. Other documents may include incoming services, structural survey, ecology report or if the building is registered as of heritage importance, a reference to the listing data. It is extremely rare for the data to be structured, referenced, or shared with the project stakeholders. The building in approaching the latest proposed intervention is more than likely in repair deficit requiring work to bring it to a satisfactory quality due in some part to poor management and a lack of a supportive framework to enhance the decision-making process.

The process wheel in Figure 9 '*…intended to provide a common framework for facilitating collaboration of project stakeholders …*' McGibbon et al (2017, p.1) to aid effective project delivery. However, this does not recognise the Project Information Repository should include details for heritage value and significance which precedes any Project Appraisal, Phase 1 of the wheel. The gathering of data, especially digital and digitalisation of repositories is important information to become the baseline for any future project which once analysed should form the understanding of the building's heritage value. McGibbon and Abdel-Wahab (2018) propose an e-Condition report for capturing objective structured data deploying digital technologies (laser-scanning and thermography) which was successfully demonstrated, here again there appears lack of understanding of the building heritage value which should drive the intervention proposed and even the resultant financial impact.

McGibbon et al (2017) propose the repair and maintenance practice in heritage assets has much subjectivity being reliant on the tacit knowledge of those involved throughout the process. The lack of objective data generally leaves project completion over time and budget, the proposed introduction of a management framework would make visible an explicit workflow to reduce

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Figure 9: Structured digital workflow phases McGibbon et al (2017)

poor decisions leading to unnecessary interventions. The inclusion of digital technologies would capture objective data thereby optimising the work and increasing project performance. The presentation of this data in digital format is paramount as it would need to be made available to all stakeholders. The paper by McGibbon et al (2017) identifies initiation in the Royal Institute of British Architects (RIBA) and CIOB project frameworks to promote a more collective approach to project delivery but does not reference the CIOB. The COTAC framework is used as a comparable and whilst there are some similarities these do not reflect the eight-point wheel in the COTAC (2016) Historic Building Information Model (HBIM) Framework part 1 released the previous year. However, the starting point for any heritage project should be significance, according to ICOMOS Charter of Krakow (2000) essential recording should "*… permit informed management and control of construction works and of all change to the cultural heritage*" ICOMOS (2000, p.1) and it goes on "*… ensure that the maintenance and conservation of the heritage is sensitive to it's physical form, it's materials/construction technology, and it's historic and cultural significance."* ICOMOS (2000, p.1). The detail for the exercise should be sufficient to guide a sustainable use, and "*… the effective research, management, maintenance programmes and construction works may be planned*." ICOMOS (2000, p.2). Responsibility for recording should

be collective, specialist and non-specialist, and should be appropriate for the level of intervention being considered.

Furthermore, identified in McGibbon et al (2017), a more industry-relevant framework is required yet Phase 1 of the structured digital workflow phases makes little of the need for heritage data to drive the decision-making process. The silo nature of codes of practice, consultant work package, specialist contractor and supplier all point to a need for a more integrated project delivery model. A lack of a framework to define the repair and maintenance process was alluded to. The nature of intervention in any heritage asset as has previously been discussed is the individualistic nature of the project due to the 'one-off' structure. The framework cannot be too prescriptive, detail would bring a lack of adaptability and therefore adoption. The data collection methods should be objective, rigorous and create a current repository for stakeholders to access.

HES has made great strides in the system of asset management which builds on the paramount prerequisite in determining significance. The barriers identified include a lack of awareness, particularly in contexts where analogue methods have traditionally sufficed, endemic resistance to change and engagement within the construction industry, and the challenges associated with skills development, exacerbated by the transient nature of the construction workforce. COTAC (2016) promote digitisation in heritage to focus on priority, support scheduling and monitoring progress to ensure positive project management result.

COTAC (2016) suggests divergence of BIM from Conservation Philosophy which lays the foundation for the approach to historic assets. The information model is relevant for these structures but as the asset is physical, the initial strategy as identified in BIM will be born out of the Asset Management Strategy followed by the research for significance and value, shape options, survey needs and finally determining interventions. The existence of the asset requires an extensive understanding of the need informed by a detailed survey and analysis of the current situation overlaid by the significance and the risk to that value. COTAC use BS 7913-2013 as the staging point where the objective of building conservation is to protect built heritage for future society, and this can be merged with their proposed Conservation Process

Flowchart. The standard theme for "*Good conservation depends on a sound research evidence base…*" according to BS7913-2013 (2013, p.1) and in the conservation process after Drivers for Change comes Informed Viewpoint. Understanding of significance ensures effective decision taking in the application of asset management principles and the body of evidence should be proportionate to the significance and proposed intervention. Conservation management has two levels strategic, covering the current, the future and the required direction of travel to join the two, and operational, being the effective organisation and coordination of services and resources to deliver the strategy, especially in the day-to-day administration of the asset, BS7913-2013. Where there is vulnerability in the asset, especially when it is of high value, more frequent control and monitoring events should be programmed to aid management and conservation.

Conservation management plans are an important document for both the strategic and day-to-day administration, based on the four steps; what do we have?, why are they significant?, what are the vulnerabilities?, and noting these vulnerabilities, how can any impact be mitigated? These should be graded to define a list and be reviewed on a formal cyclical basis to include any change. Throughout the building lifecycle, the management should take account of significance from strategy to occupation in all stages especially when interventions are intended.

Best practice for survey intervals is four to five years, these should monitor the condition, determine priorities and program interventions including maintenance. Furthermore, this information should be disseminated to all persons working on the project to ensure their understanding of the significance held in the asset. As the work progresses, detailed photographs and records should be kept, updating the retained data and support future decision-making. The COTAC model, see Figure 10, proposes a cyclical workflow revolving around the Information Model however it would appear simplistic as projects can run concurrently and be at different stages which would require a more integrated solution. The information gathering should extend throughout the project especially as the work area is accessed, opened up, intervention enacted and made good. All the gathered data should be verified and placed within the digital Management container.

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Figure 10: Emerging HBIM Framework Diagram COTAC (2016)

The Organisation for Security and Co-operation in Europe (OSCE) guide to standards in Kosovo for Heritage Management Plans underscores the critical role of effective management in safeguarding and promoting cultural heritage. Robust management is deemed essential for preserving heritage for future generations. The framework necessitates identifying legal structures, administrative systems, and resources, with regular updates and a participatory approach to maintain heritage value. The OSCE's "spinning wheel" model of cultural heritage management, rooted in OUV, emphasises understanding, valuing, protecting, and enjoying heritage.

Management plans integrate conservation, use, and development, balancing protection with stakeholder consent, legal policy, and professional ethics. Data collection is foundational, involving maps, reports, and advanced techniques like LiDAR and photogrammetry to ensure comprehensive and accurate information. This stage includes documenting site conditions, erosion, structural deformations, and historical context, all crucial for understanding significance.

The subsequent analysis phase involves setting objectives and planning actions based on comprehensive, unbiased data. Sustainability and stakeholder involvement are key, ensuring heritage assets' longevity and societal contribution. The management plan should present a clear vision, strategic aims, and objective statements supported by all stakeholders. Actions must align with the heritage's type, value, and condition, following the SMART and Contract, Listen, Explore, Action, Review (CLEAR) methods, and be feasible within available resources.

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Figure 11 – Angkor Heritage Management Framework APSARA National Authority (2013)

Ultimately, the heritage management plan relies on objective data to define significance, guiding management strategies, aims, objectives, and actions. This ensures that heritage assets are preserved sustainably, with continuous

stakeholder engagement and updated records, contributing to cultural continuity and societal enrichment for future generations.

The Angkor Heritage Management Framework (2013) see Figure 11, establishes a foundation for the site's maintenance, regulation, and conservation, guiding current and future management. It outlines the State of Conservation through surveys and reports, prioritising projects and recommendations. This information supports other critical areas like the Risk Map and Tourism Management Plan.

The framework categorises ten policies into high, medium, and low priorities. Notably, the Information Management Plan in the Angkor Heritage Management Framework (2013) is given medium priority, which seems inconsistent given the high volume of data necessitating robust management. The research contributes by mapping the site, documenting current conditions, and aiding planning efforts.

The framework emphasises historical, aesthetic, scientific, and social values, integrating digital models to visually represent these aspects, which are crucial for conservation practices and guidelines. Management documents include publications and maps, producing reports on zoning, environment, and master plans. This repository tracks progress and reassess challenges posed by visitor numbers, land use, population growth, environmental degradation, and climate change.

Protection aims to enhance the site's OUV by managing threats and balancing tourism sustainability with governance constraints. An accessible repository is essential for informing and educating, thereby supporting asset management. Policies are detailed to ensure digital information management aids stakeholders in decision-making, emphasising consistency, accuracy, completeness, quality, and integrity, APSARA National Authority (2013)

The UNESCO Operational Guidelines state that each property should have a management plan clearly defining the OUV shared by all stakeholders as a tool for strategic coordination and monitoring. The Durham World Heritage site utilises this guideline in a research framework structure similar to that promoted by Historic England based on Petts "*Assessment or What we know*",

"*Agenda or What do we need to know*" and "*Strategy or How to plan future research*" Petts (2015, p.7).

The extent of the framework is broken down into timeline, location and boundaries and beyond the physical. The framework should be a dynamic and open-ended live document. The agenda has three priorities, understanding the site, the built resource and the archaeology. There is an action for consistency in approach though no further discussion as to how this will be collated, stored or disseminated. Petts (2015) identified that the requirement for reports before heritage intervention has led to a plethora of hidden data not used to its full potential, hard to access with little context and interpretation. Such reports could inform the wider stakeholders, feed into management reports and provide understanding of the OUV for a site, and may even stimulate further research generating greater knowledge.

Durham World Heritage Site Management Plan builds on previous versions, fortifying and continuing actions, and highlighting new or emerging issues. The plan has several key messages which will be brought to the fore here. The clarity of the record is important especially when approaching new development to ensure no harm ensues to the significance and integrity in the process of change. The intensity of exploration and recording is dependent on the significance and proposed intervention. These campaigns should also recognise and include the requirements to support risk management, especially with environmental deviation due to climate change. When interventions are enacted, the statutory process requires works to be monitored and change recorded. Overarching the plan is a requirement to appraise, monitor and update on a five-yearly cycle, and implement repair rather than replacement of building fabric. This, however, does not tie the requirement back to the appreciation of value, significance and condition all of which may require shorter periods and in the interest of repair, again the monitoring cycle may need to be varied depending on the condition. Reflection on the appraisal, coupled with contemporary discoveries, may impact the OUV, and conversely, the need to monitor/record/conserve. This monitoring can be divided into the condition of the asset and any intervention which needs to be reported and included with the digital model. Overall, the comprehensive nature and clarity of the plan enunciates the required action placing key themes at the core of the site protection and management

upholding the World Heritage Status but more importantly the retention of the OUV.

This section of the literature review explores various frameworks that provide both macro and micro perspectives on the environment in which theoretical frameworks in heritage management operate. Recurrent themes emerge at all levels, although not all frameworks prioritise OUV, also known as significance. Surveyors often focus on the condition of assets, without due reverence to their significance. However, it is the stakeholders' perception of an asset's contribution to their memories that ultimately determines its value. Frameworks must be adaptable to address pressures and internal risks across diverse situations and asset types.

UNESCO defines OUV alongside authenticity, which dictates protection management through short-, medium-, and long-term actions, utilising a management plan philosophy based on comprehensive material. Competent management of heritage assets necessitates developing expertise in this field. The NPPF in England, generally applied to development, requires historic data to support conservation processes. The National Heritage Protection Plan prioritises sustainability but faces challenges in determining what to prioritise. This strategic framework demands accurate, relevant, accessible, and timely data to manage change effectively, whether planned or spontaneous.

Similarly, Historic Environment Scotland's asset management plan adopts a cyclical, knowledge-based approach, emphasising research, understanding, and experience. The plan advocates for accurate monitoring through regular surveys. However, the management of digital information in heritage assets is still in its infancy and needs flexibility to be relevant.

The CIOB somewhat diverges from Historic England’s definitions, focusing on inspection for construction and condition without adequately considering the fundamental construct of heritage significance. The cyclical nature of heritage management is also underrepresented. Decisions made without assessing heritage value can negatively impact or eliminate significance. Once this value is understood, informed management can proceed. The framework identifies three core elements of conservation - technical, significance, and process - supported by comprehensive research and records. HIAs categorise impacts as positive, neutral, or negative, with negative impacts potentially

mitigated by affirmative aspects, although interventions with overall negative value are generally deemed unacceptable.

The RICS excludes the stakeholder perspective, focusing instead on the surveyor's view, yet it embraces the principle of minimal intervention and acknowledges the importance of heritage asset management using a database. COTAC offers a process wheel to facilitate effective project delivery, though it too tends to overlook heritage value. ICOMOS supports collective recording efforts appropriate to the level of intervention, advocating for adaptable frameworks with objective and rigorous data collection methods.

Conservation management operates at two levels: strategic, which addresses current conditions, future directions, and the necessary steps to bridge the two; and operational, which involves the efficient organisation and coordination of services and resources to implement the strategy, particularly in day-to-day asset administration (BS 7913-2013).

UNESCO's Operational Guidelines stipulate that each property should have a management plan clearly defining OUV, shared by all stakeholders, as a tool for strategic coordination and monitoring. Conservation Management Plans advance the framework by incorporating stakeholder input and integrating recording back into the model. Risk mapping is essential to prioritise and support recommendations. Management documents should include publications, maps, and reports on zoning, the environment, and master plans. The framework should be dynamic, open-ended, and regularly updated, ideally every five years, emphasising repair over replacement to sustain significance.

The discourse has delved into existing frameworks, models and workflows within heritage conservation with emphasis on a digital process to generate expansive data advocating for downstream repositories to manage these effectively. This raft of knowledge sets the baseline at macro and micro levels for the development of the framework. UNESCO's World Heritage Convention highlights the importance of sustainable development consuming objective evaluation of heritage sites. Criteria for OUV underscores various aspects including cultural significance, authenticity, and management plans as a necessity for long-term preservation. Furthermore, competency frameworks as outlined by UNESCO aim to bridge skill gaps in heritage management,

promoting experiential learning. UK Government policy such as the NPPF stress the importance of recording and preserving heritage assets, especially in the face of development pressure.

The frameworks collectively advocate for advanced digital records to enhance accessibility and conservation efforts, emphasising the need for accurate historic information to prevent the weathering of the sites. Emphasis is placed on the importance of robust management plans to address change, backed by strategic planning frameworks and condition monitoring. Historic Environment Scotland and the CIOB provide detailed insight to the asset management and conservation process advocating for proactive approaches to preserve significance. Likewise, the RICS stress the importance of understanding significance of the asset, prioritising maintenance based on careful assessment. COTAC identify the challenge in managing heritage asset projects, noting the lack of structured data and collaborative frameworks. McGibbon et al. (2017) propose a workflow to aid collaboration, yet it overlooks the need for data in decision-making. In suggesting integrating digital technologies for objective data capture, essential for optimising project performance. However, the industry lacks the cohesive framework thereby often resulting in subjective decisions and cost overruns. Advocating digitisation to prioritise tasks and efficiently monitor progress, they stress the importance of determining significance to guide sustainable interventions. These resources ground the theory for a comprehensive framework in successful heritage management.

3.10 Data in Digital Models

This section will explore critical aspects integral to the development and application of digital models in heritage conservation. Emphasis will be placed on comparing the accuracy of LiDAR technology with photogrammetry, the precision and fidelity of digital models, and the levels of detail required for effective heritage asset management. The analysis will underscore the importance of high-resolution data capture and the integration of comprehensive digital frameworks in preserving the authenticity and integrity of cultural heritage. Additionally, the section will examine how these digital methodologies enhance the management, interpretation, and dissemination of heritage information, thereby contributing to more robust and sustainable

conservation practices. Through this detailed examination, the overarching significance of digital models in heritage preservation will be elucidated, demonstrating their pivotal role in advancing the field.

Ensuring consistency in the quantity, quality, and uniformity of historical data available for any digital model presents inherent challenges. While some elements are readily identified in listing details and Heritage Environment Records (HERs), a significant portion of relevant documents often remains inaccessible. Resources such as Pevsner's Architectural Guides provide valuable insights, yet much information lies concealed in isolated maps, local libraries, county archives, and history books detailing specific events, individuals, or locations. Private libraries, collections, local history groups, and civic societies can further enrich our understanding, particularly in specific locations. Additionally, property owners may possess inherited records or documentation related to ownership transfers and physical alterations, often encapsulated in Design and Access Statements, for example. However, these resources are seldom utilised by stakeholders in the execution of their roles concerning the future of the asset (Illsley, 2023). Therefore, bringing this data to the forefront would substantially enhance asset management.

Despite the value of these diverse sources, assembling a comprehensive understanding is time-consuming and requires meticulous effort to interpret the content accurately. The inconsistency in historical records is particularly pronounced for assets of lesser renown, where pertinent information may be irretrievable. This variability underscores the inherent challenges in creating uniform digital models for heritage conservation. Addressing these challenges necessitates a systematic and collaborative approach, leveraging available resources while acknowledging the gaps and inconsistencies in historical documentation (Moseti, 2016). By integrating these fragmented pieces of information, a more robust and nuanced digital representation of heritage assets can be developed, thereby enhancing preservation efforts and ensuring a richer, more comprehensive understanding of our cultural heritage. The aggregated knowledge significantly enhances comprehension of the model's relevance, facilitating prompt dissemination at all stages of a project. Moreover, any notable findings can be integrated back into the model, thereby enriching the record and enabling continuous improvement to benefit the significance of the asset.

Authenticity presents a significant challenge within 3D/4D representations. The integration of historical data, a timeline from the asset's inception to the present, and heritage information into digital models introduces a fourth dimension. Often based on conjecture, this fourth dimension is non-existent or relies on incomplete evidence, whether discovered but incorrectly interpreted, undiscovered, undisclosed, or unrecorded. A facsimile of the highest quality in digital format is imperative (Kenderine, 2018), particularly in response to 'cultural cleansing', which necessitates the safekeeping of cultural objects and heritage sites. As noted, "*… education about heritage is a cultural emergency and this should be taken a political and security imperative. Add to this crisis, climate change catastrophes, natural disasters and destruction of sites through mass tourism, digital replication has emerged as the key topic for cultural heritage in the present*." (Kenderine, 2018, p.xii). The quality of the final model relies on the quality of the point cloud data, that can be augmented with other evidence including meta information, Crisan et al, (2024). Jeffry identifies five key traits that digital objects must overcome: their lack of physical substance compared to real objects, their lack of native location, the ease of their infinite reproducibility, their inability to degrade, and the difference between original ownership and digital licensing. However, this perspective is debatable, as digital files can degrade, be lost, corrupted, or subject to hacking.

The utilisation of 3D replicas for the preservation, analysis, and dissemination of cultural heritage is now well established. The practice of digitally replicating heritage raises fundamental questions about the 'authenticity' of heritage and whether it can be 'reproduced'. This issue also touches on the ontological debate about how we define authenticity and what constitutes an authentic object (Di Franco, Galeazzi & Vassallo, 2018). They further highlight the contemporary *"… obsession of the age for the original, and how this obsession increases as more accurate copies of the original become available and accessible."* Di Franco, Galeazzi & Vassallo (2018, p.2). As heritage assets become more prominent and culturally significant, the fascination with them increases. Digital copies or twins facilitate accessibility, thereby amplifying their importance. The creation of digitally accurate models assumes that accuracy lies in the digital element, though conjecture remains. The London Charter serves both specialists and laypersons by providing guidelines for digital heritage documentation.

In developed countries, parametric representation is seen as the foundation for an accurate experience, enhanced by historical interpretation, with metadata and para-data illustrating how conclusions were reached. It is crucial to view this as an evolutionary process: "*The digital form of monuments and artefacts is simply another stage in their long life-span, which does not undermine the authenticity of these objects*." Di Franco, Galeazzi & Vassallo (2018, p.3). Conversely, earlier texts argued that commoditisation, such as through tourism, undermines authenticity. Today, however, engagement and experience are deemed more important, with legitimacy becoming marginalised. Furthermore, Jeffrey posits that "… *digital heritage objects produced for a specific audience (or better, co-produced with them), free to use and re-use for any purpose, clearly creative, explicitly authored, and reliably and permanently accessible."* Jeffrey (2018, p.55).

The visualisation - data collection, storage, processing, analysis and dissemination – can include the current features either whole or in part, eroded, or revised/removed elements can be complex. Consistency across all parts is difficult to maintain, the initial model generated in software collected through a process can be parametrically accurate with obscured areas of limited textural content. In the contextual data, there may be unaccounted adaptations or pinpoint accuracy where documents cover specifics; in each case, the information reveals or conceals a version of the truth when melded into an entity, a best-fit scenario.

The London Charter (Denard, 2009) provides a framework for the rigour of the model, the foundation on which to build inclusiveness, benchmark, contribute to knowledge and therefore extend understanding of the asset. The consumer encounters the fact that modelling elements have been randomly included but more importantly excluded therefore the resultant is not exacting, remaining unfinished. Further, it must be noted this is not a complete reproduction, only the visual is sated, all other senses are information wanting, the model limited, and this deficiency cannot be recreated therefore the argument returns to the best-fit scenario.

The London Charter (Denard 2009) has six fundamental principles for digital inclusion to ensure transparency, intellectual accountability, and future dependability.

Implementation, only the aims with coherence in the Charter and the application are implemented and where the application is applied, the activity builds on and monitors the strategy justifying intellectual integrity.

Aims and methods, ensure the most appropriate computer-based visualisation addresses the research or dissemination of the data and it is justified on the successfully meeting the aim.

Research sources, considering digital and non-digital information directly or indirectly shaping the model, with each selected and evaluated before synthesised with the existing. Furthermore, where these are visual the para- and meta-data should be considered before acceptance.

Documentation, should enhance the practice, support robust analysis of the visualisation yet protect the intellectual property rights. The model has states of robustness, elements that lack intelligibility therefore there is a need to clarify the Level of Detail, Level of Accuracy, etc. The location of all documentation should be stated and linked to the model and the process of modelling and data evaluation both parametric and historic requires transparency. Robustness based on current understanding will be lucidly disclosed allowing future revision following discoveries in either parametric or historic information. Furthermore, understanding should be universal with standardisation of framework, language and definition, not limited to the individual fragments of knowledge but to the interlinking relationships providing the synthesis.

Sustainability, strategies should ensure the long-term sustainability of cultural heritage-related computer-based visualisation outcomes and documentation, to avoid the loss of this growing part of human intellectual, social, economic and cultural heritage. Data is by nature invisible, without a software platform irretrievable, making it vulnerable therefore this mediator has to be robust, mature and sustainable to ensure longevity. Furthermore, the past was contained in physical often dissociated repositories, currently, the digital archive is still spread around, search functions allow identification with subsequent collation. Under all circumstances, data storage should be sustainable, indestructible, accessible, modifiable hence resilient.

Access, in creation and dissemination of computer-based visualisation should be planned in such a way as to ensure that maximum possible benefits are achieved for the study, understanding, interpretation, preservation and management of cultural heritage. The elements discoverable here are the accessibility of the asset in the universal definition of equality covering the container and the content. Where a building or object becomes inaccessible or is destroyed the model can provide a stand-in, however, the model can also provide greater understanding in the fourth dimension 'visualising' the change and disseminating the resultant instantaneously across space.

The range of stakeholders provides a measure of difficulty for any model building. The data both parametric and time focused must be accessible without encumbrance, by either professional or layperson. The format of the access platform and the data must encourage use for all levels, this can provide a very difficult conundrum. Complex schema or inaccessible technical language or acronyms can leave individuals peripheral, equally simple arguments for professional consumers. The importance of the model cannot be understated if it is to engage all stakeholders, perceptions are everything, inaccuracy at contextual, local or micro levels will disengage the user. If the model is a deficient representation, this will relinquish confidence, the process of data capture or creation is often replete, yet once disseminated there is little time spent in the maintenance or accessibility of the model, *"It still often remains the case that more attention is paid to data capture and data creation than is routinely paid to how that data will be maintained in the long term, and where and how stable points of access to the data will be."* Jeffrey (2018, p.53) for example hyperlinks going to the standard error message.

To improve or convey the model into the current state of the asset, there must be authority in the capture and representation of the data. Jeffrey states that "… *currently digital recording of cultural objects in three dimensions remains both skilled and highly interpretative; the trend is towards both automated processes and integrated workflows."* Jeffrey (2018, p.54). This shift towards automation can enhance consistency in quality. For instance, real-time model construction can identify areas requiring immediate rectification or additional data capture. Automatic image capture settings can standardise the process and metadata, reducing levels of interpretation. However, the use of high dynamic range in image capture can introduce hues

not associated with the asset. Without a clear understanding of the materials and the technicalities of image capture, such discrepancies may go unrecognised, potentially leading to misleading representations.

Excessive automation risks excluding skilled operatives who possess crucial process knowledge and the ability to resolve inconsistencies. Rectifications not immediately enacted will persist in the data, requiring future resolution and greater resource expenditure. The workflow from instrument to model is an integrated methodology; just as an artist cannot accurately represent a subject without being present, neither can the modeller and the data capture be exclusive. Decisions must be made during the process, as Jeffrey notes, "… *there is an undeniable level of technical skill required to create 3D models of complex real-world objects. There is also a large degree of creativity, interpretation, and even artistry.*" Jeffrey (2018, p.54), which will impact the resultant quality and authenticity.

This will become increasingly important as models become data-rich, evolving from visual representations to integrated data sets of synergistic material. Jeffrey (2018) suggests that current digital models are technically oriented, whereas the future lies in the integration of extensive heterogeneous datasets, spanning from archival to contemporary society. Authenticity will allow these 4D models to be amalgamated with broader heritage examples. Their dynamic nature will provide a platform for extensive data integration, employing the Gemini Principles and Artificial Intelligence to identify previously unexplored links within digital networks. While these models will not replace the original assets due to the absence of certain sensory elements, the networks of data consensus or divergence will shed new light on the asset.

Historic England is a strong advocate for the utilisation of BIM for heritage projects, particularly in the development of the Asset Information Model (AIM). To this end, they have produced a guidance document (Historic England, 2019). In their foray into digitisation, Historic England commissioned a digital model of the first Iron Bridge, spanning the gorge of the River Severn in Shropshire, which recently underwent a year-long conservation project. They emphasise digital documentation through laser scanning and photogrammetry as 3D data capture techniques, though BIM

has yet to become a standard in repair, maintenance, or conservation projects.

The inclusion of an AIM for building lifecycle management, as identified by Duong and Lin (2022), provides a dedicated database for facilities management, addressing the dual issues of missing and fragmented information. Point cloud technology can facilitate geometric modelling, object identification, and quality inspection. For instance, geometric quality can be routinely interrogated to detect faults, thereby extending the service life of assets. However, a limitation of the point cloud as an information model is its lack of data between surfaces, such as the structural build-up. Furthermore, unlike BIM in mainstream development, historic projects often begin with the collation and continuation of data throughout the asset management delivery cycle. In this situation data determining the format and materiality of hidden elements may be collected and recorded. This workflow is illustrated in Figure 12, based on the diagram by the British Standards Institute (BSI).

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Figure 12: Historic BIM Workflow Historic England (2019)

Historic England regards each heritage asset as unique, and consequently, each project must also be unique. Therefore, frameworks are necessary if digital models are to become customary, a notion reinforced by Brusaporci et al. (2018). To support this assertion, Historic England has produced three supplementary templates: Organisational Information Requirements, Asset Information Requirements, and Exchange Information Requirements. The management of heritage assets is grounded in the conservation principles of enduring maintenance with minimal intervention for maximum preservation, which must form the foundation of any framework. Given the uniqueness of each asset, the management approach must also be tailored, with a focus on custodianship and exposition.

Historic England recognises that asset management plans should be centred on "… *knowledge-based decision-making based on comprehensive and current data*." Historic England (2019c, p.12). PAS 55-1:2008, as provided by BSI, defines Asset Management Information as "… *meaningful data relating to assets and asset management …"* BSI (2008, p.2) which should encompass a plethora of historical and contemporary documents, including maps, drawings, photographs, specifications, and instructions. The asset information system accumulates, processes, and conveys data over the asset's lifetime. However, when applying this system to a historic building, it should be supplemented by historic and conservation data.

Historic England (2019c) proposes a workflow for the incorporation of information, beginning with the management strategy and culminating in the Heritage Asset Information Model, as depicted in Figure 13. This workflow acknowledges the existence of legacy data and asset information, highlighting the potential for cyclical data gathering that upholds the principle of maintaining current and comprehensive information through accuracy. BIM is inherently a collaborative process, facilitating the acquisition and sharing of data among all stakeholders. This collaborative approach is essential to ensuring the sustainability of the asset throughout its lifecycle.

Key considerations include the robustness of the workflow, such as software requirements, which will determine the appropriate file types and data exchange protocols. This ensures that the digital information remains accessible, accurate, and usable by all parties involved. By addressing these

issues, the BIM process can effectively support the preservation and management of heritage assets, ensuring their longevity and continued relevance.

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Figure 13: Workflow for Proposed Heritage Asset Information Management Process, Historic England (2019)

When considering what is required Historic England (2019) believes the questions may provide an outline before an intervention, what is the historic value, required to gain consent, necessary to understand and manage the task, needed to maintain the installed plant/equipment and to be presented? The document goes on to list a range of information to be included. Extracting the most essential for this research they propose Statements of Significance, asset condition and intensity of use, technical data and management data.

The AIM transcends mere 3D modelling by offering multifaceted benefits across management, conservation, repair, maintenance, and dissemination

efforts. Beyond geometric data, the repository encompasses maps, plans, photographs, databases, reports, surveys, manuals, and interactive non-geometric datasets. Undertaking such comprehensive data management may necessitate a business case, although the quality of conservation efforts significantly improves with a robust knowledge base.

In the heritage context, there is a compelling argument for initiating an Asset Information Model proactively, rather than reactively following an intervention (Historic England, 2019c). According to Historic England, "*An AIM can provide a single source of validated information to be used in such (heritage conservation) decision-making processes.*" Historic England (2019c, p27). Furthermore, it acknowledges that this model can evolve gradually over the asset's lifecycle, enriched by ongoing contributions as part of the Organisation Information Requirement (OIR).

Maintaining the AIM involves considering the frequency of data renewal, tailored to the unique needs of each asset. The process of data collection not only yields a rich resource but also facilitates continuous enhancement, yet accessibility challenges identified by Brusaporci et al. (2018) may hinder effective exploration, planning, or decision-making among stakeholders. Therefore, an AIM stands as an efficient and effective framework for the structured classification and exchange of heritage data, particularly when integrated with a 3D model. This approach ensures comprehensive and validated information supports informed decision-making and sustains the preservation of heritage assets over time.

Historic England (2019c) has demonstrated in their case study that "*3D data capture through laser scanning and photogrammetry has proven effective in digitally documenting historic assets, with resultant point clouds serving as valuable visualisation and engagement tools to aid in the creation of 3D models.*" Historic England (2019c, p.44). Furthermore, they assert that "… *the addition of bespoke conservation data parameters to the model, such as element condition, significance, and urgency of repair/maintenance, can enhance its utility as a visual planning tool and is particularly valuable for analysing and interrogating data for CRM planning*." Historic England (2019c, p.45). The discussion highlights a noted absence of specific guidance on preservation-focused record parameters aimed at Historic AIM. However, the

perennial challenge remains the limitation of resources required to achieve the most complete and accurate representation in support of sustainable conservation practices.

Given the iterative nature of this process, it can be argued that the AIM will always evolve and may never achieve perfection. Therefore, initiating the process with clear parameters and a comprehensive understanding of its inherent limitations can establish a solid foundation upon which to build the repository of historic asset information. This approach ensures that the model continues to improve over time, adapting to new insights and technological advancements while supporting informed decision-making and effective heritage preservation strategies.

The interface and software hub must maintain close integration, yet the development of universal software packages capable of capturing and manipulating data in a multitude of formats is unlikely. Legislative information and planning data often require interpretation before application to the model and consequently impact decision-making processes outside of software capabilities. This necessitates a clearly defined yet transparent division within the hub: certain information feeds directly into the hub, while other data undergoes transformation in the interface to ensure compatibility.

In current information model frameworks, Industry Foundation Classes (IFC) serve as repositories for data exchange readable by modelling-associated software. However, applying these standards to heritage contexts often requires multiple iterations to become serviceable. Moreover, achieving consistent data classification in heritage contexts necessitates adherence to standardised protocols and naming conventions. However, implementing such standards poses significant challenges, primarily due to the unique and diverse nature of heritage assets.

In the realm of heritage preservation, standardisation efforts encounter complexities stemming from the historical, cultural, and architectural diversity inherent in these assets. Each heritage site possesses its own distinctive characteristics, histories, and significance, making it difficult to impose uniform classification frameworks across the board. The intricate nature of heritage assets demands nuanced approaches to data classification that can accommodate their specific attributes and contexts.

Diara and Rinaudo (2020) emphasise the challenge of inconsistent semantic classification, which heavily relies on subjective analysis, particularly in understanding nuanced aspects of heritage. This subjective approach is crucial for sharing fundamental knowledge, facilitating comprehension of historic asset evolution, and analysing phenomena such as deformation or weathering. Such analyses are essential for implementing preventive and iterative interventions aimed at preserving asset significance. In a similar vein, for data to be mined or pushed by stakeholders, both involved and peripheral, inclusion should be based on clear parameters which need to be rigorously applied. For accuracy, interoperability and search facilities the terminology needs to be consistent across the whole model including the directly and indirectly linked data. The use of a gatekeeper, which may be the owner, would ensure the data consistency and appropriateness in terms of the quality and taxonomy however this will interrupt automation in the flow of data.

Nevertheless, the fixed schemas embedded within proprietary software and employed in IFC data exchange frameworks are rigid, presenting significant limitations in accommodating the unique and complex nature of heritage conditions. This inflexibility underscores the need for a shift towards a more adaptable, ad hoc system to enhance heritage asset management and preservation. Such an approach would allow for more nuanced and context-specific classifications, better aligning with the distinct characteristics and requirements of each heritage asset.

Model accuracy conventionally set at the best achievable within parameters appears too high for present technology, hardware and software, is time-consuming and considered expensive therefore models remain unexploited. If the resultant historic information model was considered to be 'as built' material, then Level of Detail, LoD 500 would be satisfactory, but this would exclude the specific details in mouldings or door furniture for example. A hybrid is a potential, merging the 'as built' as a macro view and the detailed 'original' features have a micro model embedded within the bigger picture.

Linking stakeholders in the process of building the model will allow a greater understanding of the required parameters and potential which will extend into the future. This is similar to the Level 2 requirement of the BIM process where

the client at the outset of the project determines the output from the model at contract completion. As the federated model becomes robust and accuracy matures technological advancements may provide the answer through artificial intelligence Pasikowska-Schnass and Lim (2023) however this aspect is beyond the limits of this research.

Despite the difficulties in software platforms, security etc. the lack of data for hidden features needs a sea change in the approach of the BIM community where accuracy is factual or attributed allowing the federated model to evolve as a tool to support the stakeholder in the decision making.

BIM transcends the notion of merely being a software database; it fundamentally drives the enhancement of collaboration among all stakeholders involved in construction projects. There is a notion BIM will advance to Level 3, leveraging IFC standards to facilitate seamless information sharing. Moreover, with the integration of the Soft Landings Framework from the Building Services Research and Information Association (BISRA), BIM's application is expected to extend into Facilities Management, delivering a multitude of benefits.

The BIM Task Group now disbanded was established to assist the Government in achieving the objectives outlined in the Construction Strategy. Their website elucidates that *"PAS1192:3 addresses the operational phase of assets, regardless of whether they were commissioned through major works, acquired through transfer of ownership, or already existed within an asset portfolio."* BIM Task Group Scottish Futures Trust (n.d.). This framework mandates the creation of an AIM to manage information exchanges with a Project Information Model (PIM) created in accordance with PAS1192:2. Additionally, it encompasses external asset information models, such as Computer-Aided Facility Management (CAFM) systems, direct supplier inputs like digital surveys, and other enterprise information systems, including financial reporting.

Empirical evidence indicates that the implementation of BIM can yield efficiencies in the construction process which could translate into similar efficiencies during the operational phase. Akcamete, Akinci, and Garrett (2010) assert that BIM can furnish as-is data and the historical context of assets, facilitating the analysis of buildings to support planned maintenance

and repair, further enhanced by visualisation within the model. This perspective is reinforced by Smith (2007) in the paper presented at the National Institute of Building Sciences 2007 Symposium on behalf of the BuildingSmart Alliance. The paper argues the potential for digital models to elicit greater efficiencies during the operational phase particularly when considering buildings as long-term assets with lifespans exceeding 100 years.

All heritage assets and construction methods have undergone evolution, necessitating their meticulous cataloguing within the BIM model. Although it may not always be feasible to precisely determine dates, the model will be constructed at a specific point in the building's lifecycle, with any subsequent changes recorded with a time datum. The objects incorporated into the initial model must be catalogued with either defined or assumed dates; these may require revisions as additional data becomes available. This approach allows for an initial comprehension of asset development, thereby underscoring the necessity of 4D BIM.

Furthermore, the xD model is likely to embody a standardised information framework, enriched with layers of historical detail that feed into the object parameters and influence the output data. This integration can impact aspects, such as extending the duration of project design and execution or incurring additional costs for specialist contractors. This enhanced model facilitates a comprehensive understanding of the historical and current state of assets, enabling more informed decision-making and efficient management throughout the asset's lifecycle.

Any system of information repository and reference should be intuitive and allow all stakeholders to interact with the data on many levels. The specific stakeholder access will need a common interface and operability to provide accessibility and should bring to their attention the location of, if not the actual data. Ergen et al support the notion, "*Effective and immediate access to information minimises the time and labour needed for retrieving it and helps avoid ineffective decisions made in the absence in information.*" Ergen et al (2007, p.356). Burcin et al move the idea forward "*Building information modelling's graphical interface can provide a unified data access point to the required data.*" Burcin et al (2012, p.435).

Ensuring the model's accuracy within the parameters of data capture and the objects it represents is paramount. The LiDAR point cloud method excels in this regard, as it retains visible voids where data is missing, allowing for precise identification and subsequent correction. In these voids, although LiDAR may lack Red Green Blue (RGB) data, it accurately records the surface profile, with laser points probing even visually obscured areas. This method, in harmony with the London Charter, guarantees transparency and accuracy within the data, as highlighted by Beacham et al. (2006).

Conversely, the photogrammetry method relies on algorithms to merge images into a 3D Digital Surface Model (DSM). At the edges of surfaces, where data diminishes, subsequent or previous images are used to fill gaps. This process can introduce inaccuracies, as algorithms interpolate missing data, often resulting in artefacts that are not immediately apparent and thus frequently accepted. Identifying and eliminating these artefacts is particularly challenging in complex external environments.

Utilising LiDAR allows for the addition of surfaces to infill data voids with precision and tenacity, rather than depending on algorithmic interpolation. This approach enhances the model's overall fidelity and reliability, ensuring a higher degree of accuracy in the representation of captured objects.

Ali et al. (2018) explored the relationship between LOD and the use of BIM in heritage assets and building preservation. Incomplete or poor-quality data presents significant challenges in managing heritage assets. However, accurate, comprehensive, and structured data stored in a digital repository—forming a "golden thread"—becomes fundamental to the management plan and robust decision-making, essential for achieving comprehensive OUV.

The information inventory for heritage assets should encompass a wide range of data, including asset condition, usage, descriptions, maintenance records, materials, technologies, risks, and significance. The accuracy of this data is paramount, necessitating the highest level of LOD, specifically LOD500, which represents 'As Built' status with verified graphical representation and accuracy. At this level, the model becomes a reliable resource for asset managers overseeing maintenance, reordering, and repairs of the fabric and systems, thus supporting effective management.

For contemporary structures, such data can be directly extracted from the BIM model. In contrast, for existing and especially heritage buildings, this documentation must be meticulously gathered, constructed, researched, analysed, validated, interpreted, and integrated into the repository. This is a time-consuming, costly, and skill-intensive process. Once amassed, the data must be stored in the cloud, incurring recurring costs, and updated throughout the asset's lifetime to ensure its ongoing relevance and accuracy. Maintaining current, robust data is crucial for the management and preservation of the asset's significance.

The considerable investment in time and capital required for this process may be prohibitive for many heritage assets. Nevertheless, the necessity for a sound basis for decision-making cannot be overstated. In such cases, prioritising accurate, high-quality data over comprehensiveness may be essential to achieve effective asset management.

Graham et al. (2018) advocate for integrating the current concepts of LOD, Level of Information (LOI), and a novel Level of Accuracy (LOA) to achieve a comprehensive understanding of the model. This approach diverges from the previously considered Level of Development. The unmodeled point cloud plays a crucial role in this integration and can be incorporated into the BIM or digital model. Each model will be unique, based on a point cloud derived from LiDAR or photogrammetry, and should include historical data.

The paper highlights that when point cloud data is not available, drawings, images, and other secondary sources are referenced. However, these sources often lack robust relational, dimensional, and geospatial data, if they include it at all. The five stages of LOD range from LOD100, which represents a basic 2D model, to LOD400, which provides an accurate representation. When applied to heritage, LOD does not account for material loss or structural distortion. Conversely, a comprehensive image library could incorporate these factors as flags within the point cloud.

PAS 1192-2 (2013) outlines a seven-stage model aligned with the RIBA Plan of Work, though this added complexity may overcomplicate the situation. LOI considers embedded information, ranging from LOI 0, which requires no information, to LOI 4, which includes specific manufacturer details, elements, and links to manuals, generally reserved for facility management. Lastly, LOA

addresses the model's accuracy, from no deviation to LOA 4, which includes a mesh from the point cloud containing all deformations.

These considerations are crucial when determining the data to be incorporated into the model. Certain elements of the asset will be precisely understood, while others will remain inadequately known, making consistency within the model improbable converse to the models used in new build projects.

The case study referenced in Graham et al. (2018) employs a comprehensive array of tools, with the point cloud serving as the primary source of accurate surface precision. Beyond this, the study utilises photogrammetry, archival drawings, historic catalogues, and photographs. Nevertheless, the standard falters when unique characteristics, such as weathering or deformation, are identified and documented. Categorising each component and assigning a level to each attribute (LOD, LOI, LOA) while integrating an appreciation of their significance would highlight areas where robust data exists and where supplementary data is needed.

Adopting a dashboard approach to tabulate the data could facilitate an immediate and straightforward visual comprehension of the model, thereby enhancing accessibility. However, the nuanced condition of each component may undermine the efficacy of such an approach. The underlying materials and technologies, whether original, replaced, or repaired, significantly influence the data's quality and the historical narrative, which may not always be documented or attributed accurately.

Furthermore, within the heritage sector, the integration of existing data, the requirements for future data, and the processes by which this data will be augmented and synthesised through ongoing discoveries remain ambiguous due to the absence of a formalised policy. Consequently, it may be postulated that the only truly accurate information is the geometric data captured at a specific juncture, as historic data inherently contains elements of artistic licence and nuance. Moving forward, this accurate model can be integrated into the historical record to more effectively manage the asset.

A LiDAR survey, when coupled with historic research, can precisely document assets to construct intelligible narratives regarding their development. Nevertheless, such research often remains open to interpretation, introducing

a level of inaccuracy, whereas the point cloud, even after registration, can achieve millimetre precision. The point cloud captures only the current state, which may include artefacts from the past, but without supplementary historic data—such as photographs, maps, and drawings—it cannot be fully interpreted.

Shotton (2018) advocates for retaining geometric scan data in a point cloud as a method to ensure that users of the model appreciate the inherent accuracy, unmarred by the approximations introduced by parametric or mesh models. The transparency of this representation is particularly valuable in chronological models that include hypothetical reconstructed forms, where melding historic evidence, such as photographs, with the point cloud model is beneficial. However, presenting these combined media as an accurate or plausible representation conflicts with the ICOMOS London Charter, which calls for rigorous historic interpretation.

Developing a timeline that offers stakeholders an insightful narrative into the intricate evolution of an asset is advantageous, yet the need to express elements of uncertainty remain. Employing layers and colourisation within the point cloud can serve as indicators of data validity, and toggling these layers can illustrate the asset's chronology. While the scan data accurately conveys deformations and erosions, it communicates a sense of tentativeness, less definitive than if rendered as a mesh or surface model, Shotton (2018). Therefore, careful colourisation can effectively distinguish between historical accounts and factual data.

The framework proposed by the CIOB ZERO, as articulated by Stanton (2022), serves as a comprehensive net zero carbon playbook encompassing six pivotal topics: leadership, measurement, design, construction, and innovation. The significance of the measurement topic is particularly notable in this research, as it ensures that the language and concepts are both accessible and systematically developed.

The measurement topic is broken down into the following;

- Define what information you need and when
- Plan out who will provide the information
- Use tools to drive measurement

- Collect and check the information
- Make the data accessible and use to inform decision-making
- Use data to challenge briefs
- Ensure skills are in place
- Drive continuous improvement/feedback and learning

This structure would work as an effective measurement framework within the research however there is a need to add in the research requirements to support the measurement data. The final stage does suggest a cyclical nature, it would benefit from being more specific in this point. Therefore, the supportive descriptive narrative could be moved into the realm of conservation and strengthen the final stage to ensure a more cyclical footing.

This section critically explored the development and application of digital models in heritage conservation. It compares the accuracy of LiDAR technology and photogrammetry, assesses the precision and fidelity of digital models, and evaluates the required levels of detail for effective heritage management. Emphasising high-resolution data capture and comprehensive digital frameworks, it underscores their importance in preserving cultural heritage authenticity and integrity. Furthermore, the section highlights how digital methodologies enhance the management, interpretation, and dissemination of heritage information, thereby promoting robust and sustainable conservation practices. Challenges in achieving consistent historical data for digital models are addressed, noting the variability and inaccessibility of significant documents. The discussion includes the integration of fragmented historical records and the impact of 3D/4D digital representations on authenticity. Thus, the pivotal role of digital models in advancing heritage preservation was explored, emphasising the need for systematic and collaborative approaches to overcome inherent challenges.

Acknowledgement was that Historic England emphasises asset management plans should be driven by "… *knowledge-based decision-making based on comprehensive and current data."* Historic England (2020, p.12). According to PAS 55-1:2008, meaningful data for asset management should include a range of historical and contemporary documents, processed and conveyed throughout an asset's lifecycle. For historic buildings, this data must be supplemented with conservation information and the section outlines a

workflow for integrating asset information, from strategy to the Heritage Asset Information Model, acknowledging legacy data and emphasising cyclical data gathering for accuracy. BIM supports collaboration among stakeholders, crucial for asset sustainability. Key considerations include robust workflows and software requirements to maintain accessible, accurate, and usable digital information.

The AIM offers benefits beyond 3D modelling, including management, conservation, repair, and maintenance and should evolve proactively, enriched by ongoing data contributions. Challenges include data consistency and standardisation, crucial for effective heritage asset management. Despite complexities, AIM supports informed decision-making and sustainable preservation.

Technological advancements like 3D data capture via laser scanning enhance the documentation and planning of heritage assets. However, proprietary software limitations necessitate adaptable systems for nuanced classifications. Effective BIM implementation requires comprehensive, high-quality data, accentuating the importance of continuous improvement and stakeholder collaboration. Accurate data, crucial for managing heritage assets, must be meticulously collected, validated, and integrated into digital repositories, despite the significant investment required.

2.11 Theoretical Framework

Here, the theoretical framework is the developed from the conceptual framework. Theories encompassed in the framework can be drawn from existing literature or can emanate from the understanding developed in the empirical work, according to Riggan and Ravitch (2011), and through aggregation elucidate aspects of the conceptual framework hence the theoretical framework developed at the end of the project. Theoretical frameworks provide the critical glue binding complex multi-layered themes together yet is the theory grounded in the literature or originating from within the researcher? The literature review frames and grounds the problem whereas the empirical work develops solutions to the problem. Theoretical postulation in research means there is an explanation as to how and why things work the way they do, "*A theory provides an explanation of reality*." Ngulube (2018, p.5). The initial literature review provides the conceptual

framework 'bins', yet becoming too intent on this agenda can limit the value of the case study to provide the requisite theoretical effectiveness. As seen earlier in the chapter, the flexibility allows the shift in the researcher and research, identifies components in the theory or employed to interpret the data.

Moving to consider the advanced theoretical framework, presently, engagement by the public with the digital model is absent, the lack of 'aura' limits ingestion to professional actors thereby inhibiting the decision-making capacity, Jeffrey (2015). For impromptu or enduring management decisions aligned with the ICOMOS Burra Charter, the model should be consumed, change actioned and the outcome recorded back, i.e. dynamic. However, for strategic or functional decision-making the currency of the data should be questioned and, where necessary, a new campaign actioned utilising the framework. "*3D surface representations … performed regularly … can be metrically compared so that any perceived changes can be both quantified and digitally mapped*" Bryan (2009, p.25). When additional data certifying the historic detail, for example, records or documents are identified, the model can be utilised to endorse the quality in the evaluation phase and the data included. There is a need for a facsimile, of the highest quality in a digital format according to Kenderine (2018) hence the need at each iteration to evaluate the data before inclusion. The proposed framework as a principal force provides a synthesised flexible dynamic core to the operation of the model, a new contribution to knowledge in the heritage arena.

This model should be shared with all the actors prior to and during all stages of any planning or works and should be consulted to define the significance of the whole and the parts before the intervention even in the event of an unforeseen demand. Temporary works can cause interventions which impact on the significance, by interrogating the model a strategy design can limit undue fabric damage. A known issue in disseminating knowledge and building understanding between the tradesperson and the consultative or professional person exists, a digital model can provide the insight in visual terms with instant access to plug the gap thereby aiding collaboration. Augmented reality can provide the interface between the model and the asset with little training for all actors.

It may be seen that others have made proposals for similar frameworks, yet the approach was without the rigour of the fundamental heritage requirement being that of conservation to ensure future socioeconomic benefit. McGibbon, Abdel-Wahab & Sun approach starts at the "*… demand for high-quality economical and sustainable historic building repair and maintenance* …" McGibbon, Abdel-Wahab & Sun (2017, p.1), leaving out the conservation element which precedes any intervention as determined in UNESCO directives.

Budiman, Wati & Norhidayat (2019), propose a 5R adaption framework covering timing, location, device, user and content however this is focused on the capture of data to improve organisational performance in the creation, sharing and use of knowledge, not for management but for dissemination. Sustainable management relies to some extent on interest in the artefact, conservation is an ethical approach required for heritage assets to maintain prominence for all generations. The Durham World Heritage Site proposed a Research Framework in 2015, Petts (2015) stating a systemised and contextualised approach to provide structure in countering the changes to the planning system in England and the revisions to evaluation in the management of World Heritage Sites. World Heritage Sites have prestige yet are not protected under the listing but under the local planning system. If not robust the planning system allows development which challenges the status resulting in delisting as with Liverpool Maritime Mercantile City.

A comprehensive framework that emphasises an active model, wherein the initial content is constructed with future requirements in mind, will develop in tandem with the evolving understanding of the asset. Heritage policies, digital tools, and stakeholder input will significantly influence the resultant framework. Nevertheless, the content must remain adaptable, and the digital tools employed should not be so specific as to constrain the choice of software packages. Key components will include management strategies in planning, interventions, documentation of actions and findings, development strategies, and maintenance, among others.

As a digital repository, this solution will be enriched by the historical knowledge of the asset, ultimately becoming the superior reference point. The management process for heritage assets will encompass various levels of

control: Strategic, Intermediate, Operational, and Utilisation. Additionally, feedback loops and goal-setting mechanisms with performance indicators will play critical roles. While this research does not concentrate specifically on these elements, it acknowledges their importance and integrates them within the framework using variable naming conventions as dependencies.

The concepts and variables as required by a theoretical framework are drawn out as defined by Varpio, Paradis et al. (2020). A theoretical framework can provide the basis of data capture and dissemination for inclusion in the conservation management plan in the deliberation of interventions and when faced with a requirement for immediate repair (temporary or permanent) after damage (accidental, in conflict or vandalism). The framework will generalise the concepts within the conservation lens applied, in this approach elements may have been left unconsidered. The final framework provides the linkage of these concepts into theories to develop understanding.

The theoretical framework serves as the backbone for understanding and addressing complex, multi-layered themes within heritage management. Theories can stem from existing literature or empirical work, ultimately forming the theoretical framework at the project's conclusion. This framework, anchored in literature, helps explain the reality of how and why things function as they do. The literature review frames the problem, while empirical work develops solutions. The framework should be adaptable, incorporating feedback loops and performance indicators to remain dynamic and relevant.

Current frameworks lack public engagement, which limits their effectiveness to professionals only. To support strategic and functional decision-making, the framework must facilitate continuous updates and reassessments. High-quality digital facsimiles and augmented reality interfaces can enhance understanding and collaboration among stakeholders. Unlike previous approaches, this framework integrates conservation as a fundamental requirement, ensuring future socioeconomic benefits.

The theoretical framework emphasises a flexible, dynamic core to manage heritage assets, incorporating management strategies, documentation, and maintenance. It bridges the gap between tradespeople and professionals, aiding collaboration and ensuring the asset's historical knowledge is preserved

and enriched over time, thus providing a new contribution to heritage management knowledge.

The theoretical framework, developed from the conceptual framework, binds complex, multi-layered themes within heritage management. Theories from existing literature or empirical work form the project's theoretical foundation, explaining the reality of how and why things function. While the literature review frames the problem, empirical work offers solutions. The framework must be adaptable, incorporating feedback loops and performance indicators to stay dynamic and relevant.

Current frameworks often lack public engagement, limiting their utility to professionals. Continuous updates, high-quality digital facsimiles, and augmented reality interfaces can improve understanding and collaboration. Unlike previous approaches, this framework integrates conservation as a core requirement, ensuring future socioeconomic benefits. It bridges gaps between tradespeople and professionals, preserving and enriching historical knowledge, thus a novel contribution to heritage management.

2.12 Heritage Surveying

According to Blake (2007), there are two primary types of surveys: metric, which involves systematic measurement, and observational, which focuses on capturing historic and conditional details. They also acknowledge that surveys can be conducted without collecting measurements, relying instead on sketches, photographs, or descriptions. Metric survey techniques may include tape measures and rods or total stations for simpler buildings, a traditional methodology, whereas major projects typically require CAD drawings, which demand a high level of training and technical skill (Historic England, 2016a). Furthermore, Historic England states that "*Hand-drawn illustration techniques are also the most flexible and widely applicable, delivering the requisite level of detail and type of end-result for many projects*." Historic England (2016b, p.3).

The level of detail/development (LOD) is determined by the survey's purpose. Drawings intended for historians may lack the accuracy needed for conservation, repair, or intervention (Dallas, 2003). For instance, repairing an ashlar façade requires identifying each stone, especially those needing

attention, yet there is often a shortage of personnel with the time to undertake such a task. Additionally, maintaining accuracy with measured surveys using tapes, triangulation, and offset techniques is nearly impossible (Dallas, 2003). Nevertheless, Bryan argues that measuring a building by hand offers the benefit of a deeper understanding of the structure, stating that "*As well as facilitating direct measurement using conventional tapes and scale bars, hand surveys and drawing enable an immediate appreciation of both form and condition to be captured and recorded."* Bryan (2009, p.26). This method supports tracing the development, interrogating, and analysing the fabric to provide a narrative for understanding the building's heritage (Historic England, 2016b).

LiDAR surveying instruments are particularly effective for conservation recording as they are generally employed at ground level, obviating the need for expensive and potentially harmful access arrangements (Barber, 2006). Terrestrial laser scanning systems *"... are able to record building facades with a density of hundreds of laser points... dense enough to recover both facade contours and small details."* (Pu and Vosselman, 2009, p.576). This technology provides a robust data foundation for decision-making in conservation and preserving significance. However, Whyte and Hartmann (2017) highlight the unstable, transient nature of digital inclusion, where application is an adaptive process. Furthermore, experienced surveyors specialising in heritage assets, essential for obtaining precise, high-quality, and comprehensive data, are scarce. This is exemplified by software updates, and digital obsolescence poses a continual threat (Belhi et al., 2017). Conversely, digitising buildings and monuments in 3D models is revolutionising user perspectives, opening new avenues of understanding (Kenderdine, 2018), and providing a foundation for professionals to shape solutions within the legislative framework for maintenance, repair, conservation, and retrofitting of the built environment (Historic England, 2018).

Despite the precision of millimetre accuracy, it leaves no room for reflection or interrogation, as all elements are equally portrayed. This marginalises detail, particularly in point cloud data, where planes are elucidated but edges and transitions often lack definition. In contrast, inspection and recording by hand allow the surveyor to become intimately familiar with the asset. As in

any research, the surveyor decides what to include and to what level of detail, potentially shifting the narrative in a particular direction at the expense of factual accuracy. This may not be intentional; a portion of a sketch could be more meticulous if the surveyor had greater access to it, as identified by Dallas (2003). Hand surveys are time-consuming and again require highly skilled surveyors, especially when recording detailed heritage assets. Digital solutions, however, can be more efficient, accurate, and less prone to errors. Traditional survey methods benefit from condition assessment, where the specialist surveyor becomes familiar with the building while gathering data. However, this is challenging for hard-to-access elements, such as high-level locations or those adjacent to watercourses or main roads. Close examination often requires scaffolding, posing risks to the asset, erectors, public, and surveyors, and leading to considerable costs (Bryan, 2009; Bosche et al., 2015), which impact site sustainability. An alternative is to extend the interval between surveys, though this may lead to material degradation, loss, or impact on other elements, resulting in a loss of significance.

A standardised example of surveying is the quinquennial inspection of church buildings under the Ecclesiastical Jurisdiction and Care of Churches Measure 2018 (ChurchCare, n.d.). A qualified surveyor is appointed every five years, and their report forms the basis for ongoing maintenance and improvements, ensuring the building remains in good repair. The report, which includes marked-up plans and photographs, covers the internal and external elements of the building, safety, access, and sustainability in accessible areas. Generally conducted from the ground, unmanned aerial vehicles/systems are increasingly used for high-level inspections, but many inaccessible areas remain unrecorded.

Asset management in practice benefits from constant review, particularly concerning facade materials, which depend on weathering and their position in the refurbishment cycle. Geo-location, orientation, material, detailing, and weather features are some determinants in this period, though variability means no two sites are precisely comparable. In critical material significance, the time variable could be based more appropriately on identifiable changes or weathering between surveys and the rate of change compared to subsequent surveys. English Heritage’s Building Conservation and Research Team regularly uses decay mapping techniques to characterise deteriorating

surfaces before intervention, assessing historic and current rates of decay and loss during projects (Fidler, 2018). Change classification may include no change, surface reduction, or surface expansion. Additionally, in stone weathering, subsets of these groups affect the surface, and vegetation impacts on the material must be accounted for.

The section identified two primary survey types: metric, involving systematic measurements, and observational, capturing historical and conditional details. Surveys may also rely on sketches, photographs, or descriptions without measurements. Traditional metric techniques, such as tape measures and total stations, suffice for simpler buildings, while major projects often require CAD drawings, which necessitate advanced skills, equally, hand-drawn illustrations which are valued for their flexibility and detail. The required LOD varies based on the survey's purpose, with historical drawings potentially lacking the precision needed for conservation. It can be argued, hand surveys foster a deeper understanding of structures but are labour-intensive. Modern techniques like LiDAR provide precise, efficient data collection without extensive access arrangements. Digital methods offer efficiency and accuracy but face challenges such as digital obsolescence. Combining traditional and digital approaches enhances conservation practices yet the cost is prohibitive. Regular inspections, such as quinquennial church surveys, ensure ongoing maintenance, often incorporating unmanned aerial vehicles for hard-to-reach areas. Effective asset management requires continuous review, for example facade materials, with decay mapping techniques assessing deterioration which LiDAR supports.

2.13 Digital and Heritage

LiDAR surveying instruments can capture enormous, accurate parametric and pictural datasets quickly with little or no impact on the material, the public or the surveyor, Vela et al (2010). In a second stage, the data is imported into software and aligned to form an accurate 3D accessible digital model as a record at the instance of capture. Although this is not the complete workflow to become invaluable further software is required to manipulate the model to clean, colourise, texturise, segmentise, or prepare for analysis. This data is invaluable in managing the asset according to Brumana et al (2017) where a digital model can be used to inform all stakeholders in decision-making for

the conservation process. This same model when used by the consultants can simplify access to data and link to information collected over the lifetime of the asset. The dataset includes additional quality information which when interrogated with the parametric and pictural data could provide a tool to aid the surveyor in monitoring the condition of the building and the conservation as Mezzino (2017). LiDAR can support before and after conservation interventions in heritage according to Vela et all (2010) providing the user with models for inspection which should be uniquely stored in the database for the asset. In the paper by Tang et al (2010), the discussion revolves around the extraction of a digital model from LiDAR data, being the smartest yet most accurate method for large assets. It is recognised, that this is a time-consuming exercise using highly skilled operatives with a high-cost point, further exacerbated by the operator-dependent variable quality. Whereas the software for point cloud development can include visualisation tools eliminating the need for surface representation stages in the data workflow.

In support of the use of LiDAR Haddad states, *"3D laser scanners (LiDAR) should … be considered as one of the most effective instruments in monitoring (3D monitoring)."* Haddad (2013, p.223) Even when low accuracy besets the data the large number of points makes for a good understanding of the surface therefore this should be the focus of technical and geodetic professionals. The point density is such that it can be considered a surface model, geometric information can be extricated in support of instantaneous decision-making, Fassi (2013). Surveys are generally fixated on immediate need, a reactive stance, not suitable when pursuing conservation principles to retain the fabric, wherever possible maintaining significance which infers a proactive approach. Moving forward to this research Bryan states, *"… laser scanning, can provide more complex, 3-D surface representations that, if performed regularly over a duration, can be metrically compared so that any perceived changes can be both quantified and digitally mapped."* Bryan (2009, p.25)

The captured data is accurate within the auspices of the resultant model coordinate system however some variable elements are impacting the data capture. Li and Cheng (2018) focus on the issue concluding the surface of the material is an integral variable for accuracy where some tribulations remain unidentified. The research addresses this issue by looking for change

rather than a definitive accuracy and use a range of data in 3D models to consolidate the solution. Zeibak and Filin (2007) consider a change for analysing deformations and asset evolution using terrestrial laser scanning data. The angle of incidence negatively impacts this possibility when considering the horizontal plane yet with vertical surfaces the opportunity to note change remains. Their work relates to the scan scenes from multiple locations in the same epoch but not the potential of campaigns separated in time. Moreover, in the vein of incident angle, Bosche et al (2015) suggest at the higher limits terrestrial scanners may struggle to identify areas of weathered fabric however this is not developed in the paper.

There are constraints with the proposal to use LiDAR, the strength of the information can be influenced by the instrument Tan and Cheng (2016) and Soudarissanane et al (2014) therefore, the product may have limitations and thus provide no additionality in pursuit of robust data on which to make the decisions. Others concur, Yang et al (2016) propose an automatic 3D building façade material recognition from images using photogrammetry as they consider laser scanners as expensive, delicate, unportable, and require skilled operators. Between solutions of photogrammetry and laser scanners are research conclusions promoting comparable outcomes in quality terms, yet there are distinctions for example cost of equipment, Hassan and Fritsch (2019).

To assemble the most complete 3D model, the requisite is to merge data from LiDAR and photogrammetry, especially from aerial systems Bianchi et al (2016), this limits the occluded areas especially at high level and top edges of details potentially at the expense of overall precision. The accuracy of LiDAR data is recognised, Temizer et al (2013) coupled with the speed of data acquisition and flexibility, conversely, they also acknowledge the limitations, especially in use. Photogrammetry is more likely to record accurately the edges whereas LIDAR is more capable of recording the surfaces, Blake (2007), de Oliveira Santos Junior et al (2012), which when linked with the potential accurate dense point cloud is the most appropriate. Photogrammetry requires ground control points to provide accurate metric data, Gonizzi Barsanti et al (2013), and is limited due to the need for consistent light conditions and in a similar vein to LiDAR by reflective surfaces, Bosche et al (2015). Yet the issue is bringing the two data sets together, at the junctions the overlap often leads

to disparate surfaces which need to be cleaned from the data. Brumana et al (2017) discuss the automatic extraction of boundaries from the 2D CAD drawings to identify weathering in fabric, comparison of these from alternate campaigns would generate an understanding of change. Furthermore, the inclusion of RGB images documenting the scene as detailed by the LiDAR instrument could be used with artificial intelligence (AI) to automatically identify and quantify weathering on stone material, specifically flora in the form of moss or lichens and plants such as buddleia.

Quality in the model is of paramount importance which is built on the capture of the data. The methodology has four facets impacting the excellence: the instrument, the environment, the scanned material and the location of the instrument, Alkan and Karsidag (2012). The surveyor has limited influence over the instrument accuracy as the parameters are set at the point of manufacture other than to ensure regular maintenance and calibration. The environment can to some extent be accounted for if only by excluding capture on days with weather conditions impactful on the data especially if beyond the instrument operating parameters. The material cannot be changed however the parameters, the qualities such as colour, texture of the surface, reflectiveness, dimensional stability etc. need to be accounted for. These should be considered in conjunction with the main addressable variables available to the surveyor being the location of, and the settings on, the instrument Tan and Cheng (2016). Alternatively, exceeding the required level of quality will add to the time appropriated for the capture of data potentially with additional travel, increasing the post-processing time and hardware requirement all increasing the cost and impacting the sustainability. In accepting the need to record before intervention, all drawbacks notionally prolong the disengagement with the monitoring, maintenance, repair cycle, extending the interval between the surveys again potentially leading to a loss in significance. Furthermore, there is a need to acknowledge the complexity of detail in building facades, for example, parapets, capitals or tympanum especially where carving decorates the element. In these locations the data capture should be extended to take account of the complexity, Barber et al (2006) through increasing the point density.

The model provides 3D dimensional accuracy, the data can reduce the risk to the historic asset, and proactive management based on sound knowledge and

information determines the need for a timely and appropriate intervention, especially at the surface level, for the repair of the material. The time and cost invested in gaining access would be reduced with an accurate, comprehensive texturised model, the information would allow replacement material to be cut and worked ready for insertion. Certain materials, for example terracotta, also known as faience, require moulds to be taken from the existing surface to manufacture a replacement. A 3D model could be used to produce a positive replica thereby allowing a mould to be taken and a replacement cast before the access provision is required. The risk to the asset of implementing a repair can be reduced by offsite premanufacture, and dismantling of areas, especially in the external envelope are often required early to determine the need for replacement. This leaves the fabric external and internal open to the elements favouring further damage therefore loss, premanufactured accurate replacement can be brought to effect immediate insertion thereby reducing the risk, Poirer, Staub-French and Forgues (2014).

The importance of the built heritage for the individual and the collective has been identified. Recognising this significance builds the argument for management techniques which retain the original fabric. 3D point cloud models are a recording technique for example in masonry facades. The accuracy of LiDAR data in generating these models is acknowledged as are the limitations. Historic England states "*… by repeating surveys, a stone carving can be monitored for its rate of erosion, which will assist the conservator in determining the appropriate protection*." Historic England (2018, p.1)

It is seen LiDAR surveying instruments can quickly capture large, accurate parametric and pictorial datasets with minimal impact on the material, public, or surveyor. These data are imported into software to create a precise 3D digital model, which, after further manipulation, becomes invaluable for managing heritage assets. The model aids stakeholders in decision-making and simplifies access to data throughout the asset's lifespan. LiDAR data supports conservation interventions, allowing detailed monitoring and comparison of changes over time, yet despite its advantages, it has limitations, such as operator-dependent quality and high costs. Combining LiDAR with photogrammetry can enhance data completeness, though it presents challenges in merging datasets. Overall, 3D point cloud models from

LiDAR provide crucial accuracy for proactive management and conservation of heritage assets.

2.14 Conceptual Framework

The conceptual model built from the literature review thus underpinning this research is structured around four fundamental pillars: Management, Asset Significance, Stakeholders, and Ethics/Policy. These pillars collectively ensure the effective and sustainable management of heritage assets. Within the literature review, the conceptual framework is delineated as the guiding structure for the study, outlining its scope, while the theoretical framework elucidates the interrelationships among its elements. According to Merriam and Simpson (2000), the conceptual framework serves as the foundational bedrock of the research, facilitating methodological development and steering the interpretation of findings. This framework not only identifies and defines key variables but also highlights their interconnectivity, which is crucial as these elements are deployed in subsequent research phases. Over time, the framework matures into a theoretical solution, culminating in a conclusion that directly addresses the research's objectives.

The literature review positions the conceptual framework as a means of setting intellectual boundaries and justifying the relevance of the research problem. The resulting model integrates heritage management within the UK context, focusing on asset significance, stakeholder engagement, and the constraints imposed by legal and ethical policies. This integrative approach ultimately advances a comprehensive strategy for sustainable heritage conservation, ensuring the preservation of cultural significance.

The conceptual framework (see Figure 14) as a tetrahedron marks out the key attributes within which is the digital model, to support the four stages of management. The model provides the data for decision making, the core of which is sustainability in pursuit of the conservation mantra. Proportionality is the inhibitor to determine the final content.

Ethics and Policy are the driver ensuring acceptability in behaviour, a moral compass incorporating individual, group, commercial and civil impacts and controls. Ensuring longevity of the asset through conservation principles to maintain and, where information/intervention reveals elevated prominence,

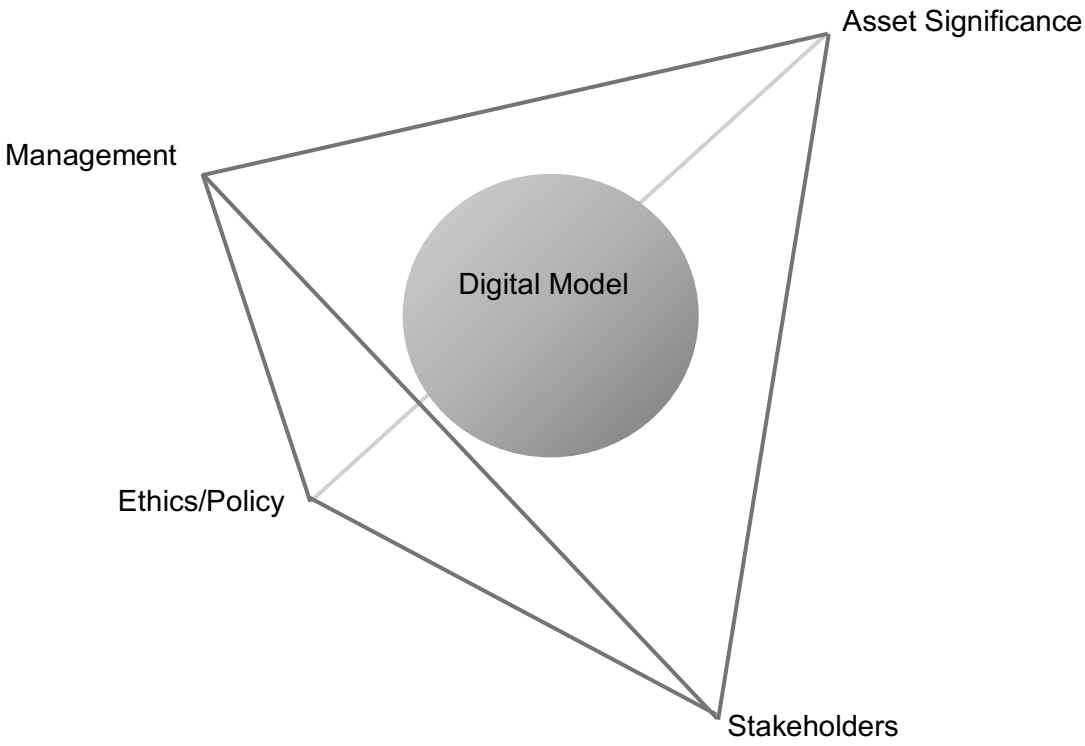

Figure 14 - The conceptual model for the management of heritage assets (Viewed in plan from above the Asset Significance sits at the centre of Stakeholders, Ethics/Policy and Management, rotate and the same occurs with the other three concepts) (By author)

augment significance in pursuit of sustainability. This influences all stakeholders and the asset development, hence the inclusion in all stages of the management decision-making process for strategic, intermediate, functional and for heritage projects emergent issues requiring instantaneous intervention. The policy in the UK is government-driven in Planning, Listing, Conservation and specific environmental requirements, Conventions, World Heritage Sites, Archaeological, etc. The ethical policy is for example dictated by the ICOMOS Ethical Principles for members as adopted promoting conservation, respect, sustainability, inclusivity, professionalism, collaboration, and objectivity ICOMOS (2014).

Stakeholders have been defined in detail in an earlier chapter comprising two elements involved and peripheral. The involved are directly linked to the management tree for example the owner, occupier, employee, contractor, surveyor etc. There may be some confusion in the crossover between management and stakeholders, however, in this discourse management is used as verb rather than noun. Within this thesis, management is the act of

managing applied to heritage i.e. employing management techniques to conserve and/or develop the asset sustainably retaining significance for stakeholder benefit into the future.

The term will also include local and national bodies such as Civic Societies or Historic England, Cadw, Historic Scotland for example. The UK Government has a stakeholder interest in Planning, Listing, Conservation and specific environmental requirements, Conventions, World Heritage Site, Archaeological, etc. which are enforced but generally adhered to by those involved. Alternatively, the peripheral stakeholders are visitors, local community, interested parties, schools etc. The definition is not limited to users as the heritage asset may be privately or publicly owned, accessible or not, yet has a societal benefit within and external to the community. For example, it can define a place, an industry or an artistic movement, a visual link to memory yet not embedded in a recent event. Hence, the definition of stakeholder is being sought to be inclusive as involved and peripheral.

The term "asset" is a deliberately chosen less contentious concept that comprehensively encompasses the heritage object, its associated site, and all intervening elements. The thesis begins by establishing clear definitions that form the foundation of the proposed framework. As the research progressed, it became evident that assets often reside in public ownership, integrated into various stages of societal life. Some assets may be restricted from peripheral stakeholder access, such as private residences. Others, like Nottingham Castle, allow access to peripheral stakeholders under specific arrangements. Additionally, certain assets, such as Newstead Abbey, are situated in open spaces where public access is constant, with public footpaths traversing the grounds.

At this juncture, ethical principles and policies safeguarding the significance of the asset must be uniformly applied to all stakeholders. However, in practice, it is the asset’s significance that emerges as the decisive factor, advancing towards a more inclusive understanding that incorporates both tangible and intangible heritage. This aspect of significance is most profoundly influenced by the interplay between stakeholders, policy, ethics, and management. The site, therefore, exists within the sphere of influence

dictated by the asset's significance, situating the asset firmly within this framework.

The proposed framework elucidates that the four key principles are well-supported, with the model at its core providing the necessary data to facilitate informed decision-making for the sustainable conservation of heritage assets. The conceptualisation of a rotating tetrahedron allows each principle or defined point to occupy the central position within the digital model, while the remaining three principles align in a triangular formation, continuously feeding into the model. This dynamic structure supports all four stages of asset management—strategic, intermediate, functional, and emergent—by effectively integrating stakeholders with the asset, particularly its significance, within the boundaries of ethical and policy considerations pertinent to heritage management.

This research is structured around a conceptual model comprising four key pillars: Management, Asset Significance, Stakeholders, and Ethics/Policy. These pillars collectively guide the effective and sustainable management of heritage assets. The conceptual framework served as the foundation of the study, setting its intellectual boundaries and justifying the research problem, while the theoretical framework elucidates the interrelationships among its elements. This framework facilitates methodological development and interpretation of findings by identifying and defining key variables and highlighting their interconnectivity.

The empirical backbone of this study is grounded in action research conducted through detailed case studies, which complement the theoretical insights derived from the literature review. This approach underscores the importance of legal and ethical principles in heritage management, shaping the framework's development. The research involves iterative revisions in data collection and model construction to adapt to emerging insights, promoting a more investigative and adaptive approach.

The proposed conceptual framework integrates UK heritage management, focusing on asset significance, stakeholder engagement, and ethical and legal constraints. It emphasises a comprehensive strategy for sustainable heritage conservation, guided by ethical principles such as those outlined by ICOMOS, and includes all stages of management: strategic, intermediate, functional,

and emergent. Stakeholders, including involved and peripheral groups, play a crucial role in this process, with their engagement influencing management decisions and asset development.

The framework employs a rotating tetrahedron model to illustrate the dynamic interrelationship of its principles, supporting informed decision-making for sustainable conservation. This model ensures that all aspects of heritage management, from planning to implementation, are underpinned by ethical and policy considerations, enabling a holistic approach to preserving cultural significance.

2.15 Summary

Fabric retention is important in the historic built environment to maintain the significance thus upholding the value to all stakeholders. To support the management, especially when intervention is required the heritage practitioner records the asset condition as a reactive measure, the majority utilise photographs, sketches, and manual metric techniques. The objective of this section was to investigate the current research available in the areas of heritage management, heritage data, digital recording, contextual frameworks and surveying of heritage building fabric especially where this crosses into the retention of significance. Current research falls short in not investigating and presenting an appropriate accurate system for fabric monitoring overtime which could bestow a proactive solution to reduce inappropriate intervention.

Heritage is essential for individual and collective identity, influencing our present and future. The ICOMOS Venice Charter (1964) highlights the duty to preserve the authenticity of historic monuments for future generations. Digital models offer cultural preservation potential but face challenges such as limited physicality and public engagement. Heritage façades are significant in collective memory and urban experience, requiring careful management to maintain their significance and avoid inappropriate interventions. The degradation of heritage materials, exacerbated by climate change, natural elements, human actions, and poor maintenance, highlights the need for proactive management. This involves understanding the form, materials, history, and significance of heritage assets.

Effective heritage management includes routine maintenance, accurate surveys, and context-informed decision-making, balancing stakeholders, legislation, and systems to emphasise asset significance and sustainability. BS 7913:1998 outlines conservation principles aimed at preserving historic buildings for societal benefit. Digital solutions like BIM facilitate decision-making and data management, enhancing conservation strategies and aligning with SDGs and the NPPF.

Technological advancements in ICT have improved heritage data management, storage, and dissemination, fostering dynamic and interactive engagement with cultural heritage. Digital models, including LiDAR and photogrammetry, enhance the accuracy and completeness of heritage documentation. However, challenges in data integration, consistency, and standardisation remain. Combining traditional and digital approaches can improve conservation practices, though costs are significant.

Frameworks for heritage management must be detailed and dynamic, supporting day-to-day management and strategic planning. These frameworks advocate for advanced digital records, accurate data, and robust management plans to address changes. Historic England and other organisations stress the importance of knowledge-based decision-making and comprehensive data for asset management. A Decision Support System enhanced by the Theory of Change promotes continuous revision and improvement, integrating policy changes and contextual factors for effective strategy relevance.

The conceptual framework driven out of the literature review, built on four key pillars: Management, Asset Significance, Stakeholders, and Ethics/Policy. Ethics and policy serve as guiding principles, ensuring sustainable, inclusive, and legally compliant practices. Stakeholders are classified as involved (e.g., owners, contractors, government bodies) and peripheral (e.g., visitors, local communities), both playing essential roles in the conservation process. The framework promotes strategic, intermediate, functional, and emergent decision-making, applying ethical standards such as those of ICOMOS to uphold significance and sustainability. The term "asset" is deliberately used to encompass tangible and intangible heritage, avoiding ambiguous terminology. The rotating tetrahedron model illustrates the dynamic

interrelationship of the four principles, enabling a flexible, data-informed approach. Overall, the framework advances a comprehensive, ethical, and stakeholder-inclusive methodology for managing and conserving heritage assets across diverse contexts.

The literature emphasises the need for flexible, comprehensive frameworks that incorporate diverse perspectives and expertise. Digital technology's role in contemporary society, especially in the construction industry with BIM, transforms project management and fosters sustainable building practices. Integrating digital models in heritage conservation aids in maintaining historical structures, facilitating informed decisions, and supporting sustainable management. This approach balances utilisation and preservation, ensuring the retention of heritage significance while adapting to evolving challenges.

Chapter 3.0 Research Methdology

3.0 Introduction

The purpose of this chapter is to substantiate the methods employed and elucidate how they coalesce within the overarching methodology to support the research objectives. The framework outcome necessitates a qualitative approach that stands in contrast to the quantitative resolution. Social research, with its multifaceted nature, is particularly well-suited to the study of heritage subjects, as it incorporates diverse perspectives on the world, eschewing a singular viewpoint in favour of an interpretivist stance. Additionally, the outcomes of such research are inherently debatable, contingent upon the evaluator's beliefs and preferences, which in turn influence their acceptance. Nevertheless, a shared understanding provides a foundation upon which to build further insights into themes such as purpose, relevance, design, accuracy, and originality. This chapter will critically examine the research design to justify the methods employed, emphasising their alignment with the study's objectives and their contribution to the overall integrity of the research.

The interpretivist approach acknowledges the subjectivity inherent in social research (Pervin and Mokhtar, 2022), embracing the complexity and variability of human experience. The researcher's trajectory - from the outset of the study, through the empirical phase, to the analysis stage - plays a pivotal role in shaping the development of the research and the conclusions drawn. Consequently, critical questions must be raised to interrogate the *who*, *how*, and *why* of this interpretation, ensuring that its persistence is well-understood. This approach aligns with a relativist perspective, wherein the researcher’s position inevitably influences the interpretation, giving rise to a nuanced outcome. Such a stance not only reflects the complexity of the issues at hand but also facilitates a more profound understanding of the subject matter. By adopting this methodology, the research captures the multifaceted nature of heritage studies, allowing for a richer and more exhaustive exploration of its complexities. Through this lens, the chapter will articulate the rationale behind the selected methods, demonstrating their suitability and effectiveness in addressing the research questions and contributing to the broader discourse within the field.

The methodology has progressed through a transformative evolution, transitioning from the initial focus on practical advancement and testing of strategies from tangible projects to a more sophisticated and analytically driven application of theoretical frameworks in concluded case study projects underpinned by stakeholder support. Within this progression towards an elevated academic rigour, typified by a subtle distinct exploration of theoretical foundations and their practical implications. Such an approach enhances the depth of academic understanding whilst fostering a wide-ranging integration of theory and practice to enrich the discourse around strategic decision-making in sustainable heritage management.

Considering development of frameworks, the methodology is grounded using the literature review and advanced through empirical examination utilising three case studies in an iterative process analogous to action research in developing understanding. The subjectivist inductive approach as found in this research utilises the gathered data to develop and process the theory from that data in constructing the framework. Furthermore, the theory should be considered flexible undergoing refinement, the shift taking place in the researcher and/or the research. In this situation, the theory can develop out of the research, be a major component in forming the research or be exploited in interpreting/analysing the data to conclude.

At the data capture stage exploring the use of instruments capable of millimetre accuracy has determined a workflow to build parametric models which will morph into the data repository. The HER, Historic England's or Cadw's Listed Building records, Local Lists and Pevsner, or similar texts, being part of the current dispersed repository, linked to local maps often in library collections and served using the notes of the local authority conservation officer to limit the proposed building improvements. In this endeavour, the case study of Nottingham Castle Ducal Palace from inception to reinvention as a municipal gallery and museum found important plans, detailed construction information and historic records in repositories across Nottinghamshire. This data needs to be located in a federated model, either directly or indirectly using linked web-based files, built on the parametric data, a single source of truth, efficiently and effectively accessed and searched, a usable framework for the stakeholders.

Grounding in qualitative methods enables a comprehensive exploration of heritage as a multifaceted subject, beyond the limitations of binary outcomes, thus facilitating nuanced inquiry. The social research approach, employing open-minded self-realisation, recognises potential biases, allowing participants to maintain the necessary level of objectivity. This methodological structure is robust yet acknowledges the inherent influence of the researcher's subjectivity. Complete objectivity is unattainable, but recognising this bias fosters an ethically sound and honest approach, appropriate for the heritage theme. An open-minded researcher can thus effectively investigate all aspects of sustainable heritage, ensuring that the management of assets retains their significance. This approach not only ensures thorough analysis but also enhances the ethical integrity of the research, aligning with the complexities of heritage studies. The objective is not to overlook nuance, but to encompass the fullest range of viewpoints, thereby enhancing objectivity and reducing bias.

Heritage, specifically assets are complex structures containing multiple materials and technologies, designs, structures, scales, qualities, which are then elevated by the stakeholder's embrace to positions of monuments. An interdisciplinary approach allows a greater range of themes to be explored, for frameworks to operate at a multitude of levels and captures ranges of data to solve the research problem. The inclusion of the stakeholder adds a social dynamic which is at one with the subject, heritage, the sustainable requirement, the research stance and the imbued significance. As will be seen as the methodology develops, the stakeholder takes a role in the development of the final framework.

Advancing the discourse in social research, three additional domains where the solution aligns with the heritage theme are identity, memory, and social justice. Heritage significantly shapes identity, fostering social cohesion and national identity. Embracing all stakeholders, including those on the periphery, strengthens the case for research by presenting a robust framework. Heritage has the power to invoke, preserve, and maintain memory, a cultural construct that social research aims to address. This argument extends to social justice, where heritage plays a critical role in promoting inclusivity and equity. Grounding the research output in policy and governance is essential, necessitating a thorough evaluation and a

comprehensive literature review to contextualise the heritage situation. This rigorous approach ensures that the research is methodologically sound and relevant to contemporary societal needs.

Social research in heritage increasingly relies on digital technology to meet fundamental requirements. Upholding society's cultural needs is paramount, and digital platforms offer inclusivity and equity by engaging diverse audiences. However, it can be argued that these advancements may marginalise individuals without access to digital mediums, alternative methods of engagement may be necessary to maintain inclusivity and address the digital divide. Alternatives to the social construct may have currency in alternative themes yet in heritage appropriateness would be difficult to justify.

3.1 Case Studies

Beyond the initial literature review, the first proposed method is case studies, which are excellent for examining existing conditions, Denscombe (2010). These studies provide a deep understanding within a narrow construct, requiring intellectual analysis of a small sample to identify causal or influential impacts on other elements, thereby defining links between observed themes. Although variables can become unwieldy, a clarified theoretical framework helps to focus the analysis. Case studies are valuable for investigating practical issues, solving research problems, and proposing changes to improve situations, Naoum (2013). Solutions derived from this approach must be both original and practical, ensuring their relevance and applicability. This philosophy embodies a critical realist stance, distinguishing world experience from factual and empirical knowledge, Emuze (2016). However, the inherent complexity in such studies can obscure the problem, potentially disadvantaging the framework.

On the other hand, the broader research methods often miss nuances which are key in the phenomenon being investigated, whereas the case study can provide rich, contextual insight. Heritage assets as complex, physical entities with many unique elements are ripe for this approach. Empirical data builds on the themes highlighted in the literature review to provide theoretical advancement in the framework.

Flyvbjerg identifies five common misconceptions regarding the inclusion of

case studies, notably the belief that "… *theoretical knowledge is more valuable than practical knowledge: …*" Flyvbjerg (2006, p.219) and that generalisations cannot be derived from a single case study. However, context-dependent knowledge fosters stakeholder development towards expertise, exemplified in the paper's central argument that true expertise is attained through the practice of relevant skills. The nuanced understanding of reality and proximity to real-life situations, combined with extensive details, create a rich learning environment. Strategically selecting a case study can significantly enhance outcomes, and theories can be rigorously tested, particularly when employing more extreme instances. This approach demonstrates the profound value of case studies in advancing practical and theoretical knowledge.

The method employed to gather diverse evidence is multifaceted, enabling a holistic perspective through empirical investigation. This comprehensive approach considers social, historical, cultural, and economic factors, among others. Comparability between examples can detect commonalities and distinctions for research development. Patterns emerging from this data can establish a foundation for the framework or guide future research. However, complexity of the data may generate obscurity, it may challenge the investigation's clarity and effectiveness, necessitating refined analytical techniques to maintain robust and meaningful insights.

Employing empirical investigation in case studies can prove invaluable, offering illustrative examples accessible to a broad range of stakeholders. The practical relevance of real-world situations ensures the outputs are both tangible and functional for heritage professionals and policymakers. Engaging stakeholders fosters a participatory approach, thereby enhancing the richness and depth of the research. This method not only augments the credibility of the findings but also promotes collaborative, informed decision-making within the heritage sector. Enhancing the investigation through longitudinal methods in single or multiple case studies offers depth, though the extended timeframe can be a drawback. Nevertheless, this approach provides valuable opportunities for future research endeavours, potentially uncovering greater insight.

The case study method possesses elements that may render it less desirable. Its specific nature can challenge the application to other contexts; however,

in this investigation, the resulting framework will incorporate flexibility. The inherent complexity of case studies often leads to limited campaigns, restricting data capture and hindering a nuanced understanding of processes. The interpretive nature of case studies may introduce bias, thus compromising the reliability of findings, Priya (2020). Additionally, the empirical approach demands substantial time for data collection and collation, particularly in multiple investigations, which can strain resources.

The rich data generated by case studies presents analytical challenges that require advanced skills. The researcher's proficiency in empirical data collection, especially with technical instruments, is crucial for ensuring high-quality research output. Case studies are sometimes perceived as anecdotal and lacking academic rigour, particularly if the structure is unsystematic or the data quality varies. This perception can undermine the robustness of the research. Moreover, the difficulty in replicating case studies challenges verification through repeated studies.

The descriptive nature of case studies can impede analysis and theoretical contribution, further detracting from the perceived rigour of the research. Addressing these issues necessitates careful methodological design, rigorous data collection, and a clear analytical framework to enhance the study's validity and reliability. Overcoming these challenges ensures that the case study method contributes robustly to academic discourse and practical applications.

Case studies are beneficial for examining existing conditions, providing deep insights into narrow constructs, and identifying causal impacts, but their complexity can obscure issues. They offer practical solutions and theoretical advancements, crucial for nuanced, context-dependent knowledge suitable for the heritage asset management. The multifaceted empirical investigation includes social, historical, cultural, and economic factors, enhancing research richness and stakeholder engagement. However, case studies' specificity, potential biases, and substantial time demands challenge their applicability and perceived rigour. Effective methodological design and advanced analytical skills are essential to overcome these challenges, ensuring the method's robustness and contribution to academic and practical knowledge.

3.2 Action Research

The second method is Action Research, a well-established approach in construction practice renowned for its emphasis on continuous improvement and sustainability. This approach influences not only the resultant solution but also the epistemological insights acquired by the researcher taken forward to future problem solving. Action Research, with its reflective nature, inherently biases the methodology towards qualitative techniques; however, data collected from questionnaires will guide the design of the research framework. This dual-method approach ensures a comprehensive understanding of the problem by leveraging qualitative insights.

This research examines and defines the shortcomings of current conventions in building management, particularly within the context of heritage assets and significance. Best practice has been identified in the literature review to ground the research, building on the case studies the action research will develop the solution, thus the study will identify best practices before exploring alternative solutions. This method is particularly effective for practical problem-solving within specific contexts, allowing researchers to develop and implement solutions in real-time while observing the immediate effects of these interventions, Naoum (2013).

The construction industry exemplifies Action Research in practice, wherein situations and solutions are iteratively implemented, assessed, and refined. Each scenario is inherently distinctive - a confluence of individuals, organisations, challenges, geographical contexts, materials, resources, operational formats, and external influences. These variables exert asymmetrical pressures, from which context-specific solutions emerge. While such solutions may initially be deemed successful, their continued evaluation over time fosters a more nuanced understanding of their long-term efficacy. The researcher, operating as a seasoned professional within the field, adopts a pragmatic, hands-on approach that aligns closely with the investigative ethos of Action Research. This methodology enables a rigorous exploration of optimal solutions, with an emphasis on quality, durability as a benchmark of excellence, and sustainability as a guiding principle. Thus, the journey of the researcher through the case studies will impact and the sought solution will play to the strength, mindful of the bias and seeking objectivity in the analysis

veering away from simplification to embrace the most effective and superior synergistic solution. Consequently, engagement with each case study not only provides the empirical data building into the framework but additionally reflects a conscientious negotiation of subjectivity, striving for academic rigour in pursuit of the most contextually resonant and synergistically effective outcome.

Heritage assets, being tangible and historical entities, are ideally suited to the Action Research methodology. The core principle of this approach, often referred to as the Problem-Solving approach, is to address the limitations of current practices in managing heritage buildings. The integration of LiDAR data collection and utilisation is posited as a potential solution to these limitations. Although the intended outcome is improvement, the possibility of reverting to the status quo remains, particularly in the delicate balance of managing the significance of monuments.

A notable strength of Action Research is its emphasis on participant involvement and collaboration in framework development, which aligns well with the nature of heritage asset management. This inclusive approach not only enhances sustainability but also ensures that the research is grounded in real-world experiences, providing relevant and practical solutions to the identified problems, Scott (2016). Embedding the research within the heritage context and adopting a problem-solving approach ensures that the outcomes are not only effective and relevant but also beneficial from the outset. The researcher, through this immersive process, gains valuable insights and experiences that drive further exploration and understanding of the topic.

Action Research is inherently iterative, allowing for incremental improvements on core themes. Each small step can yield significant benefits, and the flexibility of the approach allows for adjustments and exploration of alternative solutions as new insights are gained. The cyclical nature of action, observation, reflection, and recording provides a structured yet adaptable framework for the research, allowing sufficient time for thorough study and analysis, Scott (2016).

Furthermore, Action Research bridges the gap between theory and practice. By applying theoretical concepts in real-life contexts, researchers can observe

tangible outputs that advance both scholarly understanding and practical implementation. This method is particularly advantageous in heritage contexts, where the benefits are not only perceivable but often replicable, providing a robust framework for ongoing improvement and sustainability.

Ultimately, Action Research serves to deepen the learning process by heightening the cognisance of the research team, thereby furnishing a more robust epistemic foundation upon which to critically appraise potential solutions. Moreover, the strategic application of this emergent knowledge in planning subsequent iterations introduces a dynamic quality to the investigative process, enabling the experiment to evolve in a manner that sharpens the focus of inquiry. Each phase of the case studies incorporated evaluative input from the principal investigator, the wider research team, and a diverse array of stakeholders. Feedback was solicited from individuals such as modellers, planners, students, academics, property owners and occupiers, as well as historians and archaeologists, among others. This input was gathered through both formal and informal channels, including organised events, structured meetings, and spontaneous interactions. Such feedback not only informed the development of outputs but, in keeping with the ethos of Action Research, also influenced the trajectory of the investigation and contributed to the synthesis of knowledge acquired by the researcher.

While there are compelling arguments for Action Research, several adverse elements must be acknowledged. The dearth of contributory research employing this method may be interpreted as corroborating the assertions, Levin and Greenwood (2011). The participatory nature of this methodology, as observed in case studies, can introduce bias, thereby affecting objectivity. To mitigate this, researchers should employ consistent behaviours and maintain a resolute stance. The context-specific nature of Action Research may limit the adaptability of solutions and results to other situations. However, developing a comprehensive framework can counteract this limitation by reintroducing a broader perspective.

The iterative cycles inherent in Action Research are resource-intensive, requiring substantial commitment from participants. Despite this, the resultant rich data can provide unique insights and innovative solutions. The complexity of this rich data presents challenges in analysis, as diverse

qualitative data demands significant skill from the research team to distil valuable output. Additionally, the collaborative nature of Action Research can lead to conflicts that hinder progress and outcomes.

The dynamic nature of Action Research may affect the clarity and coherence of the thesis due to difficulties in systematic documentation and reporting. This challenge is exacerbated by the dual role of the researcher as both observer and participant, which can impact the credibility of the research and pose difficulties for those involved. The specificity of the context, subject, and stakeholders leads to variability in outcomes, making replication challenging and potentially marginalising the benefits to heritage assets.

In summary, Action Research offers a dynamic and collaborative approach to tackling complex problems in heritage asset management. By involving stakeholders in the qualitative methods, and allowing for iterative improvements, this methodology ensures that the research is both rigorous and practically relevant, ultimately contributing to the enhancement of building management practices in heritage settings. Ensuring that academic standards are met is crucial to overcoming the challenges. Researchers must strive to maintain rigorous documentation, clear communication, and a balanced approach to manage the complexities and enhance the robustness of Action Research in heritage asset management.

3.3 Case Studies with Action Research

Utilising case studies in conjunction with action research in an iterative process provides a robust solution grounded in real-world conditions. In the nuanced, multifaceted realm of heritage, particularly in sustainable asset management, rich contextual data is invaluable. The amalgamation of case studies and action research offers context-specific insights, producing grounded findings that satisfy asset stakeholders, whether they are professionals, policymakers, skilled practitioners, or members of the public.

Integrating the conceptual framework with case studies and the practical implementation of action research creates synergistic solutions that are both practical and academically sound. The iterative learning inherent in this approach enables cyclical reflection and adaptation, gradually advancing towards robust outcomes informed by comprehensive insights from case

studies. This combination offers a holistic understanding, capturing the detailed narratives from case studies and the dynamic processes of action research.

The reliability and validity of the research are enhanced through the convergence of data from case studies and action research, addressing potential biases and adding robustness. Additionally, the participatory nature of action research, coupled with in-depth analysis, promotes greater stakeholder engagement, thereby enriching the research.

Given the complexity of these methods, the practical nature of action research, informed by the detailed insights of case studies, can facilitate innovative, context-specific solutions. The conceptual framework can dynamically evolve into a theoretical framework through continuous refinement. This process would yield comprehensive documentation as the multifaceted outcomes of the case studies are developed through iterative action research.

Ultimately, the integration of case studies and action research not only fortifies the methodological framework but also ensures that the research remains relevant, reliable, and impactful, Dey et al (2015). This approach cultivates a deeper understanding of sustainable asset management within heritage contexts, advancing both academic and practical knowledge. However, the intricate details inherent in this methodology may present challenges. The complexity of the data can obscure the narrative, rendering the framework unwieldy or overly specific to the case studies. Resource constraints, particularly in terms of time, could hinder the completion of the research, while the intensive management required might leave the study underdeveloped. These issues could compromise the credibility of the findings, undermining both academic and practical contributions.

Nevertheless, some of these challenges can be mitigated through triangulation of the outputs. Triangulation dispels bias and transforms the anecdotal nature of case studies into more analytical insights through repetition. By addressing these methodological concerns, the research can maintain its robustness and contribute valuable, actionable insights to the field of heritage asset management.

In summary, the flexibility and adaptability inherent in combining these methods allow for adjustments to changing conditions and emerging insights, thereby maximising the impact on both academic discourse and real-world application. The complexity of detailed, narrative-driven perspectives from case studies, combined with the iterative nature of action research, provides an opportunity to revisit and holistically view the research problem.

3.4 Research Design

The objective is to observe and assess current practices, propose enhanced methodologies, evaluate alternatives, and develop a framework for stakeholder consideration. Conversely, quantitative research necessitates a substantial, readily accessible sample to substantiate binary trends, which is not feasible in the heritage context. A pragmatic approach leverages case studies in the iterative process of action research to develop a framework for sustainable management of heritage assets. This framework supports the administration of the significance in determining potential interventions or continued monitoring as a proactive management strategy. This method capitalises on the rich, context-specific insights provided by three case studies in making it highly suitable for the nuanced requirements of heritage stakeholders. See Figure 15 for the flow diagram based on McNiff diagram "*A generative transformational evolutionary process*" McNiff (2013, p.66).

The methodology, as supported by McNiff (2013), involves an iterative, action-research framework applied across three distinct case studies: Arkwright, Hawara, and Nottingham Castle. This cyclical process integrates Geometric Data collection and analysis, emphasising reflection and refinement to progressively build expertise and enhance subsequent research efforts. Alongside each case study is the historic data capture used to support understanding of the asset and specifically the significance resulting in the Ducal Palace timeline.

The research design commenced with a comprehensive literature review, which was not only foundational but continued throughout the empirical research phase. This dynamic interplay between theory and practice allowed the literature review to evolve alongside the empirical findings, ensuring that the research remained well-informed and theoretically grounded throughout.

Each case study followed a structured campaign involving plan, action, observe, and reflect on Geometric Data. The iterative nature of this approach meant that insights gained from earlier campaigns directly informed the subsequent ones, creating a continuous learning loop. For example, the knowledge and skills acquired during the Arkwright Case Study were instrumental in refining the methods used in the Hawara and Nottingham Castle case studies thereby following the Action research method.

In the Nottingham Castle case study, five distinct campaigns were conducted: two pre-intervention, one during the intervention, and two post-intervention. These iterations were not static but were actively shaped by the principles of action research. Each campaign was a deliberate attempt to enhance the process through iterative reflection, refining methodologies, and improving data capture techniques at each stage.

Action research was not limited to high-level campaign planning but extended into the minutiae of each case study. For instance, the researcher engaged in continuous decision-making to optimise data collection methods, adjusting equipment settings, and refining post-processing techniques. This recursive approach, particularly evident in the Hawara Case Study, proved crucial for generating robust, actionable knowledge.

Ultimately, the cumulative effect of these action research cycles led to the development of a Quality Model framework. This model emerged as a culmination of the lessons learned and refined through numerous iterations, ensuring that the research outputs were not only theoretically sound but also practically valuable to stakeholders.

Case studies as explored in Section 3.2 offer deep insights and practical solutions but can be complex and time-consuming. Methodological rigour and advanced skills are vital for ensuring their effectiveness. Defined as a pragmatic study into a current phenomenon existing in an everyday setting, the case study is especially powerful where there is congruence between the situation and the context. The strategy involving three sites provides elements of similarity and dissimilarity as the basis for robust investigation. Coupled with the iterative improvement of the action research workflow for the repeat operations seeks to eliminate variables to focus on elements which are most likely to provide the solution.

The case study based on accrued data will exemplify the appropriate/inappropriate in the method supporting the dual purpose of finding answers to practical difficulties and augmenting theoretical/conceptual knowledge, Case studies are generally considered as a qualitative method providing confined schemes with time bound multistrand data for analysis. The proposed data analysis will identify the method and limitations in application thereby proposition to the stakeholders. This pragmatism identifies and understand the problem in the broadest context, before providing the most appropriate solution. The removal of the linear study utilising action research allows flexibility thereby transitioning to the method achieving the most robust design for real world problems. The inductive, bottom-up approach allows the exploration of the assembled data from the scanning campaigns be it RGB, intensity or metric within a media.

Action research explored in Section 3.2 emphasises continuous improvement and sustainability, combining qualitative methods with stakeholder feedback data to develop a comprehensive research framework. The framework addresses shortcomings in heritage building management practices, offering practical, real-time solutions and integrating innovative techniques like LiDAR data collection. Central to this method is participant involvement and collaboration, ensuring research is grounded in real-world experiences, providing relevant solutions, and enhancing sustainability. Despite its resource-intensive nature, action research bridges theory and practice, although challenges in objectivity, documentation, and replicability remain.

Finally, in Section 3.4 integrating case studies with action research provides a robust, iterative solution grounded in real-world conditions, essential for sustainable heritage asset management. This approach offers context-specific insights, enriching stakeholder engagement through participatory methods. The combination of detailed narratives from case studies and the dynamic processes of action research enhances reliability and validity, ensuring a relevant, impactful research framework. Despite challenges in complexity and resource constraints, triangulation mitigates bias, transforming anecdotal data into analytical insights, thus contributing valuable, actionable knowledge to sustainable heritage asset management.

The digital model output from the case study—whether point cloud, meshed, photogrammetric, raw, or processed—will be thoroughly examined to identify the most appropriate processing method. A 'goal-free' evaluation facilitates the description of actual effects rather than imposing a theoretical stance, thus allowing the research to explore a wide range of possibilities within the collected data. This approach, devoid of predetermined goals or specific outcomes, enables a comprehensive examination of data for real changes and the attribution of variations to specific weathering typologies. While the primary objective involves using LiDAR data for proactive heritage asset management, the method of achieving this remains flexible. Critics argue that the absence of clear goals complicates organisation and innovation; however, this freedom may reveal the most suitable methodology, minimising tunnel vision. The ultimate intention is not merely to fulfil the initial proposition but to assess LiDAR's efficacy in managing heritage significance, yielding practical outcomes beneficial to stakeholders in maintaining asset significance.

Action research necessitates an iterative process, which is supported by the utilisation of multiple case studies. In one of the case studies, composite campaigns will allow for repeated processes at the same location, revealing subtle nuances. While certain elements of the case study are intentionally repetitive, specific requirements may evolve, adding real-world pragmatism. The selection of case studies has been meticulously considered to maximise experiential understanding. The imperative to remotely capture data, independent of physical presence at the campaign, underscores the pragmatic challenges within heritage contexts. Likewise, heritage managers frequently depend on geotechnical experts without a full grasp of their needs or the potential outcomes.

Exploring alternative processes can enrich the framework by introducing additional methodologies and improving conceptual clarity. Consequently, the range of experiential understanding is enriched through the diversity of case studies. This comprehensive approach not only supports the iterative nature of action research but also ensures that the findings are grounded in real-world applications, ultimately advancing both theoretical and practical knowledge in heritage asset management.

Taking this a stage further, pragmatic research necessitates determining the suitability of the solution within the context of the conservation community. To test this, it is proposed to utilise the output of a short questionnaire with stakeholders and examine the resultant data providing understanding of the appropriateness and potential improvement in the given situation. In the action research proposed feedback from the stakeholders will provide rich data to uphold the research direction or to make adjustment for improved application.

In one case study, multiple campaigns are undertaken, implying a longitudinal approach. However, this assumes a linear progression from start to end, despite the unpredictable nature of events. The presence of variables across campaigns provides an opportunity for comparing model outputs and conducting evaluations. To maintain authenticity and robustness, it is proposed to minimise research variables by maintaining certain features as constants throughout data campaigns. Where this is impractical, such limitations are acknowledged and documented. The objective is to mitigate constraints and establish a method that is reproducible, facilitating the assessment of material changes over time and their implications for managing asset significance.

While the nature of campaigns precludes exact duplication, the consistency in workflow and data transformation into models reduces the necessity for replication. The accuracy of the data in subsequent campaigns will be pivotal in effectively applying the proposed methods. An ongoing challenge lies in the manual effort required for result interpretation by professionals. Although transitioning to semi-automatic processes using artificial intelligence is a recognised industry aspiration, it falls outside the scope of this research, highlighting potential avenues for future investigation.

This study aims to observe and evaluate current practices in heritage asset management, proposing enhanced methodologies and assessing alternatives to develop a stakeholder-oriented framework. Utilising case studies within action research allows for iterative improvements and addresses the nuanced challenges of heritage management. The integration of qualitative insights from multiple case studies enhances the robustness of the research, offering practical solutions and advancing theoretical understanding. Despite the

complexity and resource demands, this approach bridges theory and practice, enhancing sustainability in heritage management. Triangulation of data mitigates biases, ensuring reliable and impactful outcomes. Furthermore, the study explores the digital modelling of heritage sites, emphasising a 'goal-free' evaluation to explore various data possibilities. The pragmatic inclusion of stakeholders through feedback mechanisms enriches the research direction and application. This comprehensive methodological approach not only supports iterative research cycles but also contributes to the advancement of theoretical insights and practical applications in sustainable heritage management.

3.5 Empirical Research

There are three case studies proposed which offer varied understanding, the Arkwright Building at Nottingham Trent University city campus, the Hawara pyramid, Fayoum in Egypt and the Nottingham Castle Ducal Palace. Being part of the campus, the Arkwright case study was situated locally, ensuring ease of access and a clearly defined event chronology, thus rendering it a convenient and pragmatic choice. It may be regarded as a pilot study, facilitating preliminary testing of the conceptual framework and enabling the generation of outputs with minimal associated risk. Contingency measures, including site revisitation in the event of unforeseen complications, were readily achievable. The building in question holds a Grade II listing, signifying its status as a heritage asset, and has recently undergone comprehensive refurbishment.

The Nottingham Castle research initiative employed a purposive and convenience sampling strategy, catalysed by seed corn funding provided by the Centre for Architecture, Urbanism and Global Heritage (CAUGH) to facilitate the exploration of emergent research opportunities. This aligned strategically with a longstanding objective of Nottingham City Council to enhance the public offer at the Castle and address a persistent maintenance backlog - an ambition that had remained on the council’s agenda for many years.

To operationalise the project, the authority consented to lease the site to an independent trust, thereby enabling access to third-party funding streams. The initial seed corn investment supported a comprehensive investigation into

digital modelling methodologies, encompassing the site's transformation as an heritage asset including detailed interior elements and the roof topography.

Concurrently, archival materials were systematically examined to construct a chronological narrative of the Ducal Palace's engagement with the site—from its inception and active use, through phases of deterioration and subsequent refurbishment, culminating in its adaptation as a gallery space. As the project evolved beyond the initial funding phase, the council facilitated access during the preliminary archaeological survey, while the Y Trust—established as the managing entity—continued to support research activities following the building's refurbishment.

The site's location within the city of Nottingham afforded logistical advantages, notably ease of access and minimal travel time, thereby reinforcing its suitability for convenience sampling.

Following the conclusion of the seed corn funding phase for the Castle project, CAUGH secured a subsequent grant which incorporated digital modelling of the Hawara pyramid, Fayoum, thereby introducing an international dimension to the research. This remote case study, characterised by greater complexity than the two preceding local investigations, served as a valuable context for advancing methodological inquiry - particularly in relation to the deployment of geospatial targets, the specification of data capture protocols, and the operational dynamics of remote collaboration.

The acquisition and analysis of historical data for the pyramid were facilitated by collaborating investigators within the funded consortium. The project's timeline proved conducive to the overarching research trajectory, with its outcomes integrating effectively into the compilation of the thesis.

It is essential to reassert the centrality of the Action Research aspiration underpinning this investigation. The triangulation of the three case studies—each offering rich, contextually embedded data - affords a robust platform for examining the phenomenon of interest. The convenience sampling was further justified by the temporal alignment of the projects, which enabled the iterative cycles of planning, action, observation, and reflection that are fundamental to Action Research methodology.

The Arkwright project started the cycle followed by Phase 1 Nottingham Castle

(Permanent Art Gallery), Phase 1 Hawara Pyramid (data capture and modelling), Phase 2/3 Nottingham Castle (exterior/archaeology), Phase 2 Hawara Pyramid (Project close out/seminar), Phase 4/5 Nottingham Castle (post-refurbishment exterior/temporary gallery).

Returning to the Arkwright Building façade data was collected over two days, reflected in the quality of the data. The Hawara pyramid data was collected by a 3rd party using a particular methodology which will need analysing. A visit to the site determined an alternative solution and raised discussion points. Finally, the Nottingham Castle was due to be refurbished which provided a unique opportunity for before and after data capture. The initial data acquisition unusually included the roof areas whereas the post refurbishment event did not. Furthermore, part way through the enabling works an archaeological dig identified foundations bringing forth an opportunity to create a digital model for inclusion in the original campaign. The final operation was undertaken in the new galleries which emanated from the original entrance area post-refurbishment.

In all but one instance involvement of the investigator allowed knowledge generation and adaption of the workflow. Firsthand observation may bring forth rich in depth understanding providing a constant in the data, yet as identified the iterative process also has the secondary outcome in repositioning the investigator. The benefit to the research is determined in the output i.e. whether there is incremental improvement or deterioration in the digital model.

The Arkwright building at Nottingham Trent University visibly exhibits the effects of weathering and historical events on its façade, data providing stakeholders with clear insights into material changes. The precision of the output model enables an immediacy of understanding not typically available. Cross-referencing this data with historical records, such as images and references, broadens comprehension of the building's heritage. The contextual analysis, including adjacent buildings affected by the event, enhances the thoroughness of the data.

The Hawara pyramid case study faces several data capture challenges due to its remote location, lack of identifiable objects, and the materials used in its construction. In urban environments where natural targets are plentiful,

automatic registration is typically effective. However, when targets are required, the workflow must be adapted to include target identification and verification to ensure robust outputs. The site's remoteness necessitated third-party data capture, which parallels the asset manager-geotechnologist dynamic. For the pyramid monument, with its exceptionally featureless landscape, additional measures are necessary, such as leaving targets in place to verify accuracy. Stakeholders, particularly in international contexts, play a crucial role in the project, this knowledge will influence the framework.

The Ducal Palace at Nottingham Castle with four data capture events highlights several opportunities to contribute to the framework. The site's parametric data capture utilised two instruments, a Leica P20 and a BLK360, with the resultant datasets registered and merged. Software issues and data quality remain risks. Access to the roof—an unusual opportunity—introduces potential weather-related impacts on the outcome.

Archaeological findings, often concealed within the fabric or ground, can provide significant insights or pose new questions. The kitchen yard at the building's north end, previously used as a car park and storage area, will be examined during refurbishment for final development into additional gallery space. This may offer further data capture opportunities, contributing to the framework.

Post-refurbishment, the case study may be revisited for campaigns to validate cyclical data capture. Internal areas can be modelled to exemplify layout revisions, offering opportunities for display and virtual modelling of the new gallery space for planning purposes. Additionally, revisions to the gallery entrance, where a colonnade was infilled to support internal environmental enhancements, will be recorded to document the development for historical records.

In summary, the empirical research methodology is seen to address Objectives 3 to 5 with the iterative development using the three case studies highlighted in action research paradigm. At each stage the framework will move from conceptual to theoretical to emerge formed and robust. Within stages two and three stakeholders will be quizzed as to their views on the potential to support heritage assets. It should be noted Objectives 1 and 2 are to be satisfied utilising the literature review hence are not developed in

this section.

The carefully chosen case studies have been justified and shown potential to develop the research theme. The complexity of the case study is exemplified in the three chosen. A unique façade with historic damage showing features resulting from conflict exemplifying the lack of resources to create an exact replica. A remote eroded edifice of material weakness, exemplifying archaeological vandalism with technical and environmental extremes and variable results. Finally, the asset undergoing a second whole refurbishment and development, multiple campaigns to exemplify a cyclical historic digital model overlaid with a historic timeline drawn together from local repositories.

3.6 Summary

The methodology was designed to meet the research objectives through an iterative action research process, using case studies to substantiate methods and clarify their integration within the overarching framework. Heritage studies benefit from social research's interpretivist stance, which acknowledges subjectivity and the evaluator's influence. This approach facilitates shared understanding and deepens insights into themes like purpose, relevance, design, accuracy, and originality.

Recognising the complexity of human experience, the interpretivist approach justifies qualitative methods as ideal for heritage studies. The methodology, evolving from practical strategy to sophisticated theoretical application, integrates theory and practice in sustainable heritage management, supported by stakeholders. Utilising a literature review to ground the research and three empirical case studies, the research employs an iterative, subjectivist inductive approach, refining theory through data.

At the data capture stage, precision instruments create parametric models for a digital model, underpinned by historical records. Qualitative methods enable nuanced heritage exploration, transcending binary outcomes and fostering objectivity by acknowledging researcher bias. This ethical approach ensures comprehensive sustainable heritage management investigation. An interdisciplinary stakeholder-inclusive framework enriches the research, aligning with themes of social dynamics, identity, memory, and social justice.

Digital technology enhances inclusivity in heritage research but must address the digital divide for equity. Despite their complexity, case studies provide deep insights and practical solutions essential for nuanced heritage management. Methodological rigour and advanced analytical skills are crucial to navigate these challenges.

Action Research, involving stakeholders in iterative improvements, ensures practically relevant research, enhancing heritage management practices. The methodology's adaptability maximises impact on academic discourse and real-world application, proposing enhanced practices and developing a stakeholder-oriented framework. Triangulation ensures reliable outcomes, with stakeholder feedback enriching research direction and supporting iterative cycles. The empirical methodology addresses objectives through iterative case studies, evolving from conceptual to robust theoretical frameworks, with a literature review addressing initial objectives.

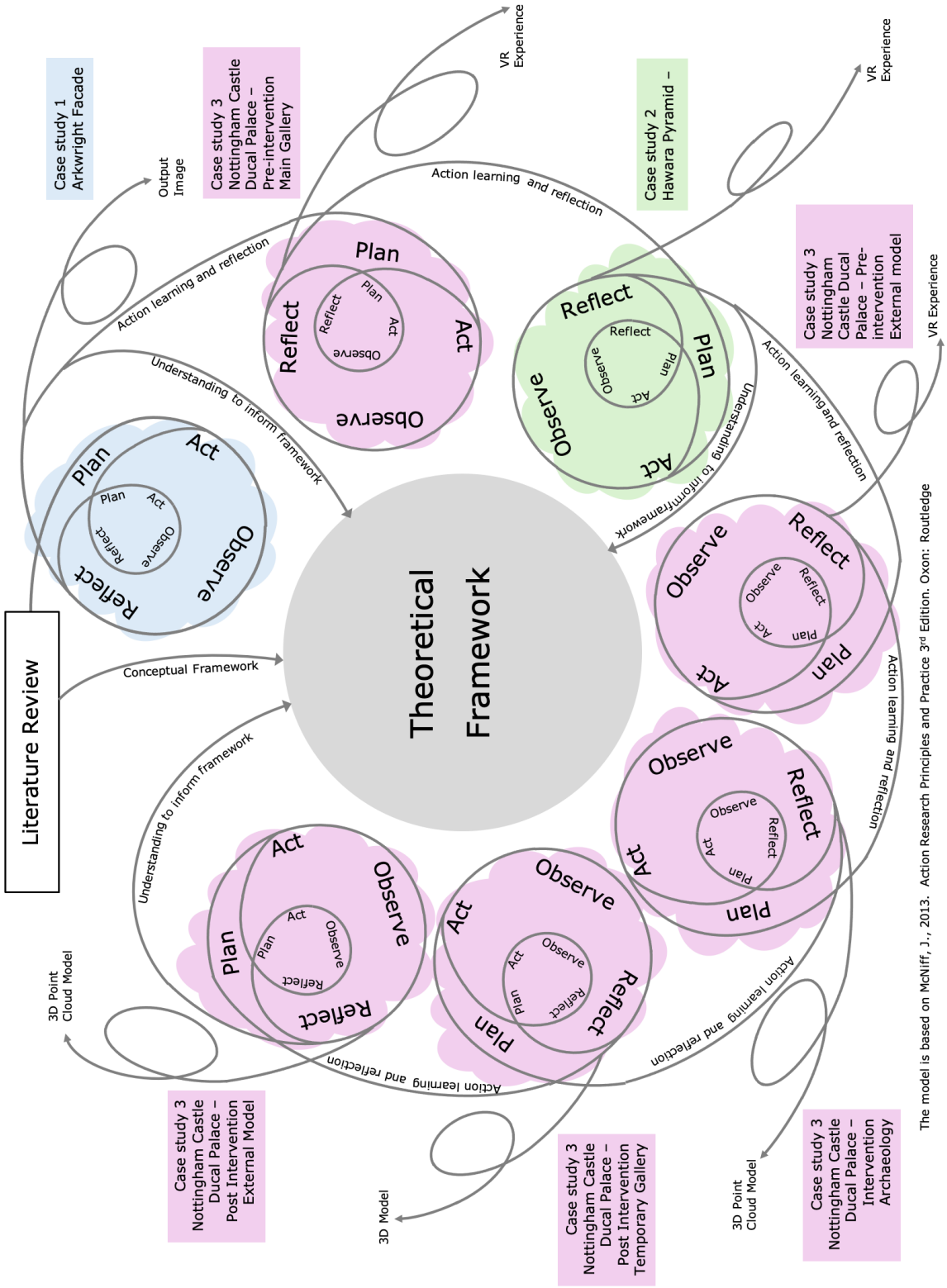

Figure 15: Action Research - investigation methodology encompassing three case studies

Chapter 4.0 Case Studies

4.0 Introduction

This chapter delves into the empirical research associated with the three case studies. The insights gleaned from the literature review formed the foundation for the conceptual framework, and the empirical research will further develop this into the concluding theoretical framework. An iterative process of action research, beginning with a simplified heritage project, will be employed across the three case studies. Through a cycle of analysis and revision for both historical and geometric data, the research aims to enhance proficiency for both the process and the researcher, thus improving the quality of the digital model. Insights from the first case study will inform the subsequent ones.

Each case study will be introduced and expanded upon comprehensively later in this chapter. The first case study examines the Grade II* listed Arkwright Building at Nottingham Trent University, specifically its main façade - a simple, north-facing symmetric elevation, comprising two storeys, a basement, and a pitched roof with third-floor dormer windows. The second case study focuses on the Hawara Pyramid, which presented a challenging environment, involving a third-party team, unfamiliar equipment, and extreme material conditions. This case study explores the methodology used to determine resultant data, identify flaws, and propose alternatives to enhance quality. Archaeologists provided the historical data, and the extreme parameters offered a steep learning curve, which informed the final case study.

The final case study examines Nottingham Castle's Ducal Palace, concentrating on its development from an initial house, through the fire that destroyed it, to reconstruction as the first provincial gallery and museum. This project included an initial campaign, a post-refurbishment revisit, internal space surveys, and an archaeological dig for geometric data. Historical data sourced from local archives and a nationwide search, produced a comprehensive timeline. The extensive dataset generated from this study provided a wealth of knowledge, forming the basis for summarising the empirical research and constructing the theoretical framework.

In summary, the iterative action research methodology, applied across these case studies, systematically refined the conceptual framework and culminated in a robust theoretical framework, underpinned by rich empirical data and comprehensive historical analysis.

The chapter will initially consider the strategy, methods, data capture and security, before moving onto targets and groups, processing of the data and the colourisation of points and finally, data application. The next three sections cover in depth each of the case studies broken down into detail, analysis and providing a summary. The case study analysis will synthesise the outcomes and the chapter will conclude ready to be thrust forward into the theoretical framework.

4.1 Workflow

The historical architectural methodology for heritage asset records involved taking numerous manual measurements, which were prone to errors. For areas that were inaccessible, photographs were captured, and dimensions were extrapolated based on the regularity of components. For instance, a panel of bricks at a lower level could be measured, and an object at a higher level could have its dimensions inferred from the brick measurements. This method assumed a level of accuracy within a certain tolerance but did not account for irregular components or revised methodologies in the construction. Additionally, deviations from vertical plumb were not recorded, and measuring curved surfaces in elevation or section required specific tools or templates to achieve accurate records. Archaeologists often mitigate these inaccuracies by including sketches with scales alongside critical dimensions, which can be invaluable when discrepancies arise in the recorded data.

The primary benefit of manual recording for stakeholders, and thus for the heritage asset, is the intimate connection between the observer and the object, fostering a deeper understanding and more nuanced assessment. This level of detailed observation may diminish when the interaction is mediated through a computer screen.

Data acquisition can be challenging in certain situations, such as along transport routes or with fragile structures that are susceptible to damage or natural deterioration. Recording under these conditions may necessitate

additional precautions, which can increase costs or put individuals in unsafe positions. Therefore, alternative solutions should be considered, especially when time or the risk to the data gatherer is a critical factor.

It is imperative to ascertain the purpose of the data at an early stage, as this will dictate the parameters of data capture. When the data is intended to serve as a historical record, it must be comprehensive and of high quality to be effective. The LoD, LoI, and LoA should be commensurate with the heritage asset under examination. Conversely, if the data is intended for the construction of a model, it is often sufficient to capture only the general dimensions necessary for creating the objects. For instance, when modelling a structure with windows, it suffices to locate the structural openings in the wall and record their height and width. Beyond this, a compilation of referenced images can provide the requisite details and be linked to the model, thus obviating the need for extensive data acquisition. This ensures that the methodologies employed are both appropriate and efficient, striking a balance between the need for detailed, high-quality records and the practicalities of data acquisition.

4.2 Laser Scanners

Laser scanners, continuously evolving, are integral to accurately recording data within a reasonable timeframe. This data underpins a 3D interactive model, precisely dimensioned and overlaid with images, thus informing all stakeholders, involved and peripheral. Regular data capture not only facilitates model evolution and ongoing knowledge development but also establishes a foundation for revolutionary and expansive understanding for future generations.

Originally, lasers, or Light Amplification by Stimulated Emission of Radiation, were developed by the military as rangefinders before being adopted in construction for maintaining line and level accuracy. The first scanners, utilising a spinning mirror, were installed in aircraft for ground mapping before terrestrial applications were envisaged. Modern laser scanners, mounted on robust tripods, can capture millions of points per second, creating 3D point clouds. These instruments also capture digital images within the same device. The individual data sets are subsequently merged in a post-processing operation known as registration to produce dimensionally accurate 3D models.

Manufacturers offer specialised versions tailored to required accuracies (with sub-millimetre precision possible) and distances (exceeding 250 meters), employing various range finding technologies. The resultant data is a point in space defined by x, y, and z coordinates from the reference location. Enhanced accuracy is achieved by repeatedly pulsing the laser at the same point and, after excluding outlying results, recording the optimal value. These quality adjustments can mitigate the challenges posed by curved and non-reflective surfaces, thereby promoting accuracy, as will be discussed later in the chapter.

Handheld and platform-based unmanned aerial systems (UAS) scanners now employ SLAM technology, integrating LiDAR laser units and cameras. This technology accepts diminished accuracy as a trade-off for expedited data capture. The UAS or handheld unit traverses the area to be recorded, with data capture quantity contingent on speed, allowing the model to build in real-time. However, handheld units have reduced range and lower points per second, imposing certain limitations. For historic assets, tripod-based systems are preferred due to their superior accuracy and data quality, particularly with complex surface shapes, weathered faces, or mirrored planes.

Internal to the terrestrial tripod-mounted scanner, a mirror on a horizontal axis spins rapidly, reflecting the laser pulse towards the target object, except for the bottom quadrant (approximately 90 degrees). The mirror also directs the returning laser reflection to the receiver. The housing rotates on the vertical axis, capturing a full hemisphere of points within the instrument's range. Data is stored on an internal hard drive and can be immediately verified on an integral touchscreen or a mobile device. If necessary, a second 180-degree body spin captures images within the field of view, saving them as image file extensions. These individual files can form a comprehensive database of high-quality images for future reference.

The precision and reliability of tripod-mounted scanners make them indispensable for documenting historical assets, where the intricacy of surface details demands high-resolution data capture. Conversely, while UAS or handheld scanners with SLAM technology offer rapid and flexible data collection, they are best suited for applications where speed and accessibility

are prioritised over minute precision. A dual approach enables a balanced methodology, optimising both the quality and efficiency of data acquisition processes.

4.3 Scanning Methodology

The scanning methodology follows a consistent procedure for all instruments. A quality tripod is set on stable ground and approximately levelled by eye across the machined top face. For survey-grade tripods, the instrument is securely attached to the top face before being accurately levelled using three screws in the baseplate, guided by the level located in the casing. For proprietary tripods, the legs may be adjusted to accommodate excessively uneven surfaces. Once this process is complete, the internal compensators correct any slight residual deviation. Using the screen on the instrument or remotely on a mobile device, the quantity and quality of the captured data can be adjusted and monitored. It is vitally important to have stable ground for the tripod; for instance, placing it on a poorly bedded paving slab is inadvisable, as any movement during data capture could cause the instrument to become out of level and stop functioning.

The scanner instrument operates on a line-of-sight principle, meaning that only objects in direct view will be recorded. This presents a limitation in scan data, necessitating multiple scans to capture unseen areas and build a complete model. Additionally, the data captured forms a 'skin' of co-located points without links to any other points, lacking depth, thickness, or material composition. At this stage, significant investment is required to enhance the digital model to the object level, replete with comprehensive data.

When obstructions exist between the scanner and the building, the device cannot see through or around these objects, resulting in incomplete data. This issue can be mitigated by carefully selecting additional scanner positions to capture missing zones. However, it is important to note that some data may still be missed, leading to visible gaps in the model. It is prudent to consider the quality of the asset and the final use of the model before conducting extensive additional scans to record every aspect and infill these gaps. Undertaking numerous scans is time-consuming and may result in an unwieldy model that could pose challenges as the project progresses.

Drawing nearer to the building can facilitate data capture, especially in protruding areas such as porch ceilings and window reveals. However, this may come at the expense of roof areas, which become obscured from the laser's view. Heritage buildings with parapets, wide overhangs, and soffits often have areas that remain invisible regardless of the instrument's location. Capturing data at roof level is generally challenging, particularly where the line of sight is acute to the building. Access to roof areas is fraught with safety concerns and equipment risks; however, the presence of a parapet can mitigate these challenges effectively. Higher ground, adjacent buildings, or the object itself can sometimes provide suitable positions to gather additional datasets. Nonetheless, the challenge lies in finding accessible and safe locations to set up the tripod without excessive movement due to exposure.

Technical difficulties also arise when capturing quality data at angles greater than seventy degrees to the perpendicular. At such steep angles, the laser often rakes off the surface, making returns undetectable, and the spacing between points exceeds the data capture specification. These issues will be explored in greater detail later in the chapter. Scanning instruments provide valuable data, yet their limitations necessitate strategic planning and careful execution to ensure comprehensive and accurate models, particularly in the context of heritage buildings. Balancing the need for detailed data with practical considerations is essential for the success of such projects.

When selecting locations for data capture, it is essential to thoroughly assess the site, carefully considering the advantages and disadvantages of each potential station. Best practice involves planning and documenting scan locations on a site drawing as the project progresses. This documentation aids in the registration process, facilitating the integration of scan data to form a cohesive model.

The latest scanning instruments incorporate embedded cameras with SLAM technology and an Inertial Measurement Unit (IMU) to track the scanner's movement through the site to subsequent stations. This innovation significantly enhances the speed and accuracy of data integration.

The choice of scanning location depends on various factors, including traffic and proximity to potential hazards. Conducting a thorough dynamic risk assessment is crucial, as the safety of personnel and equipment should always

be paramount. When identifying optimal positions for the instrument, ensure there is overlap between scan data, ideally on the object itself. If connecting the scans directly is challenging, using a third reference point, such as another building may resolve the issue. An alternative solution, after registering the individual scan datasets, is to utilise GPS data to enhance the accuracy of the 3D model. However, it is imperative that this information is recorded in the metadata. Investing time in meticulous planning and risk assessment, and leveraging advanced scanning technologies, the data capture process can be optimised, ensuring both the safety of the operation and the quality of the resulting model.

For any heritage asset, the site, location, and setting are integral aspects of the object being documented. Listed objects may have significant but distant elements that are crucial to their setting or usage. As the scan data encompasses a 360-degree horizontal view, an additional layer of information is recorded, which must also be considered. Consequently, more scans might be necessary to fully capture the surrounding context, even though these scans may be secondary to the main object. The quality of these scans can be adjusted to reflect a hierarchy of data.

Ideally, an exclusion zone around the scanner and the building should be established to prevent interference from people, vehicles, signage, etc., thus enhancing the data's robustness. These may be removed in post-processing however there will be a zone of missing information for the building. Furthermore, although many instruments are rated at Ingress Protection 54 (IP54), which means they have limited protection against dust ingress (5) and are protected against water splashes from any direction (4), extreme conditions of rain and dust can still affect the data. However, the latest firmware for scanner instruments, in conjunction with advanced modelling software, can address these issues through sophisticated algorithms. It is possible to pause and resume data collection to avoid disruptions from large high-sided vehicles, although this can extend the project's on-site duration. Solutions such as early starts, late finishes, weekend work, holidays, or night shifts might be necessary, especially if the asset is on a major transport route or if winter conditions with bare deciduous trees are preferable. These considerations can also influence the recorded accuracy during the modelling stage.

4.4 Targets

Targets can take many forms, survey-grade, permanently applied surface types used with total stations may be beneficial for scan data capture. However, given the sensitivity surrounding historic assets, particularly regarding material degradation, this type is often dismissed. Surveyors must record the approximate locations in a drawing and provide unique identifiers. The necessity for targets is limited, especially in urban environments where building elements may be utilised. Unique features, such as flag poles, TV aerials, tower corners, parapet details, and windowsills, can serve as reference points. These features must appear in more than one point cloud and be positioned in three diametrically opposite locations, avoiding alignment on the same vertical or horizontal plane.

For land surveys or areas lacking such features, targets should be introduced with careful placement. Placing targets in front of key artifacts or details can disrupt the cloud consistency. Standardised targets include 100mm white non-reflective spherical types and 112.5mm flat check targets in circular or square patterns. These can be mounted on posts for tribrach connections or magnetic plates. With a tribrach, they can replace the scanner on the tripod. Ground mounting allows them to double as survey targets, linking data from scanning with UAS photogrammetry data.

A final consideration is the scanning instrument. Some instruments can identify targets within the data and include unique identifiers. For highly accurate data, scanning the targets at a higher resolution is crucial. For flat check targets, adjustments should ensure that none present the same face profile to the scanner, aiding the recognition software in uniquely identifying them. These targets can also pivot or rotate while maintaining a consistent centre, facilitating the scanning process as the instrument moves through the scene.

4.5 Images for Colourisation

When planning the scanning data collection, it is also essential to consider image acquisition. The instrument will capture either individual pictures in a second 180° vertical spin of the scanner body using the mirror or will utilise cameras located in the body to elicit a panorama. In low light conditions some

scanners have integral light emitting diodes (LED) to light the scene. Finally, the cameras can utilise standard or High Dynamic Range (HDR) capture where the camera merges three images natural, overexposed and underexposed settings. However, a note of caution, this can enhance colours leaving a less than natural outcome.

The instrument offers basic control settings to handle overcast or sunny conditions, as high contrast can lead to inconsistencies in the model information. If the images are vital for building surveying and recording, it might be necessary to capture data under overcast skies or on facades not exposed to direct sunlight. Direct sunlight can sometimes enhance 3D understanding by adding shadows when using standard cameras, but this is not always beneficial with scanning instruments. Complete scan data provides infinite viewing possibilities, aiding examination and understanding, particularly in complex models. Therefore, uniform lighting conditions are advantageous for improving model rendering and the accuracy of the information in the image.

Certain scanning instruments are able to capture thermal images to colourise the points. If the scanner has no temperature capture capability a thermal image can be used to colourise the points in an additional process post registration. The data can provide understanding of monument air leakage, thermal integrity, thermal resistance, water ingress, water leaks and moisture detection. All support the sustainable management of heritage assets.

4.6 Scan Data

The quality of scan data is evaluated based on the comprehensiveness of the point cloud, specifically the minimal presence of non-data zones. This assessment is often intertwined with, but distinct from, accuracy. Accuracy is typically measured in two ways: internally, by comparing two clouds containing the same physical object, or externally, by referencing a measured physical object. Moreover, accuracy can be considered in two internal dimensions: the distance between each point on a single plane and the precision of determining the position of each point in space. Resolution, within the survey domain, refers to the ability to identify features in the point cloud and is influenced by point density on the object.

Factors such as the complexity and uniqueness of the object's surface can affect the amount of information to be gathered. Quality can be defined by the spacing between points; reducing the distance between points increases their number, thereby enhancing the data quality. However, this also results in longer data capture times and larger file sizes. This parameter can be adjusted on an instrument based on the distance from the object. For instance, a large, simple area that is easily visible without obstructions like trees may require fewer scan positions from a greater distance. Conversely, capturing more details of the object necessitates higher point density or resolution.

Another feature of the survey instrument is the capability to define specific areas to be scanned, thereby reducing data capture time and file size. However, this feature is not available on all scanners, particularly the SLAM type where a slower pass achieves a similar outcome. While this capability can save time, its significance is often minimal when constructing the model. For some instruments, completing a full dome scan and image capture with reasonable accuracy and medium quality can take less than five minutes. With a skilled operator, the entire process, including setup, can take as little as ten minutes. One advantage of area definition is the ability to scan small, detailed areas, such as statues, friezes, and tympana, at a higher resolution. This feature is also effective for capturing difficult surfaces, such as highly reflective ones.

To ensure comprehensive data for highly detailed surfaces, it is necessary to move the instrument frequently to capture unseen areas at higher resolution. When following this workflow, it is crucial to maintain sufficient overlap between scans to ensure accurate merging. It may be beneficial to conduct a low-resolution scan initially to assist in locating the object, followed by a high-resolution scan of defined areas to capture detailed data for the model. Alternatively, detailed areas can be captured using a camera, and a 3D model can be constructed using photogrammetry software. This method provides a high-definition surface model that may be more satisfactory for recording the condition and easier for creating a 3D printed model. Accurate measurement data may not be necessary as the dimensions were recorded during the initial scan of the façade.

Data for internal space can be captured using a laser scanner; the benefits and limitations are similar to those external to a building. Smaller spaces with simple details may benefit from the SLAM technology due to speed of capture and acceptable accuracy. The linking of space data between rooms can be problematic, therefore it can be necessary to factor in an instrument position in the smaller space adjacent to the door. Additionally, the stability of the floor can provide difficulty, in this situation remote control via mobile device can be used to start/pause and identify when the process is complete. Furniture, fixtures and fittings can inhibit data captured, especially at floor level, which may provide difficulty in assessing a building or recording details. With a building of exceptional interest, it may be necessary to remove some or all of these to record the significant elements or revert to image capture and photogrammetry.

Due to the shorter distances involved, it is possible to reduce the number of points captured without compromising the accuracy of the data. However, if the scanned area includes radius corners, detailed cornices or soft surfaces, a high-quality setting will enhance the accuracy of the recorded data. Furthermore, when certain features are particularly important, it may be beneficial to define the area and, without repositioning the instrument, rescan at a higher setting with shorter distances between points and/or higher quality and without images. Another consideration is image capture for internal spaces. While some scanners can adjust for artificial light, these adjustments are generally coarse and may not compensate for the wide range of LED sources.

All scanners have a minimum data capture distance of approximately 500mm, which can be restrictive in corridors and staircases. Certain instruments are more suited for data capture in small spaces due to their lighter and more compact design. Nonetheless, it is crucial to ensure sufficient overlap between scans to accurately position them when constructing the model.

It is crucial to establish a relationship between internal and external areas at select locations throughout the internal space scan. A complex model comprises numerous scans, and the ability to correlate multiple scans within the series allows for accuracy checks and ensures data quality. The methodology for this process is influenced by factors such as accessibility and

proximity. In a straightforward scenario, a room with a view of an adjacent structure recorded from another scanner location can provide sufficient accuracy verification. In more challenging situations, it may be necessary to place a target in a window area visible from both scanner positions. This target allows for accuracy checks within the model. The target's location should be marked on the plan, remain in position between scans, and be scanned at a higher resolution from each instrument location.

4.7 Global Location

Geo-location involves accurately positioning objects on the Earth's surface using Global Navigation Satellite Systems (GNSS), which employ multiple satellites to determine coordinates that can be integrated into the point cloud model. This methodology requires one or more instrument locations. After capturing the data, the tripod remains in position, and an antenna linked to the GNSS unit is attached. The resultant millimetre-accurate position of the scanner instrument is recorded and downloaded into the data. With the bespoke tripod, prominent points in the scene can be geo-located and the data utilised to provide this function. There are opportunities to use the accurately located model to determine local weathering impact, to precisely model energy usage, determine potential for overheating, flood risk and impact, and to understand extended heritage assessments in conjunction with other assets.

4.8 Data Processing

Once the data is captured, it should be downloaded to a computer for processing. For data security, it is advisable to store a copy on a second device without processing. Additionally, surveyors should copy all image files to a third location, labelled with the position cross-referenced to a drawing and indicating the direction for the first image. At this stage, consideration should be given to how the model will be compiled. It may be advantageous to segregate external and internal data sets and further divide them floor by floor for large buildings. This reduces the size of the data being processed by the computer, which can be beneficial. It is important to refer to the stations drawing to ensure all data sets are included and to note overlaps between each data set.

The use of mobile devices has significantly revised the workflow in this process. The ability to perform registration in the field and export digital point cloud models is now commonplace. Using partial clouds, an initial data registration is completed, facilitated by scanners with visual recognition capabilities. The resulting data can be downloaded in common file formats such as ASCII (XYZ/OBJ/E57/LAS/PTX/PTS). Similarly, SLAM technology exports as a complete digital model in these formats.

Another crucial aspect to consider is the computer hardware used to process the data. While the speed and size of RAM are important, the graphics card is particularly critical, especially when regenerating views of the model on the screen. To illustrate file sizes, eight medium-quality scans can result in a file size of 8.5 GB. Registration can eliminate duplicate points, and for buildings of minimal complexity, cloud decimation can reduce the cloud size without losing important details. In a subsequent meshing process, the points are converted into a digital surface model, known as a digital outcrop model (DOM). This involves linking the points with polygons to form surfaces. Proprietary software can merge and simplify these surfaces; however, this process can compromise data accuracy.

Alternatively, there may be a need to remove extraneous areas and clean the cloud. Vehicles, people, and unwanted details can be carefully cut away and deleted. In the most advanced scanning instruments, algorithms are capable of detecting movement within the field of view excluding the affected points. A cleaning process can occur at two stages in the workflow: individual clouds can be cleaned before registration, or the resultant cloud can be cleaned after registration. Cleaning individual clouds can be quicker, but it might remove information useful for the registration process. Dynamic elements recorded in the cloud can leave gaps in geospatial or colour data, so it is often beneficial to spend more time during the data capture phase to pause and restart the scanning instrument as necessary.

The algorithm-based registration of point clouds has the capability to rapidly integrate clouds, typically resulting in a high-quality model. However, this process can occasionally be challenging. There are several manual methods available: adjusting the 'xy' coordinates before verifying the 'z' axis or selecting three approximate points in both scenes and executing a command

to join and optimise the consistent features. Once the registration is complete, unnecessary parts of the cloud can be deleted. However, if multiple data sets are being combined into a single model, it is advisable to defer deletion until the entire process is complete, as the discarded data might be needed for alignment. Data may have been collected using instruments from different manufacturers due to size or weight considerations, but most software can accommodate this when constructing the model.

Regarding data cleansing, there is often extraneous data collected through window glass, usually ceilings or internal walls, which should be carefully removed. Similarly, external features captured during internal data collection should be eliminated. Each point cloud can be individually opened and unwanted points removed before stitching the clouds together. A secondary consideration is that working within a single point cloud reduces the risk of accidentally removing important data. However, opening and closing each cloud can be time-consuming, depending on the data quality. Once the cleansing process is complete, the point clouds are auto stitched and finally merged into a single model. For data security, it is prudent to back up the model by copying it into another model space and appropriately naming the file. If the data has been divided into multiple sets, these need to be consolidated into a single model. It is important to retain file links when building the model; otherwise, moving the files or saving them to a new location may necessitate rebuilding the model. It may be observed at this stage that there are areas of the model without data—holes where objects obstructed the laser, even with multiple sets of scan data.

Like any other 3D computer model, the point cloud model is interactive, allowing for navigation and zooming to examine areas in greater detail. Since the model is dimensionally accurate, distances between two points in the cloud can be measured in three axes or as direct lengths. Additionally, areas and volumes can be identified, defined, and stored within the model. The complete digital model can have specific areas highlighted while the rest of the cloud is hidden. The remaining, smaller cloud segment is easier to manipulate and can be regenerated or exported into another software package for further manipulation.

The data can be viewed in both orthographic and perspective modes, with 2D images easily extracted. The point cloud can be colour-coded using a 'rainbow' palette based on the intensity of the reflected laser light, which generally aids in data visualisation. There is also often an option to view the data in greyscale. If images were captured during scanning, the software can analyse these and assign the recorded colours to the corresponding points, thereby recreating the model as it appeared on the day of capture. However, this process is influenced by lighting conditions, which can affect contrast and colour rendering, similar to issues encountered in standard colour photography.

It should be noted that the images do not always accurately represent the scanned situation. For instance, if the scan data shows an empty highway but the image includes a vehicle, the colour from the image will be assigned to the road surface data, resulting in a 'flattened' appearance of the vehicle. Similar discrepancies can occur in records of heritage assets. While there are solutions to common problems in colourisation and digital capture, they were not utilised in this research.

Upon completing the registration process, a series of checks must be conducted to ensure accuracy. Slicing through the data can reveal the layering of lines, which should be examined horizontally and vertically at opposite ends of the data to identify any distortions. Measurements should be taken between points in the cloud and corresponding points on the building, both horizontally and vertically, as well as between the clouds. This due diligence is necessary to confirm accuracy before proceeding to final outputs.

4.9 Data Application

The outputs can take various forms. For example, a fly-through video can be created directly from the point cloud, providing informative narratives for tourism or educational tutorials on heritage assets. It is important to note that holes in the data can distract viewers and cause confusion, especially if other parts of the cloud are visible beyond these gaps. Record images can provide in-depth knowledge that can be integrated with historical data to generate a comprehensive understanding.

The data can be sliced very thinly in any plane, facilitating the construction and recording of plans and sections. These slices can be cleaned of noise, unrequired features and prepared for record with appropriate labels or dimensions. Additionally, slicing the data at different intervals can detect any movement in the object, allowing for comparisons over time to determine the direction and extent of any deformation. This capability can aid in understanding structural issues and supporting solutions, which can be monitored similarly after implementation. Moreover, buildings that are accidentally or maliciously damaged can be reconstructed using point cloud data due to its renowned accuracy.

It is possible to determine the accuracy of the data from the model once it has been registered, although this may not reflect the true situation. When scanning in external locations the movement of fauna or flora, detritus, overhead cables, light fittings etc. will cause variances in the data and these will be recorded as an error which does not reflect the accuracy in the solid object. Excessive errors may show there has been a problem in the registration; further investigation is then required to determine if the clouds are accurately aligned, or refinement is required. The software may also perceive overlap in the scans where there was nothing - in this situation the links between the data sets may require breaking and manually repositioning to improve the accuracy.

Currently there is no software available to go from point cloud to a solid object-based model in a single step. Recognition of floor, wall and ceiling planes is possible, standardised pipes and steel sections, and if trained, window openings can be identified. Heritage assets, however, especially those of the older order, are anything but regularised making this solution less than effective. Artificial Intelligence (AI) may provide solutions yet is beyond the scope of this thesis. The solution is to use a workflow to transform the data by tracing the objects for inclusion in a BIM model however this will capture acute corners and edges but will simplify the model even remove nuances and important artifacts thus sanitising the record. There are algorithms to extract certain standardised objects, for example pipes and sectional steel structure, from a point cloud, and to show these as solid objects. It is often necessary to carefully check the objects and the data from which they were drawn to ensure the software has correctly identified the

object. These objects will need extruding to complete the run and flanges or fittings added to create a complete model. Where there are valves and pumps it may be necessary to use a high-quality setting to capture the data for the object due to its complex nature.

Furthermore, when implementing building modifications in plant areas, clash detection is available, integrating a proposed 3D model of service runs with a scan of the existing conditions. The software can identify clashes and generate a schedule for operator review. However, not all detected situations are genuine clashes, as the system detects points coinciding with solid objects. If these points are reflections from surfaces, the results may be spurious. This necessitates that the operator meticulously clean the scan data before merging it with the model to minimise such errors and expedite the process.

Advanced systems can be effectively employed for monitoring building movements and changes. By creating a model based on simplified geometry and comparing it with a point cloud using specialised comparison software, deviations can be visualised through heat mapping. Subsequently, a new point cloud of the same areas can be captured and processed through the same workflow. By cleansing and comparing the new data with the original heatmap, immediate and accurate results regarding changes can be identified.

External data capture can be particularly challenging when flora is in proximity to the heritage asset, with seasonal variations, such as deciduous foliage, offering certain advantages. Internal spaces with furniture also pose difficulties. However, the data gathered can reveal additional features not identified in other surveys. For instance, fluctuations in wall surfaces previously containing window openings, doors, staircases, or detailed features such as taller skirting boards, dado rails, or picture rails can provide insights into the property's evolution. Slicing the data for sectional or plan views allows for the determination of wall and floor/ceiling void thicknesses, leading to predictions about the materials or construction details used.

Point clouds can be enhanced with flags visible during interrogation, with additional information such as asset registers or equipment installation/service manuals hyperlinked to these flags. In heritage assets,

bespoke products and unique design features often result in extensive registers, though these documents may lack vital information not accessible without dismantling and rebuilding the asset. Additional information can only be collected during maintenance, repair, or refurbishment. Nonetheless, the primary objective of the digital model is to foster collaboration, improve efficiency, and utilise the 3D model as a tool for better interrogation and dissemination of information.

The use of flags in the point cloud benefits the storage and retrieval of heritage asset records. SLAM instruments can add images, voice notes, and data files during and post-survey. Hyperlinks can guide users on journeys of discovery. Once scanned, documents can be catalogued, referenced to the point cloud, and the two data sets can synergistically enhance knowledge and understanding. Both data sets can be searched and analysed, with the visual model offering immediate insights; surrounding flags serve as starting points for these discoveries. Comparing the point cloud with visual records provides clues to the asset's development without necessitating frequent site visits. Additionally, construction records can aid in developing object data for integration into the digital model.

Laser scanners, which gather and present data in a 3D format, offer high accuracy and mitigate some human errors. However, several challenges currently hinder their universal application. For instance, the inability to record features out of the line of sight often leaves critical areas, such as roofs, without data. For low-rise buildings, pole-mounted cameras can survey roof-level masonry without using access systems, reducing injury risk and costs. Similarly, UAS with camera or scanner payloads can capture data to complete the digital model, though data overlap can pose issues. Photogrammetry requires precise scaling to accurately merge point clouds with scanner data. Furthermore, difficulties also exist in colourisation issues resulting from equipment nuances and lighting conditions, and residual voids or multiple offset layers that need cleaning. This complexity makes managing the output time-consuming and challenging.

This research does not extend to the modelling and data output stages, which require extensive knowledge of software packages and project use. Yet, project management software could offer a solution by building on 2D and 3D

drawing records, allowing data storage, linking, access, and interrogation, including IFC files. The model-building stage yields substantial information in an accessible format for all stakeholders, though transferring data to an object-based digital model remains difficult.

Hosting the model in the cloud and accessing it via the web resolves data size issues, though this is outside the scope of this research. Digital data security—ensuring data integrity and future readability amidst evolving software environments—is a universal concern for all digital systems and repositories.

The cost of digital technology is decreasing while user experience is improving, enhancing efficiency and cost-benefit for clients. Eventually, conservation plans will likely include a point cloud model as a foundational record. Like the heritage asset itself, this model should evolve, providing accurate records for future custodians. This will enable historians, owners and surveyors to gain unprecedented insights into our past and the development of our surroundings.

4.10 Case Study – Arkwright Building at Nottingham Trent University

4.10.1 Purpose

The case study was to complement the literature review and bring forward the conceptual framework. As a local landmark the building has a known history and having undergone recent refurbishment this data was brought together in a single document (see Figure 16/17). However, the report had not been updated since the refurbishment therefore did not fully represent the building used in the case study. A major deviation is the document statuses the building as Grade II (Allan Baxter and Partners, 2005) whereas following the refurbishment Historic England (1972) state Grade II*.

The facade fronting Shakespeare Street is a fine example of later C19 Gothic Revival style according to Historic England (1972), is extremely well preserved not lessened by the bomb damage. The quality of the façade is hidden in part by the landscaping, specifically trees and partly as the building cannot be viewed in whole even from the opposite side of the highway. The laser scanning sought to resolve this and furthermore allowed the façade to be

viewed in orthographic detail as the original architect drawing. This simplified case study had historic presence, was accessible and local.

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Figure 16: University College Nottingham (Nottingham Trent University Arkwright Building) Northeast corner from South Sherwood Street (University of Nottingham)

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Figure 17: University College Nottingham (Nottingham Trent University Arkwright Building) Northwest corner from Shakespeare Street (Nottingham Hidden History Team)

4.10.2 Detail

The Nottingham Trent University Arkwright Building formally college 1877-81 by Lockward and Mawson of Bradford, Historic England (1972) in the Gothic Revival style, North-West corner rebuilt after WWII bomb damage. After opening in 1881 as University College, the building contained a library, a museum and the college. The image in Figure 14 depicts a recently

constructed 'college,' characterised by a striking central spire, polychrome banding on the roof, and symmetrical detailing. The building faced early structural issues around the spire, leading to its closure in 1883 for remedial work. It did not reopen until 1890, albeit without some of the details seen today, as noted by Alan Baxter and Associates (2005).

There are missing elements and repaired features, results of bomb damage and weathering, which at first glance appear subtle. These discrepancies were only identified through comparative analysis using point cloud data. Figure 1 (Page 6) highlights the detailed frog and turtle carvings near the main entrance, serving as indicators of the stone's weathering.

The scanning campaign was conducted over two consecutive days in dry conditions, though at different times of day. On the first day, a line of eight stations was established, maintaining a fixed distance to the façade from Bilby Walk to South Sherwood Street, between the trees and the building. The second day, which was much brighter, involved an additional eight stations along the north side of Arkwright Street. The approximate positions mirrored those of the first day, with trees in full leaf. The scanner was paused to avoid capturing passing traffic. Settings on the instrument were consistent throughout the campaign. No targets were used in the data capture as the building located in the urban environment was replete with opportunities both on the building and structures in the round.

The data was imported into proprietary software, where it was registered, colourised, and cleaned. A vertical slice was taken across the building's front to remove the trees, and a viewpoint established perpendicular to the main entrance. The cleaning process retained some 'ghosts' on the main entrance steps, providing a sense of scale without obscuring detail, thus indicating a digital representation rather than a photograph (see Figure 18). The output was rendered in orthographic projection and saved in TIFF format, ready for A0-sized printing. This size allows detailed examination across the entire façade. Fine details, such as the ridge iron crest, window materials, and stonework, are accurately captured. However, some areas, like the roof behind the parapet, remain in shadow, and internal features, including the main entrance staircase, are visible.

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Figure 18: Point cloud data orthographic image of Nottingham Trent University Grade II* listed Arkwright Building, revealing the asymmetric façade due to rebuilding after WW2 bomb damage (By author)

The gothic style Arkwright Building, part of the Nottingham Trent University City Campus, was damaged during the Second World War when a bomb exploded at the west end of the building. Careful examination of the image reveals discrepancies between the wings of the façade showing the extent of the original damage and the simpler details of revised materials used in the reconstruction. A dormer window is missing on the west wing, and the single arrow slit window in the gable would have originally been three. Additionally, two statues are missing on either side of the arched window in the west pavilion, and the tracery in this window is simplified. The transition from timber to steel window materials is evident, all the result of bomb damage in 1941, as shown in Figures 20/21. The North-West corner, demolished during the bombing, was reconstructed in the early 1950s in a simplified manner, as noted by Alan Baxter and Associates (2005). This simplification is attributed to a lack of skilled construction workers and limited material availability during that period.

The detail from the point cloud model (see Figure 18) brings into focus the history, providing an ability to interrogate and document the evolution (see Figure 19). All alterations become immediately visible and are reinforced by the images of the damage directly after the bombing. Other elements have been simplified and may identify revisions in materials, for example whilst not shown in this elevation, the slates on the rear elevation are Welsh rather than Westmoreland. Furthermore, some of the details remain damaged. It could

be argued the indicator of social and conflict history is more powerful than if the repairs replicated the original facade.

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Figure 19: University College Nottingham (Nottingham Trent University Arkwright Building) Northwest corner showing original details C1880 (Picture Nottingham)

The 2D point cloud image was presented to architecture students during sessions to elucidate the operation and workflow of LiDAR technology. This presentation aimed to disseminate knowledge about the advantages of integrating precise geometric data with historical records. Students demonstrated a high level of engagement with the material, expressing astonishment at the depth and comprehensiveness of the historical details revealed. This exposure led them to recognise the unique value of the point cloud as a singular record of isolated impacts, prompting further inquiry to deepen their understanding. Additionally, the exercise of a simple 'spot the difference' game was employed to provide stakeholders with accessible means to explore and comprehend historical details, thereby enhancing their appreciation of the data's significance.

In summary, the digital model reveals intricate details at both ends of the building that, at first glance, appear splendid. However, some elements are obscured by the surrounding flora, preventing stakeholders from fully

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Figure 20/21: University College Nottingham (Nottingham Trent University Arkwright Building) – Clearing up after the WWII Bomb (University of Nottingham)

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Figure 22: University College Nottingham C1945 showing the bomb site tidied and the building in use (Picture Nottingham)

appreciating the entire elevation. It is only through a comparative analysis of the building's extremities that the differences become apparent, allowing the historical narrative to emerge. The images, juxtaposed with the model, illustrate the building's evolution and a significant catastrophic event in detail. Initially, the structure featured a central spire, as evidenced in the historical images; however, the point cloud model now shows only a truncated octagonal base. Further investigation uncovered early structural failures that

necessitated the removal of the spire assembly, leading to a seven-year closure of the building, Alan Baxter and Associates (2005).

Photographs taken during the war depict the damage sustained, yet Figure 22 shows the aftermath with debris cleared, the building secured, and returned to use. Parked cars and the presence of people illustrate the resilience and continuity of life amidst conflict. The point cloud captures the contemporary state of the building, highlighting the lingering effects of the damage and the social limitations of the period. The simplification of architectural elements, resulting from a shortage of skilled masons and materials due to wartime and economic constraints, is clearly visible. The point cloud also includes images of stakeholders, showcasing the building as a hub of social interaction and congregation. Together, these elements underscore the building's historical significance, providing an understanding that extends beyond the physical monument by integrating accurate data with historical evidence.

4.10.3 Analysis

The digital model when overlaid with the historic detail synergistically edges towards the sustainable management of heritage assets through the lens of significance. The digital model as an accurate facsimile anchored in the present brought forward historic revisions which were explained and reinforced by the images throughout the life of the asset. The repairs to the building after the destruction caused by the conflict of WWII plot social history due to the skill of the masons and metalworkers, available materials and financial limitations.

The literature review showed the accuracy of the LiDAR system to be desirable when capturing the weathering, complex details and material movement. There is benefit when comparing the output of the digital scanning solution with the original manual version. The quality of the digital data is dictated by the accessibility of surfaces to the laser. Manual solutions would infill those data holes, yet the risk to the fabric and the safety of the surveyors to get close to the surfaces at high level outweighs the often-small missing areas. As the case study exhibited, accessing the area behind the flora can produce data to link with that captured at a more optimal location.

The cloud colourisation was impacted upon by campaigns spread across the day bringing forward areas of greater contrast. This would need to be considered in planning the campaign to contain in a single day period and would dictate to some extent future planning. Conversely, environmental conditions can vary hour to hour and are not predictable. In extreme situations an alternative would be to block adjust the contrast in the individual images, however this could be considered to be in contrast to the ethical considerations of honesty at every level.

The historic data captured in the images brought forward to explain the deviations seen in the façade could be faked however, these are coupled with a heritage report used in planning the refurbishment. Thus, these can be accepted as a true record for comparison.

Accessibility to the asset displayed difficulties identified in the planning and resolved using two parallel campaigns collecting quality and accurate data. The time of day allowed unhindered access to the highway with minimal need to pause the instrument however, this elicited an issue in the colourisation. Isolated areas located immediately to the rear of the parapet and either side the truncated turret were hidden from the instrument leaving holes in the data. This did not detract from identification of the impact of historic events, yet it would be necessary to utilise alternate methods if the data were to be used for survey. That said, in all survey methods these areas are difficult to study and would throw up similar issues.

4.10.4 Summary

The integration of digital models with historical details enhances sustainable heritage asset management by highlighting the significance of the assets. Digital models provide accurate representations of assets, incorporating historical revisions supported by imagery throughout their lifecycle. Post-WWII repairs highlight social history through the craftsmanship of masons and metalworkers, available resources, and financial constraints. The literature review emphasises the high accuracy of LiDAR systems for capturing weathering, intricate details, and material movement, surpassing manual methods that risk both the fabric and the surveyors' safety. The case study displays the benefits of combining digital scans to fill data gaps, such as areas behind flora. Cloud colourisation's variability, due to diurnal changes,

suggests a need for single-day campaigns or careful contrast adjustments, albeit with ethical considerations. Accessibility issues, particularly for hard-to-reach areas, require parallel campaigns for comprehensive data collection and may necessitate alternative methods for detailed surveys.

The 2D point cloud image was employed in instructional sessions to demonstrate the functionality and workflow of LiDAR technology, highlighting the benefits of integrating precise geometric data with historical records. This engagement underscored the unique value of the point cloud as a detailed record of specific impacts, encouraging further exploration to enhance their understanding.

The study as an autonomous project allowed the research to identify and solve logistical issues of a lone operator, external environments, detailed structures, instrument settings/parameters, software demands and insights to the output in digital models. Elements fed forward into the internal areas for the Ducal Palace and further forward to the external areas encompassing Nottingham Castle site. Figure 58 Considerations for a LiDAR campaign started to form within this project, providing understanding of elements in the Geometric section especially the Artifact, Equipment, Environment and Locale. Aspects for example permissions, access and safety were disregarded as the site formed part of the campus, likewise transport, availability of equipment and PPE. As a single operative People can become fully formed as can Environment.

The historic elements for the case study generally were known however, the Design and Access statement (Alan Baxter and Associates 2005) from the recent refurbishment was utilised to underpin the knowledge. This formed the backbone of the image research to confirm and compare with the model.

4.11 Case Study 2 - Hawara Pyramid, El Fayoum, Egypt

This case study emanates from the project Labyrinth: Conservation, Analysis and Virtual Reconstruction of the Archaeological Site of Hawara Pyramid and Labyrinth (El Fayoum). It was a collaboration between The Centre for Architecture, Urbanism and Global Heritage at Nottingham Trent University and The National Research Institute of Astronomy & Geophysics (NRIAG) in Egypt. Funding was received from the Arts and Humanities Research Council

(AHRC) within their project type 'Virtual Reality of Medieval Culture: Collaborative'. The Science and Technology Development Fund provided support to the Egyptian contingent at NRIAG. The Ministry of Antiquities as part of the Egyptian Government allowed access to the sensitive archaeological site Hawara Pyramid at El Fayoum and obtaining the 3D information by NRIAG which contributed to the research objectives. The Centre for Architecture, Urbanism and Global Heritage built the 3D model, supported obtaining the VR digital reproductions and film.

4.11.1 Purpose

The proposal aimed to develop a digital model integrated with historical data to create a VR experience for stakeholders, thereby eliciting feedback as part of the second iteration of the Active research method. This case study presents a unique set of challenges, primarily due to the extreme conditions it encompasses regarding heritage assets and digital capture. The location is rural and environmentally challenging, the stakeholders are dispersed with language and political barriers, and the assets include organic materials. Importing equipment to Egypt is exceptionally difficult, necessitating the involvement of a third party to navigate these issues, which in turn introduces additional challenges.

Drawing from the outcomes of the first case study, meticulous planning is essential to achieve robust results. The quality of the data is determined by the presence of 'holes' rather than accuracy alone. Overlap and the angle of incidence are particularly crucial, especially when acquiring data from elevated areas, which poses significant difficulties. Unlike the highly accessible first case study, the Hawara project presents starkly contrasting conditions.

The site of Hawara, located on the outskirts of El-Fayoum, centres around the mudbrick pyramid of Pharaoh Amenemhet III. The terrain is relatively flat, with an irrigation canal cutting through the west side (see Figure 23). This

Figure 23: The Hawara pyramid from the North-East with the irrigation canal near the pylons to the West (By author)

case study details the acquisition of data sets to create an accurate three-dimensional model of the pyramid, including the adjacent areas presumed to be the site of the labyrinth to the south and the Roman remains to the north and east. As De Felice notes, "*The use of 3D spatial analyses, Digital Terrain Models, or large-scale 3D surveys is deeply changing the core of archaeological research*." De Felice (2015, p.363).

The digital model, based on accurate survey data, served as the foundation for a 3D Virtual Reality (VR) experience. This VR experience combined the meshed model with archaeological data from museums and repositories worldwide, employing artistic impression to visualise the data on a gaming platform. The VR was showcased at the International Seminar and Exhibition "Hawara Big Reveal: 130 Years in the Making – From an Ancient Marvel of the Middle Kingdom to the Future of Tourism in Egypt" 28 -30 March 2022, as shared on the Virtual Hawara website (virtualhawara.com) to educate and provide a realistic understanding of the site. The objective was to evaluate the methodology's effectiveness in producing an accurate 3D model that could serve as a basis for archaeological records, conservation efforts, and stakeholder engagement.

Jeffrey confirms "*there is … an increasing drive towards data rich models, these are representations of the past that are not simply visual, or even*

sensual, but are specifically designed to act as points of integration for other, spatial and non-spatial, datasets." Jeffrey (2018, p.54). The model when exported and developed into a data rich repository can rise to a synergistic solution for conservation, "*… to encapsulate the semantic in the information model will soon become a virtual laboratory for cognitive systems in archaeology."* Bosco et al. (2018: p. 388).

The Labyrinth research project outputs (CAUGH 2018) were to use innovative virtual heritage technologies that will:

a) conduct accurate 3D Cloud-point to laser scan and digitally survey, record and model existing conditions of the site

b) utilise state-of-the-art geophysics underground surveys to detect, analyse and model the labyrinth's spatial layout and its water table (part of a research bid by National Research Institute of Astronomy and Geophysics (NRIAG))

c) develop a state-of-the-art interactive virtual platform that integrates remote sending indicators and dataset

d) develop virtual reality experience of the site, as well as mobile app for the site's history and navigation

The cornerstone of this project was the precise use of the 3D scanning instrument, specifically the Trimble TX6, designed for harsh environments. The practice of 3D modelling using laser scanners for archaeological sites is well-documented as an accurate digital data capture methodology (Brutto, Sciortino, Garraffa, 2017). However, limitations include time-consuming post-processing and the requirement for expensive, advanced technology, as identified by Historic England (2018). Lercari is more explicit, noting that "*… laser scanning is still the most feasible option for intra-site documentation of large and complex sites."* Lercari (2019, p.152)

The pyramid is situated in a clear area of sand desert, bordered by an irrigation canal to the west and south, with arable land beyond. The area of El Fayoum lies slightly to the north, with desert extending to the east. The stone casing of the pyramid has long been removed, leaving the mudbrick structure exposed to the elements. The resulting structure resembles a rounded knoll, where erosion has worn away the brick, with a skirt of debris

from the worn bricks at its base. The site of Hawara is fabled for allegedly housing a labyrinth to the south, although extensive investigations, including Ground Penetrating Radar (GPR) surveys, have yet to confirm this. Areas of collapse are evident in the pyramid, as is the stone entrance, although within approximately seven meters, the steps are submerged by groundwater. The region's climate is classified as a subtropical desert (BWh), with average temperatures of 26°C and annual precipitation of less than 1.0 mm, Weather and Climate (2024).

The mudbricks used in the pyramid are a composite material made from local mud and straw, sun-dried before being stacked around a stone core of passages and chambers to form the pyramid's shape (see Figures 27 and 28). Originally, the structure would have been clad in stone, with a pyramidic capstone. Mudbricks have been a fundamental component of vernacular architecture in the region for millennia.

The case study utilised the local partner the NRIAG to provide the scanning equipment and register the point cloud in Trimble RealWorks before exporting in a universally recognised file type. A specification was deemed unnecessary as the operatives were confident in their ability to capture quality data. Their workflow included the extensive use of GNSS data in the registration process. This section delivers an analysis of the workflow, initial observations from two data capture campaigns, and a review of the models produced. A subsequent short campaign in March 2020 revealed intriguing results that prompted proposals for experimental data capture. A robust narrative will examine the workflow for accurate data acquisition and outline the next steps.

The point cloud was delivered colourised and without cleaning.

The model serves as the foundation for the plan to dewater the site, establishing a critical baseline survey of both the pyramid structure and the surrounding terrain. This baseline data will be integrated with borehole measurements of seasonal water levels. A consistently accurate survey will enable the detection of any structural changes in the pyramid and provide a framework for visualising data collected through water monitoring. Comprehensive and precise data will be instrumental in computer modelling, thereby supporting informed decision-making processes. Throughout the dewatering operation, repeated surveys will facilitate the close monitoring of

any changes, thereby mitigating the risk of partial or complete collapse due to potential alterations in ground stability induced by the dewatering activities.

4.11.2 Detail

The mudbrick pyramid situated in the district of El Fayoum, south of Cairo, Egypt, is attributed to Pharaoh Amenemhet III. The local team provided a point cloud digital model of the site in an open format for subsequent cleaning, meshing, and integration into a VR game, designed to offer a visualisation of the pyramid as it might have appeared during the Pharaoh's reign. Archaeologists examined artifacts from the site and historical texts from the construction period to the present day. This research informed a reconstruction of the pyramid, which was then enhanced by a designer using gaming software before being showcased at the concluding event in Cairo.

The use of 3D modelling with laser scanners for archaeological sites is well-documented as an accurate digital data capture methodology (Brutto, Sciortino, & Garraffa, 2017). As Jeffrey notes, *"The non-contact nature of many digital recording technologies … is a real virtue for the conservation professional. However, this feature, combined with the immateriality and essential strangeness of the resulting digital object, can obscure any sense of a physical connection to the original."* Jeffrey (2018, p.51) In this research, while initial data capture by local specialists was economically beneficial, it exacerbated this disconnect, complicating the remote surveyor's ability to plan effectively. On-site visits are crucial for synthesising prior experience with local conditions to develop a methodology for precise and comprehensive data acquisition. Retaining traditional methods of physical interaction with objects may provide a more tangible connection to the data, which can be diminished by the mediating role of technology.

The limitations of laser scanning include time-consuming post-processing and high technological costs, as noted by Historic England (2018). Lercari emphasises that *"… laser scanning remains the most feasible option for intra-site documentation of large and complex sites."* Lercari (2019, p.2). Despite its potential, the technology also faces challenges, particularly in point and edge identification, as noted by Iniesto-Alba et al. (2012). While the pyramid's general appearance might seem unremarkable from a distance, detailed

examination of the intact mudbrick areas could incorporate edge data to account for erosion rates.

Environmental considerations are also crucial; the operating parameters of the scanning instrument must be acknowledged. The high temperatures, particularly during summer, can restrict the instrument's effectiveness. It is advisable to keep the instrument in shade when not in use and to ensure it is adequately shielded from extreme temperatures and dust. Pirotti, Guarnieri, and Vettore (2013) highlight that temperature and atmospheric pressure can significantly impact the accuracy of range finding and location. Metadata recording these conditions should be scrutinised during the modelling phase, and appropriate temperature ranges should be established for accurate data capture. This is especially important if using a mobile device for remote control, which must be robust enough to withstand environmental conditions.

The methodology for using the 3D Terrestrial Laser Scanner (TLS) is detailed earlier in this chapter, including data capture procedures, precedents, and initial model stages. Garstki asserts that *"… the authenticity of a 3D digital representation of an artefact should encompass an understanding of the entire production process — all of the choices, inputs, and data manipulations that affect the final model."* Garstki (2018, p.75) Without a thorough comprehension of the data's purpose and capture process, the resulting model may be inappropriate or incomplete, potentially compromising the final product's value. Ensuring the quality of data is essential for accurately recording and evidencing the site's original and current conditions.

The research design embedded in the aim of the project stated;

"The project aims to develop and implement an evidence-based strategy and action-plan to inform the sustainable preservation of the endangered archaeological site of Hawara (El Fayoum Governorate) using digital and virtual LiDAR Technologies." (CAUGH 2018)

The key questions to be answered are:

How effective is the use of digital LiDAR scanning technologies in mapping and synthesising discrete evidence-based findings on the spatial layout and conditions of underground archaeological structures? Furthermore, how this

effectiveness could guide a sustainable preservation strategy for an endangered heritage site? (CAUGH 2018)

To address the research questions, the initial objective of the project was to develop and implement a bespoke methodology for accurate 3D laser scanning and digital surveying, aiming to record and model the existing conditions of the site. The benefits of establishing a precise three-dimensional baseline model extend beyond this research objective, as it enables comparative analysis and informs subsequent phases. The initial requirement of any data schema is to define the desired output; thus, the plan for the data capture campaign is driven by the intended use of the information. Consequently, a fully detailed set of exit requirements is essential for producing a comprehensive and accurate model. Data accuracy at the point of capture is crucial; once data is recorded, natural or human-made changes initiate a new phase in the site's history, necessitating updated datasets. As natural erosion progresses, the process of 3D modelling can be repeated to create new digital models, which can be overlaid with previous versions to assess environmental impacts over time. For instance, the current model indicates that the pyramid's height is approximately 33 metres, compared to Petrie's recorded height of 46 metres in 1888. Given the relevance of climate change, periodic re-surveys (e.g., every five years) would provide valuable data for monitoring changes and assisting in predicting future impacts, which is crucial for informed conservation planning.

A relevant precedent for this project is the CyArk non-profit organisation, based in California, USA, established in 2003 to document, archive, and share significant cultural heritage. CyArk's mission involves conservation, recovery, and discovery, and the organisation has recorded over 200 sites, from the 3000 BC Scottish Skara Brae to the contemporary Sydney Opera House, using 3D reality capture techniques that combine terrestrial laser scanning and photogrammetry. This data forms the basis for engineering drawings or VR experiences and supports local partners in showcasing cultural heritage through digital media. CyArk (2020) aims to provide a time-specific record and baseline from which to monitor and protect heritage sites against threats such as climate change.

In the next phase of the project, incorporating below-ground data will enhance the model by integrating it with the above-ground parametric data. This comprehensive model will facilitate the inclusion of the fourth dimension, time, through the integration of materials from previous archaeological explorations, thus deepening the understanding of the site's heritage. As Jensen notes, *"… the use of 3D documentation encourages us to adopt a new workflow with more three-dimensional reasoning, allowing the utilization of 3D recording as a tool for continuous monitoring and evaluation of excavation progress and results."* Jensen (2019, p.59). The research output will underpin future conservation, management, and research efforts, while also informing the dissemination of the site's rich heritage. Jeffrey (2018) highlights the duality inherent in creating 3D models, where technical skill must be balanced with creativity and interpretation. The localised parametric model, overlaid with artefacts and integrated into a GIS context, will serve as a baseline for ongoing (re)interpretation as new evidence emerges and the narrative is refined.

The project's intent to facilitate dewatering of the site necessitates a comprehensive baseline survey of the structure and surrounding land, considering seasonal variations in water levels. An accurate and regularised survey will identify any changes and provide a framework for visualising data collected from water monitoring. This complete and accurate data will support computer modelling and decision-making processes. During the project, continued scrutiny is essential to detect changes that could mitigate the risk of partial or total collapse of the ground or pyramid due to adverse effects on earth stability from the dewatering process.

The mudbricks used in the pyramid's construction exhibit relatively sharp edges (see Figure 26). The distinct shadows cast by the equatorial sun suggest that incorporating a photogrammetry model could enhance accuracy and quality, especially if combined with the laser scanning outputs. Hassan and Fritsch note that *"… neither method represents a clearly superior result in terms of quality."* Hassan and Fritsch (2019, p.76). However, photogrammetry alone may not achieve the dimensional accuracy required for land monitoring, as accurate ground control points are needed to scale and merge the data, although this would not address the 'z' axis constraints. Conversely, photogrammetry is likely to provide a more accurate visual record

due to the quality of the camera used. Sordini, Brogi, and Campana note that *"... colour still represents a problem and is an issue that needs to be further developed."* Sordini, Brogi, and Campana (2016, p.389), with images often suffering from varying exposures.

Initial data was collected by local investigators during two site visits in 2019 and registered as a single model in E57 format for processing by CAUGH and the project team. The Covid-19 pandemic in 2020 left the data capture incomplete for the 'labyrinth' area and the Roman village to the north of the pyramid. Challenges included file corruption and issues with data registration accuracy, possibly due to automatic registration errors or inaccuracies in the original records. Additionally, a 'halo' effect, with planes of points emanating from the instrument at several station locations, was observed, necessitating further investigation and resolution with the manufacturer. No station locations, weather, workflow or equipment details were provided.

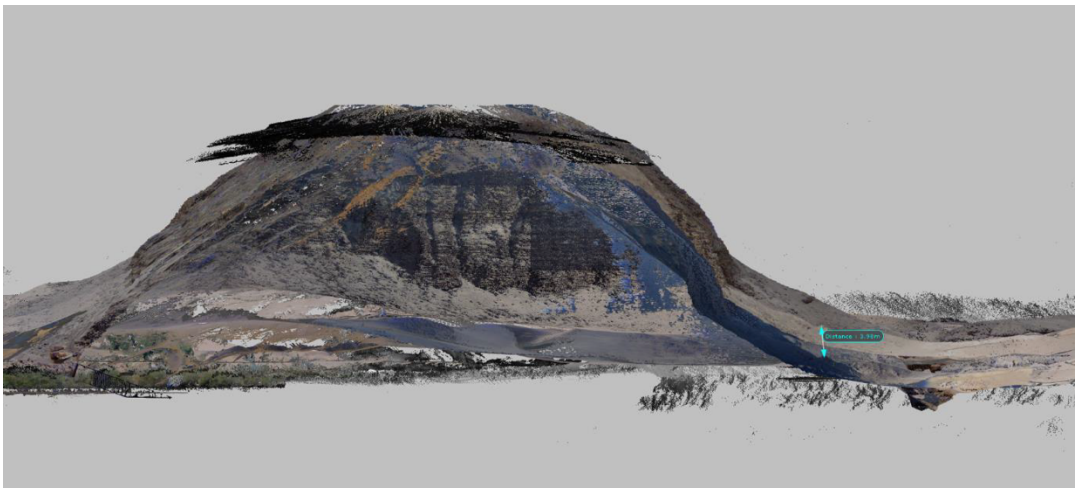

Figure 24: Pyramid point cloud data showing misalignment between Group 1 and Group 2 (CAUGH)

The model showed areas of modest quality (see Figure 24 included here with the permission of the project lead):

Points not accurately registered in the original surveys; in some locations there are multiple clouds offset in the Z axis

Objects in the point cloud data during the scan campaign e.g. people and equipment causing occlusion

Halos of points of unknown origin visible in the model, located around each of the instrument locations (see Figure 25 included here with the permission of the project lead)

Large areas in the cloud without data

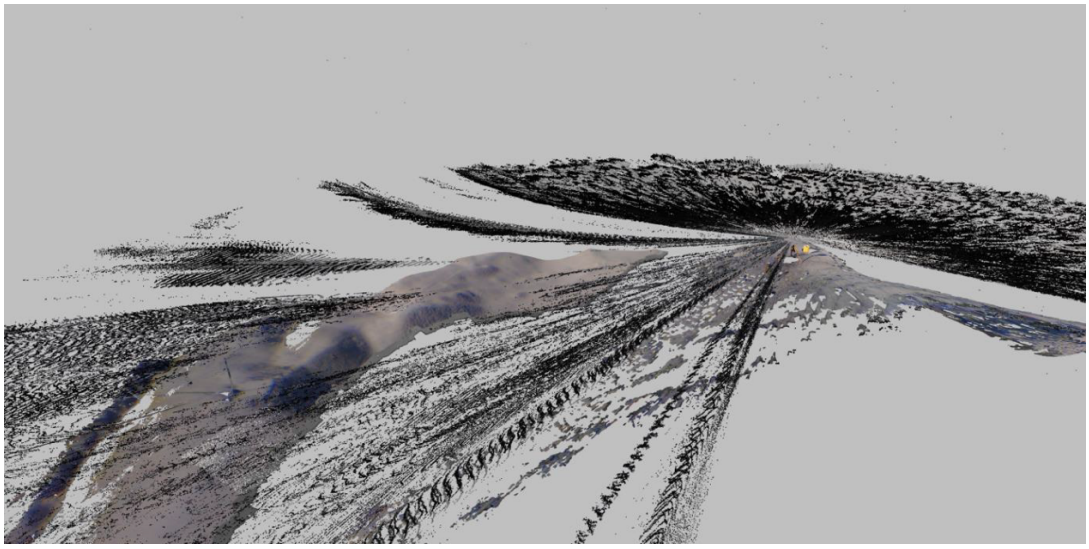

Figure 25: Image showing halo of points emanating from the scanner position (CAUGH)

The absence of topographical information for the labyrinth and the surrounding areas to the north, east, and west of the pyramid hindered accurate analysis of the pyramid's contextual features. The clouds from the two data capture campaigns were registered in separate groups, which, when combined, were found to be misaligned. These issues were confirmed during a site visit in early March 2020, where further examination revealed that the model contained six discrete layers of scanned data, rendering it highly inaccurate and therefore unusable. A set of laser scan data captured at the end of 2019 was distributed as raw, unprocessed files for registration in the UK. This workflow did not employ targets but relied on GNSS data. It was subsequently agreed that the data was unsuitable for forming an accurate model, necessitating a revision of the methodology for site data capture.

The scanner manufacturer, consulted regarding the 'halo' effect observed in Figure 24, suggested that these were parasitic points due to the lack of foreground structures. The data recorded beyond the TX6's maximum range of 80 meters appeared, with algorithms truncating the recorded distance, resulting in a point field above the ground plane. It was acknowledged that the number of recorded points was unusually high, possibly due to environmental factors. The data was subsequently cleaned and realigned using alternative software to enhance accuracy.

During the site visit to Hawara in March 2020, the team gained a deeper understanding of the conditions, and the information captured with the Trimble TX6 scanner was deemed a success, albeit only three stations were

achieved. The methodology, as detailed earlier in this chapter, was followed meticulously, employing the 'plan-obtain-register' workflow. Spherical targets were strategically placed in the field, both at ground level and elevated on landscape features. No additional scans were specifically focused on the targets; instead, the software was employed to identify the targets and use them for cloud registration.

Figure 26: Hawara pyramid east face showing Station 3 Trimble TX6 and spherical target location 03 March 2020 at 12.00hrs weather clear (By author)

The TLS data was successfully registered into a new group and thoroughly examined. The data revealed some unusual features, prompting further investigation to determine effective solutions. As is typical in action research, this led to a re-evaluation of the methodology, especially the initial assumptions. Adjustments were made, and a revised solution was developed. The following paragraphs provide an understanding based on this revised data capture system. As previously outlined in the methodology, the scanner was levelled, and the settings optimised for data capture. *"Before the first laser pulse is fired, TLS operators must choose a number of settings that determine how the instrument acquires measurements (e.g., point spacing, atmospheric correction factors, scan speed, field of view)"* (Brown and Hugenholtz, 2013,

p.368). It is crucial to note that each instrument is unique, and variations in settings significantly impact the final point cloud model.

The North-East corner of the pyramid was selected as the starting point due to its relatively level ground, located 5 meters from the pyramid's baseline at the lowest level of scree. Two additional stations were set up in a southerly direction, following a straight line parallel to the East face of the pyramid, approximately 20 meters apart (see Figure 26). Before capturing the first scan, ten 100mm white spherical targets were deployed around the area at varying heights, with no specific pattern. Generally, all targets were visible from the station locations. The equipment carry cases were strategically placed out of the instrument's line of sight, and the surveyors took care to avoid being captured in the data. However, it should be noted that other site personnel were not as rigorous in this regard.

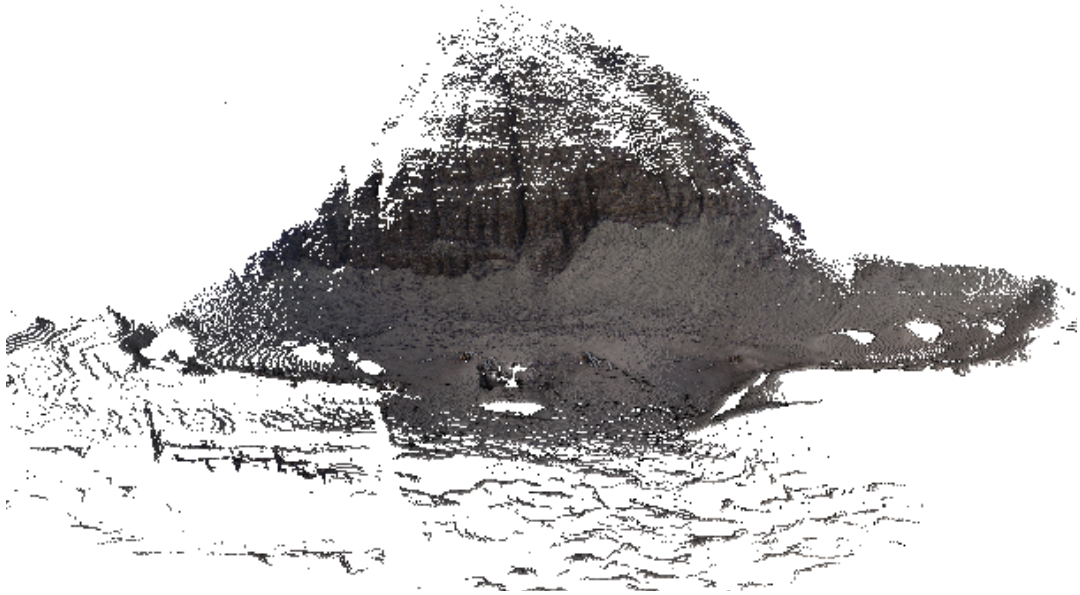

Figure 27: Point-cloud data registration from three stations along east elevation (CAUGH)

On return to Cairo the data from the three stations was downloaded and a copy made. The original data was stored as a permanent record and the copy imported into the Trimble RealWorks software for registration, initially trialling automatic techniques for coarse matching in the following order:

Auto-extract targets

Auto-register using planes

Followed by the manual solutions should the automatic fail to produce an accurate registration:

Target based registration

Cloud-based Registration

Following this the software performed a best fit algorithm on the point clouds from the individual stations for fine alignment to enhance the registration quality.

The resultant model (see Figure 27 included here with permission of included here with the permission of the project lead), was successfully generated using the target extract registration method, as previous approaches failed to yield a coherent model. Mudbricks made of adobe can be seen in Figure 29/30. The registration process was evaluated and determined to be of excellent quality, necessitating minimal post-processing and exhibiting none of the issues encountered in prior attempts. However, a notable deficiency in data was observed in the area of the exposed mudbricks (see Figure 28 included here with permission of the project lead showing project outputs), in contrast to the satisfactory results achieved for the scree and ground regions. A series of scaled screenshots was captured for in-depth analysis. Several hypotheses have been proposed to explain the data gaps, necessitating further experimentation as outlined in the subsequent section of this report.

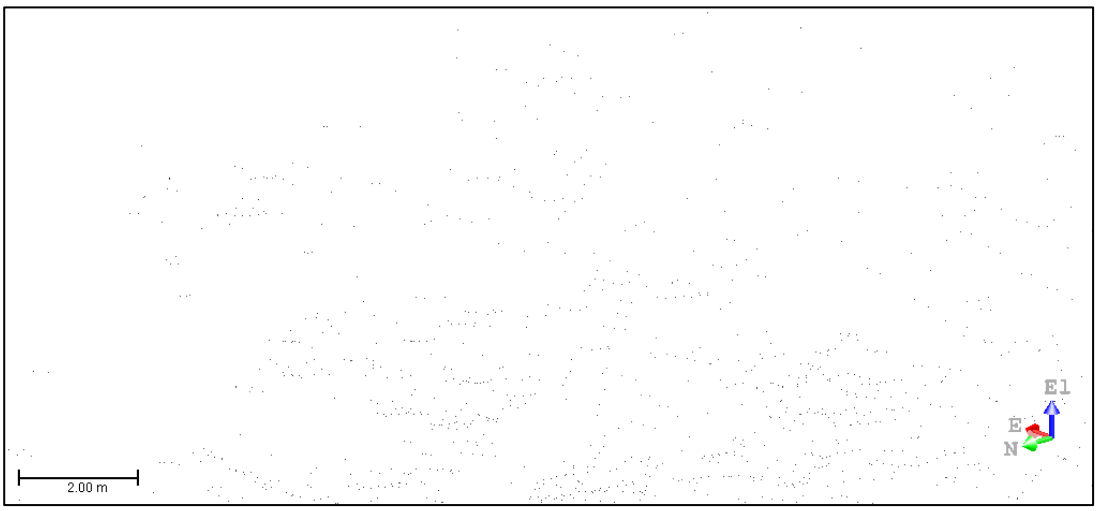

Figure 28: Point-cloud data area of the mudbrick showing sparse returns (CAUGH)

There are two distinct aspects of point cloud data: quality and accuracy. While these terms are often used interchangeably in discussions, they represent different characteristics of the data. Instruments employ established

parameters to calculate distance and location accuracy, typically measured in millimetres. As Andrews, Bedford, and Bryan (2015, p.32) note, *"Accuracy is how well a measurement conforms to its true value."* Andrews, Bedford, and Bryan (2015, p.32). In contrast, quality encompasses the number of returns recorded by the instrument, along with factors such as accuracy, precision, and the strength of the return signal. As Pirotti, Guarnieri, and Vettore caution, *"A very high-resolution survey lacking accuracy only leads to low-quality products which are prone to misinterpretation."* Pirotti, Guarnieri, and Vettore (2013, p.72).

Figure 29: Pyramid close up of mudbrick showing coarse finish with erosion deposits (By author)

Figure 30: Mudbrick of good condition showing the coarse surface and some erosion, binder straw is visible (By author)

This research prioritises precision, with a specific objective of achieving an accurate 3D laser scan and digital survey to document and model the existing conditions of the site. The secondary focus of the research question—'how can this effectiveness guide a sustainable preservation strategy for an endangered heritage site?' - underscores the critical importance of model quality. Without a dense array of accurate returns, data deficiencies will hinder the detection of changes over time. Consequently, it is crucial that all principal materials of the pyramid structure are comprehensively recorded within the conservation data. This necessity aligns with the research's overarching investigation: to develop and implement an evidence-based strategy and action plan for the site's conservation. It also suggests a need to explore methodologies that can compensate for any data deficiencies.

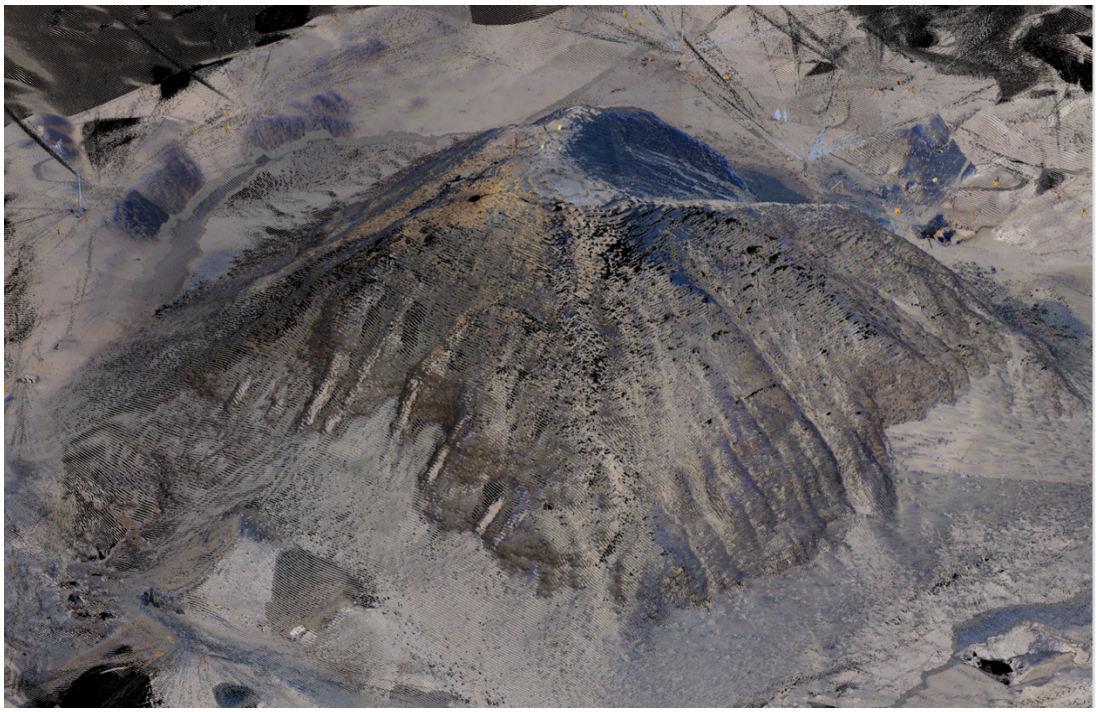

Figure 31: Hawara pyramid colourised point cloud southeast corner (CAUGH)

One consideration for improving data quality is conducting night-time scans to mitigate the issue of daylight sensitivity, as Voegtle, Schwab, and Landes observed: *"…. the accuracy of measurements at night-time has proved to be much better than at daytime."* Voegtle, Schwab, and Landes (2008, p.1061). Their research indicates a doubling of measurement error during daylight, particularly on dark materials. However, the absence of RGB data in night-time scans could be a drawback. A possible solution for adding texture to the model would be to overlay daylight images onto the night-time scans,

ensuring that any visible targets remain consistent throughout the process. Alternatively, images captured by UAS could be utilised, though the angle of capture might affect the outcome. Further analysis and proposals on these methodologies are discussed in the following section.

Returning to the original model, after the individual point clouds had been received and meticulously cleaned, they were manually brought together and registered (see Figure 31 included here with the permission of the project lead). Quality checks were completed achieving an aggregated accuracy of 2.5mm, before being exported in a file format compatible with meshing software. Subsequently, it was further exported to the modelling software for detailed analysis. At this stage, the outcomes of the archaeological research were incorporated, with the finds and conclusions providing essential guidance to the modeller. Objects from the same period were constructed using Blender, and elements of the archaeologist Petrie's account, who discovered the tomb, were utilised to recreate the journey from the entrance. Notably, some of the passages described by Petrie included blind alleys designed to mislead potential tomb robbers, which were faithfully incorporated into the model. The passage's ceiling, made of granite, features a flagstone granting access to the passage above. The chamber, discovered waterlogged with the sarcophagus lid removed and its contents absent, was also accurately represented in the VR simulation.

The virtual reality experience was showcased at the International Seminar and Exhibition "Hawara - From an Ancient Marvel of the Middle Kingdom to the Future of Tourism in Egypt" on 28 March 2022. Throughout the day, numerous attendees engaged with the experience and provided verbal feedback, offering valuable insights into the presentation's effectiveness and potential applications.

4.11.3 Analysis

As with action research, this proposal advocates for the incremental refinement of the techniques outlined in the methodology, particularly concerning registration, to achieve the highest possible quality, including the accuracy component. The planning stage, as previously discussed, is crucial for acquiring high-quality data, enabling an understanding of the site's scale, detail, context, and the current condition of the pyramid. However, this

particular case study necessitated an alternative approach: utilising local resources with scanning expertise and suitable equipment to capture the data. This strategy parallels the practice of heritage managers commissioning survey companies to produce digital models. Despite initial expectations, the quality of the output was found to be inadequate, necessitating extensive cleaning and additional registration to produce a suitable model for research purposes. There was no meta data provided, with a single point cloud file this would not help in the process the information may contribute to learning and moreover understanding for future campaigns.

Several factors contributed to the substandard quality. Initially, the local team's expertise was overestimated, as evidenced by the poor accuracy between the point clouds, particularly in the 'z' axis, suggesting a lack of target usage during data capture. Upon attending the site to oversee and observe the use of targets, it became evident that the equipment was indeed appropriate for the project. Furthermore, after returning to Cairo, the computer system and software managed to automatically register the data with commendable accuracy in a short time. This led to the conclusion that the initial failure was due to an insufficient number of stations, resulting in a poor-quality model with significant data gaps.

Areas of occlusion necessitate additional stations. To understand the quality parameters, a set of calculations was completed prior to the Egypt visit, informing the decision-making process regarding scanner locations. As Brown and Hugenholtz note, *"Simple geometric considerations … drive the majority of decisions about the settings and configuration…".* Brown and Hugenholtz (2013, p.368). During the visit, these considerations were communicated to the scanning team via a drawing overlaid on a satellite map of the area, directing the solution trialled during the site visit as previously discussed. The initial station was positioned at the northeast corner of the pyramid, on relatively level ground, 5 meters from the lowest scree level. Ten 100mm white spherical targets were deployed around the area at varying heights and in no particular pattern. Two additional stations were established along a straight line parallel to the eastern face of the pyramid, approximately 20 meters apart, moving southward. As this was experimentation the meta data was not stored, the day was clear, full sun with little wind and the stations were documented in drawings and images.

The resulting model met high-quality expectations, as evidenced by the data's accuracy (see Figure 27 included here with the permission of the project lead), in stark contrast to the initially received point cloud. The consistency in equipment and software across the campaigns suggests that the discrepancies were due to operator error and workflow inadequacies. While the overarching model appeared comprehensive, closer inspection revealed minimal data returns from the mudbrick material, falling short of expectations and warranting further analysis.

Consultation with Trimble Technical Support in the UK (KOREC Group Ltd) revealed that the colour and viewing angle of the mudbrick likely reduced the returns. This aligns with research by Su Lee et al. (2010), Alkan and Karsidag (2012), and Lichti and Harvey (2002), which indicate that instrument features, environmental factors, object surface characteristics, and angle of incidence all affect point cloud accuracy and quality. As Tan et al. advise, *"The distance errors caused by the properties of rough and dull surfaces usually measure a few millimetres."* Tan et al. (2018, p.2). Figures 29 and 30 illustrate the uneven surface of the mudbrick in the pyramid and its similarity in colour to the ground material.

Given that the instrument and environmental conditions are constant, the surface characteristics and angle of incidence remain as variables. The extensive area of mudbrick above the scree provides a range of incident angles, which could be considered constant given the consistent effect across the material. Research by Kersten et al. (2008) further suggests that the angle of incidence has a negligible impact on accuracy for time-of-flight instruments, such as the TX6 used in this study. However, the poor data returns indicate that the surface material significantly affects quality. Bucksch, Lindenbergh, and Ree (2007) recognise that the interaction between laser light and object surfaces greatly influences measurement quality, attributing this to scattering as described by the Minnaert model. Voegtle, Schwab, and Landes conclude that *"... additional materials should be included (in the research) like surfaces of industrial and cultural heritage objects."* Voegtle, Schwab, and Landes (2008, p.1066). Similarly, Tan et al. (2018) highlights the scarcity of research on distance measurement errors caused by target properties and advocate for extensive testing to analyse material sensitivity.

To address this issue, the following additional groups of stations were proposed for capture and comparison with the original registration:

Three stations, 20 meters apart, along a line parallel to and 5 meters from the lowest part of the north elevation of the pyramid, starting at the east corner and proceeding west.

Three stations along a line parallel to the east elevation of the pyramid, 25 meters from the base of the scree, starting at the corner with the north elevation and spaced 20 meters apart heading south.

Nine stations along a line parallel to the east elevation of the pyramid, 5 meters from the scree's base, starting at the north corner and spaced 5 meters apart heading south.

Research underpins the following proposals:

Increasing the mudbrick density by adding water, particularly on the shaded north elevation, which is less affected by the drying effects of the sun. Thermographic data showing a 300% difference in daytime humidity between the north elevation and the other three sides supports this hypothesis. Although all elevations experience similar humidity levels (90-100%) overnight, if this method proves beneficial, night-time scanning could achieve the desired quality. Lichti and Harvey (2002) observed improved return intensity on wet surfaces at short ranges, though not at medium ranges, possibly due to the close-grained materials used in their study.

Increasing the instrument's distance from the pyramid reduces the incident angle, potentially mitigating the lack of returns from the mudbrick. This approach, combined with existing scans, could address the data voids in the mudbrick area, as suggested by Brown and Hugenholtz, who noted that *"... data occlusion can be reduced considerably by decreasing the angle of incidence between the … [surface] and the scanner."* Brown and Hugenholtz (2013, p.372). This solution targets the coarse surface's role in occlusion, affecting quality rather than accuracy.

Reducing the distance between stations will mitigate both incident angle occlusion and mudbrick surface issues, increasing point density and the number of recorded returns, thereby enhancing data quality. The level of

improvement must be assessed to determine its impact on the model's quality.

For each group capture, all spherical targets will be uniquely positioned and visible from most stations, ensuring automatic registration in Trimble RealWorks as per the methodology. As Bevilacqua (2018) suggests, workflows introduce targets to serve as common points visible from adjacent scans or as known-coordinate points in the same reference system, linking individual scans. Simultaneously, the original three scan positions should be repeated and registered in a new group, utilising the targets for accurate registration and comparative analysis. As Mill, Alt, and Liias caution, *"In a situation where an additional laser scanning campaign is carried out, it would be difficult to merge the additional data with existing data and moreover to ensure the accuracy and quality of merged data."* Mill, Alt, and Liias (2012, p.30). Recapturing the group of three scans would provide a control registration, enabling precise data overlay in a structured sequence for comprehensive analysis.

Figure 32: Mudbrick construction collapse and material erosion New Gourna Village (By author)

The results will inform future data acquisition strategies for mudbrick structures, particularly in tropical regions, where this material is prevalent in heritage buildings. Figure 32, for example, depicts a theatre building in New Gourna Village, Luxor, constructed from similar materials, showing signs of collapse and erosion. Frequently, mudbrick structures are coated with closed-cell material renders to protect their vulnerable, granular structure. However,

where these surfaces have delaminated or natural events have occurred, this research will prove invaluable. Exposed mudbrick is prone to erosion and collapse; therefore, accurate three-dimensional models can facilitate change monitoring and predictive algorithms, aiding conservation efforts. The choice of target material remains an area for further research, particularly concerning its impact on model quality in the conservation of heritage assets.

In the quest for precision, it is crucial to consider the operational parameters of the instrument, particularly during the peak summer months. As observed, temperature and atmospheric pressure can significantly impact the accuracy of range finding and positioning instruments. Consequently, surveyors must be mindful of creating a suitable environment for the equipment when not in use. This consideration may also extend to operational periods; for example, utilising shelters or halting campaigns during extreme conditions, such as direct overhead sunlight. The instrument's metadata, which includes ambient and instrument temperature, can be interrogated during the modelling phase. Therefore, it is advisable to establish a recommended ambient and instrument temperature range for data capture periods to ensure accuracy.

To produce a high-quality model, basic calculations are necessary to determine the parameters for scan-station locations in the field. Acknowledging the necessity of a Digital Terrain Model (DTM), as Andrews, Bedford, and Bryan assert, *"Mass capture techniques need to provide a point density that is at most half the size of the smallest object to be recorded."* Andrews, Bedford, and Bryan (2015, p.33). However, as surface consistency is critical, *"... setting the point spacing to the smallest setting (e.g., 1 mm on many commercial TLSs) may lead to oversampling and smoothing of fine-scale features that contribute to surface roughness"* (Brown and Hugenholtz, 2013, p.368). A balanced approach is therefore required, adjusting settings between two data collection events at the same location to optimise accuracy. Given the challenges posed by the mudbrick material, a full panoramic scan should be followed by a focused scan of the pyramid's surface with a higher point density. Some instruments offer a quality setting for difficult surfaces; using a higher setting may extend the time at each station. This time can be minimised by first conducting a low-density scan with images, followed by a high-density, image-free scan focusing on the pyramid's surface, utilising the initial images for point colourisation.

As outlined in the introduction, the Trimble TX6 has a maximum range of 80 meters and a maximum quality setting of 7.6mm at 30 meters (approximately 2.5mm at 10 meters). With the laser axis set at an approximate height of 1.50 meters above ground level and assuming level terrain, the horizontal distance between points at maximum range is 800mm, which is insufficient for high-quality output. To ensure excellence, a maximum horizontal distance of 200mm between points at a single station is proposed for the DTM, which, with simple computation, results in adjacent stations being spaced 40 meters apart. Although 200mm still leaves notable gaps, the overlap from subsequent stations will provide a dense cloud. Moreover, to ensure even coverage, the stations should be offset 20 meters from west to east, reducing the diagonal distance to 28 meters and the horizontal point distance to approximately 150mm. A consistent row of stations around the pyramid's base is recommended, totalling 112 stations. This configuration should be communicated to the operator responsible for data capture.

This proposal offers a theoretical solution. Despite Figure 21 depicting relatively level terrain around the pyramid, actual conditions involve undulating ground due to surface disturbances, particularly from canal construction and prior archaeological investigations. Additionally, Roman archaeological remnants above ground level pose occlusion challenges and may lead to incomplete data. As previously stated, a site visit is vital during the planning stage. The final solution will require adjustments based on on-site observations and adaptations to accommodate real topography. The following sections initiate this process, but final station positions will be determined during data acquisition.

High ground should be leveraged to maximize site coverage. The expertise and judgment of an experienced surveyor are essential to interpreting the original intent. The need for a comprehensive model will guide the solution, with meticulous planning on-site being paramount. As Jeffrey notes, *"Digital recording of cultural objects in three dimensions remains both skilled and highly interpretative; the trend is towards both automated processes and integrated workflows."* Jeffrey (2018, p.54). The surveyor operating the instrument must be well-versed in the methodology and intent for the final model. As a minimum requirement, all stations should be accurately mapped, scheduled, and uniquely labelled, with metadata including group details, date,

number, and description, to support interpretation. Any changes in settings, weather extremes, or other anomalies should also be documented. This schedule and accompanying map must be shared with the management team during data dissemination.

The on-site surveyor will need to resolve data acquisition challenges as they arise. As noted by Historic England *"Usually, solutions or workarounds to most issues will present themselves, even if location difficulties can test the ingenuity of the surveyors."* Historic England (2018, p.49). For instance, stations may need to be more frequent in areas where ground depressions are less than 40 meters apart to capture accurate data. Each depression should be covered by at least two stations, and any depression exceeding 40 meters in width will require additional stations at the lower base level. The workflow must be ingrained in the site team, with quality and accuracy as integral components, communicated clearly before field operations commence.

Sight lines from the instrument must be carefully considered during data acquisition. The TX6 has a minimum operational angle of 21.5 degrees from the vertical axis; below this, data capture is obstructed by the instrument itself. The angle of repose for sand is 34 degrees, so positioning at the slope's apex should not hinder data capture immediately below. However, tripod leg positioning must be optimised to prevent data shadows and avoid partial ground collapse.

Three GNSS locations across the site should be clearly marked on a map, set to a proposed 20-meter grid. These points should be cross-referenced with the grid, and the map's accuracy verified against these geolocations. These locations must be included in the station schedule, uniquely identified on both the map and schedule, with photographs taken at each location for research reference.

At the northwest corner of the pyramid, a section of protruding stone 'road' should be designated as a Z datum or master benchmark (MBM) for this exercise (see Figure 33). This feature may historically correspond to the original ground level at the pyramid's base and provide valuable insight into its current condition for conservation purposes. This benchmark must be accurately recorded using a GNSS instrument, especially for the 'Z' axis. Two

scans, including the pyramid's main body and the roadway section, should be performed from different stations to accurately document the setting. Since this area is within the dewatering zone, an alternative reference point to the west of the canal may be necessary. A synthetic point, established as a station with GNSS reference and serving as a static survey control point, may also be considered.

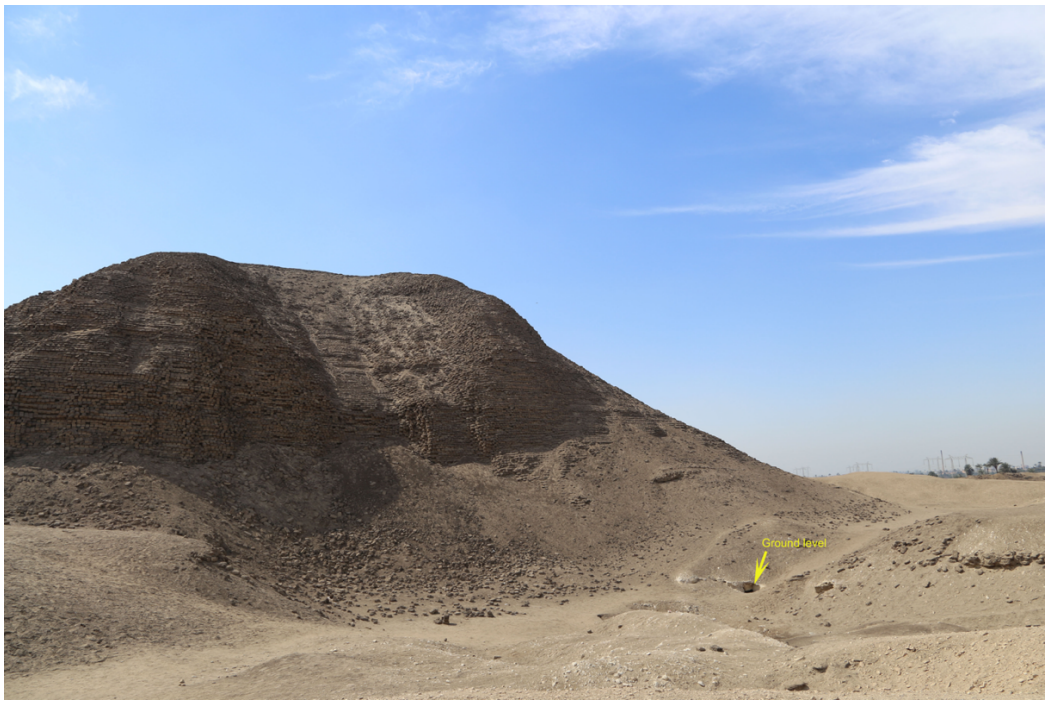

Figure 33: Potential datum for ground level (By author)

Given the remote nature of both the data capture and processing locations, a meticulously controlled workflow is essential for the methodology and documentation processes. As Iniesto-Alba et al. highlight, *"Planning for this (data capture) phase is absolutely necessary, as the optimal location of the scanner ensures the comprehensive definition of the subject, accounting for complex topography and the potential for occlusions and shadows."* Iniesto-Alba et al. (2012, p.378). Therefore, the selection of stations must be executed with precision, accompanied by thorough documentation, including detailed drawings, as part of the project deliverables. Without such a rigorous framework, achieving the precise model required for the project will be jeopardised. Given the site's remoteness, revisiting the location poses significant challenges. Moreover, even if revisits were feasible, accurately merging point clouds without reference objects would be problematic, as the site largely lacks natural reference points or defined edges.

4.11.4 Summary

The case study has concluded, revealing valuable insights into the trial of VR at the seminar. This initiative provided a unique opportunity to assess the accuracy of the geospatial model, enhanced by historical reconstructions. These reconstructions integrated both visual and verbal narratives; however, language barriers may have impeded full comprehension for some participants. Despite this, the overall reception was positive, with many attendees expressing amazement at the level of detail presented. This was particularly evident when a diver, who planned to explore submerged passage remnants, utilised the VR simulation. The diver noted the utility of the VR experience for understanding directional changes and expressed interest in further engagement, especially if the underlying model could be shared for educational purposes.

The scanning campaign faced significant challenges, with the quality of the initial model falling short of expectations. Despite the model's initial corruption, it could be opened in proprietary software, revealing significant inaccuracies. The receipt of point clouds as individual files in a universal format facilitated their import into point cloud software, followed by extensive cleaning. The point clouds were then manually aligned, optimised, and registered, resulting in a satisfactory output, which was subsequently exported for meshing and integration into game-building software. Nevertheless, concerns regarding output quality and the presence of parasitic points were addressed. It is recommended that raw data accompany the model in a common file type during export, ensuring thorough quality checks as part of the registration workflow. Adequate recognition and resolution of parasitic points require critical examination of field results, potentially utilising mobile devices for partial data verification, though this may risk missing certain issues seen in the full version.

A site visit revealed the challenges posed by the extreme environment, complex terrain, and difficult material conditions. The quality of the point cloud, essential for heritage records, was initially inadequate due to a lack of rigorous methodology and a gap in the operators' understanding of the requirements. However, thorough capture workflows demonstrated that achieving the desired quality was possible with available resources. The issue

with the mudbrick material persisted, as the points captured were insufficient for a comprehensive model.

The point colourisation revealed a blue hue on the north face, previously observed in Case Study 3. HDR imaging may be suitable for low-light conditions; however, its specific application to the north face suggests that high natural light levels may have influenced the blue shift. The merging of three representations in the HDR camera data possibly led to this colour discrepancy. Future research should consider using external cameras for colourisation, with consistent settings across all asset faces, including when the face is in shadow. However, it should be noted that this process may lack precision in the modelling phase.

The research yielded many positive outcomes, though it fell short of resolving all challenges due to limited site access. The case study presents an opportunity for further investigation, including:

Locating and processing the missing raw Trimble data from the first group for a deeper understanding of the issues.

Sharing the coordinates and context of three geolocated points, along with measurements relative to the station grid.

Conducting and storing investigatory scans from five groups, encompassing three and nine stations each, plus a control group, for processing.

Analysing investigatory models to develop a solution for consistent and accurate data capture.

Improving material point cloud quality through scanner settings, multiple scans at the same station, and photogrammetry.

Comparing digital camera images taken with manual settings to determine the necessity for image capture in point colourisation.

Capturing data for the entire site (approximately 112 stations) using a refined workflow, ensuring comprehensive documentation of data capture locations, scanner settings, weather data, targets, etc.

Registering data from campaign groups into a single model, verifying accuracy, and checking for missing data or misalignments.

This summary has reviewed the research requirements, iterating towards an appropriate workflow for precise parametric data capture at the site of the Hawara Pyramid and potential labyrinth area. A site visit has informed a robust data-gathering plan, employing synthetic targets within the field of view, aligned with the standard workflow framework: plan, gather, register, and export.

The current point cloud data has been cleansed of halo effects likely caused by parasitic points, and alignment has been enhanced, though recolouring is pending to reduce the blue hue. Additional experimental data is needed to address the lack of return information from mud-brick areas within the pyramid. The parameters for these campaigns have been meticulously defined, ensuring that operators can accurately capture the necessary data.

Despite progress, the original objectives have not yet been fully realised. Further analysis of experimental stations will inform potential workflow adjustments, ensuring the capture of robust, accurate data as outlined in the case study. Further research should investigate the impact of surface material on model quality, supporting heritage conservation efforts.

It is recommended to repeat the exercise every 2-5 years to monitor the pyramid's condition and identify areas of erosion. This approach, supported by literature, aligns with UNESCO principles for preserving significant heritage sites. A final proposal includes using the baseline model to monitor changes during the dewatering process. Fixed scanner locations, set at site extremes and frequently referenced using GNSS, will ensure accuracy. Capturing data during nighttime single stations may offer greater precision than registered clouds, enabling the identification of irregularities and changes for analysis.

When evaluating the contribution of the case study, the international dimension emerged as a critical factor, particularly in relation to the challenges posed by the materials of the pyramid and the alignment of the equipment due to surface complexity. The primary insights, as illustrated in Figure 58: Considerations for a LiDAR Campaign, centred on the logistical and technical difficulties associated with remote geospatial data acquisition. This

added layer of complexity facilitated a deeper understanding of access protocols, permission structures, local context, and environmental conditions. Moreover, the significance of the human element - 'People' - was brought into sharp focus through this case study. The principles encountered stood in stark contrast to prior experience, thereby underscoring the imperative for advanced knowledge and specialised skills to ensure the delivery of high-quality outcomes. These insights were subsequently integrated into the broader framework, enriching the scope of considerations and enhancing its overall robustness.

4.12 Case Study 3 – Ducal Palace, Nottingham Castle, Nottingham

This case study was made possible by Seedcorn funding from the Global Heritage Research Theme at Nottingham Trent University tied to the University Strategic Compact Agreement with Nottingham Castle. The Ducal Palace is located in the grounds of the Nottingham Castle and is operated by Nottingham City Council as partners agreeing to the initial stages of the project leading up to the refurbishment. Nottingham Castles Trust took over the operation of the site at the beginning of the refurbishment and graciously provided access after completion of the work as the site was being prepared to open to the public. The Centre for Architecture, Urbanism and Global Heritage at Nottingham Trent University supported the research which included the generation of the digital models, the historic research and subsequent 3D film/VR model. They also directed the arrangement of the workshop at which the VR model was tested.

4.12.1 Purpose

The section is a comprehensive exploration of the vital phase of data gathering for a digital model in the context of the Ducal Palace (see Figure 34). The research case study encapsulates both geospatial and historic data which underpin the digital model. The focus is to aggregate collected data diverging from the current common approach of vectorised and historic as single entities. The approach outlines a meticulous process to gain point cloud data alongside the analysis of historic data capture. The multifaceted methodology enables the synthesis of a robust and nuanced representation of the asset delivering valuable insight.

This archetypal project case study illustrates and tests the efficiency of the campaign for data acquisition. Elucidating the complexities provides valuable insights as to fundamental opportunities and challenges in creation of digital models for complex architectural structures. This rigorous examination of procedures associated with the data capture sets the stage for subsequent analyses and developments in the digital modelling arena.

This image has been removed by the author for copyright reasons

Figure 34: Nottingham Castle Ducal Palace atop the rocky outcrop viewed from south (Nottingham Castle)

This research initiates a resource charting the building evolution using archival material, records and surveys within a current, accurate digital model. The occupier in managing the asset will collaborate to develop a research-led digital offer, an open resource with additionality for use in interpretation and education. The 3D films were uploaded to YouTube, views show an interest from stakeholders, an indicator as to the additionality of such an output. A workshop will test the VR output to gauge stakeholder interest. The workshop was by invitation therefore all stakeholders were from the involved group. The model focused on two areas, the first-floor gallery where the gamer interacts with the art and the external areas in a 3D film.

Developing the information repository will provide organised access for stakeholders throughout the building lifetime providing resilience as the building evolves to support the needs of the community without losing sight

of the significance and social value. Notable here is the need for the model to evolve alongside the asset. Furthermore, this investigation will extend the research on digital and immersive reality of heritage to high levels of accuracy.

The iterative process of data capture allowed an action research development of knowledge for the surveyor and the data acquisition process in a plan, capture, register, review and process. The use of modern equipment also covered the use of a mobile device which allowed in field initial alignment. This can induce quality in the solution and revise the workflow to plan, capture, align, review, capture, align, review, register, process and quality assurance. It is notable the capture, align, review process can be cyclical and assumes initial planning covers the underpinning required for the process. When surveying for geospatial data utilising a LiDAR instrument the planning stage determines base information such as time required on site, equipment requirement, risk assessment, transportation, basic parameters for stations. It should be acknowledged this is a dynamic process where the plan will be revised in an iterative manner as the project proceeds.

Historic data was identified in map, drawing, photograph and written format. Nottingham Archives have a wealth of information as has the local library and the city has the advantage of a private subscription library containing local history. Bolstering the knowledge is the local Civic Society who have contributed to numerous articles and written guides, books, pamphlets which are a rich resource. Assets were also identified nationally for example in the British Library. A timeline was developed to plot the Ducal Palace development inside the Nottingham Castle walls to destruction by fire and redevelopment as the first municipal gallery outside London. This data incorporates the uses and change foisted on the structure over the time from mid seventeenth to late nineteenth century.

The models are currently discrete being digitally heavy, merging the historic data and the accurate model requires specialist software which is outside the remit of this research. The digital models include the first-floor art gallery, the ground floor temporary gallery, the external envelope with roof pre-refurbishment, the courtyard archaeological dig and the external envelop post-refurbishment.

4.12.2 Introduction

Nottingham Castle, strategically situated atop a sandstone outcrop overlooking the plain, is an important site of heritage comprising a Scheduled Monument with several listed components. The most prominent of these is the Grade I listed Ducal Palace. The castle's history is deeply intertwined with Nottingham's and, at times, the nation's narrative. Initially a timber earthwork, it played a significant role as a Civil War stronghold, surveying the Trent Valley. The stone walls replaced the timber and were slighted in the mid-17th century, and the ruin was later sold to the Duke of Newcastle, who erected the Ducal Palace. Over time, the palace was repurposed for rental accommodation and even considered for a school, but it was ultimately abandoned. In the wake of the 1831 Reform Bill riots, the palace was gutted by fire.

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Figure 35: Nottingham Castle Site today from North-east, foreground Gate House with visitor centre to left and Ducal Palace at rear (MyNottinghamNews)

The Nottingham Corporation acquired the site, transforming it into the first municipal gallery and museum outside London. Architect T.C. Hind undertook a significant restoration, maintaining much of the building's exterior and reorganising the interior. The recent refurbishment has further enhanced the site, adding a visitor centre within the walls and an additional gallery.

Nottingham Castle has long been a focal point of local and national history, with its storied past verified by archaeological findings. Like many historic structures, the castle has undergone a quiet evolution.

As the first municipal art gallery outside the capital, Nottingham Castle has undergone minimal alterations until a recent significant refurbishment, funded in part by the National Lottery, (see Figure 35). The site, comprising a Scheduled Monument, includes the walls and various listed components, with the Ducal Palace being the largest. Additionally, a cave system beneath the rock is designated as a second Scheduled Monument. This research focuses on the Ducal Palace as a tangible heritage asset visible to visitors approaching Nottingham from the south, symbolising arrival and place. The intangible heritage—comprising the stimuli and ideas shaping the building's design and its evolution—is equally significant.

The historical trajectory from a derelict castle site to a museum and art gallery is explored in the following section. The recent refurbishment aimed to ensure the site's sustainability for future use. However, many historical elements, including medieval and 19th-century additions, have not been digitally documented or analysed. In heritage-based refurbishment projects, especially those addressing maintenance deficits, there is potential for loss of material and, consequently, historical significance. Historic England defines the significance of tangible heritage, such as the Palace, as "… *the sum of the cultural and natural heritage values of a place, often set out in a statement of significance*" (Historic England, 2008, p.72). The intangible heritage—comprising collective memory and cultural value — is often tied to the tangible elements, extending beyond visual appeal. The populous of Nottingham and beyond in spending days out in exploration, or lunchtimes from work in the city roving the grounds or seeing the castle upon return to Nottingham from the south, all adds to the value of the local landmark.

The recent renovation emphasises sustainability, potentially necessitating changes that may impact the historical fabric. Appreciating historic details should guide such interventions, minimising any loss of significance. The digital model has the provision to contribute to the city's heritage management by rediscovering history and developing a data-led 3D model accessible to all stakeholders. The challenge outside this thesis lies in

arranging an accessible platform for data interrogation by owners, custodians, archivists, historians, and the public, simply the involved and peripheral stakeholders.

The literature review underscores the importance of an accurate digital model as more than a repository; it can facilitate monitoring and potentially reversing changes. Accurate data is crucial for informed decision-making, but until now, this information has been scattered across archives, accessible only to those with the means to seek it out. Listing a building, while delineating elements of importance, encompasses the entire structure, including its setting, and is protected by law from unauthorised alterations. The statement is a short summary with no nuance lacking richness required for even the basic conservation maintenance project.

The historic research charts the building's evolution using archival material, records, surveys, and an up-to-date digital model. The now-disbanded Nottingham Castle Trust collaborated in developing a digital open resource for interpretation and education, supporting future asset management through a novel methodology for information structuring via digital modelling and virtual heritage platforms. This repository will provide organised access for stakeholders, preserving the building's significance and social value as it evolves to meet local need.

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Figure 36: Nottingham Castle walls from the entrance looking south with the visitor centre just visible (Purcell)

This case study started at a pivotal moment in the site's history, with declining visitor numbers, mounting maintenance issues, and limitations due to inadequate environmental conditions. Nottingham City Council decided to transfer the site, including the palace, to a trust managed by local stakeholders, alongside funding to address maintenance deficits and secure a Lottery-funded grant for site development. This development included relocating visitor facilities to a purpose-built centre within the castle grounds (see Figure 36), freeing space in the palace. The palace was redeveloped to feature larger temporary galleries with climate-controlled environments suitable for fragile touring collections. Additional gallery space was developed in the kitchen courtyard, and a mezzanine area was removed to reveal the true height of the space. Simultaneously, work was completed to improve accessibility and improve the visitor flow.

Comprising comprehensive data, the case study includes geometric data collected before, during, and after the site's refurbishment. The archaeological dig uncovered courtyard foundations, recorded before being infilled for new gallery space. The post-refurbishment campaign revisited the site to capture internal and external features.

Nottingham City Council, as the building's owner, facilitated data collection. The Nottingham Castle Trust, responsible for the site's management and future use, collaborated in this research, utilising the data to support educational aspirations. The digital model of the temporary gallery space will aid in planning exhibitions. The Trust handed back the building to the City Council who are again tasked with making a success of the asset, another step in the historic journey. This academic overview provides a comprehensive understanding of Nottingham Castle's historical and cultural significance, underscoring the importance of its preservation and the innovative methodologies employed in its recent refurbishment.

4.12.3 Historic Narrative

This history emanates from text published since the sixteenth century found in local archives to provide the social context surrounding the development of the Ducal Palace on the Nottingham Castle site. Important events populate the timeline (see Figure 37).

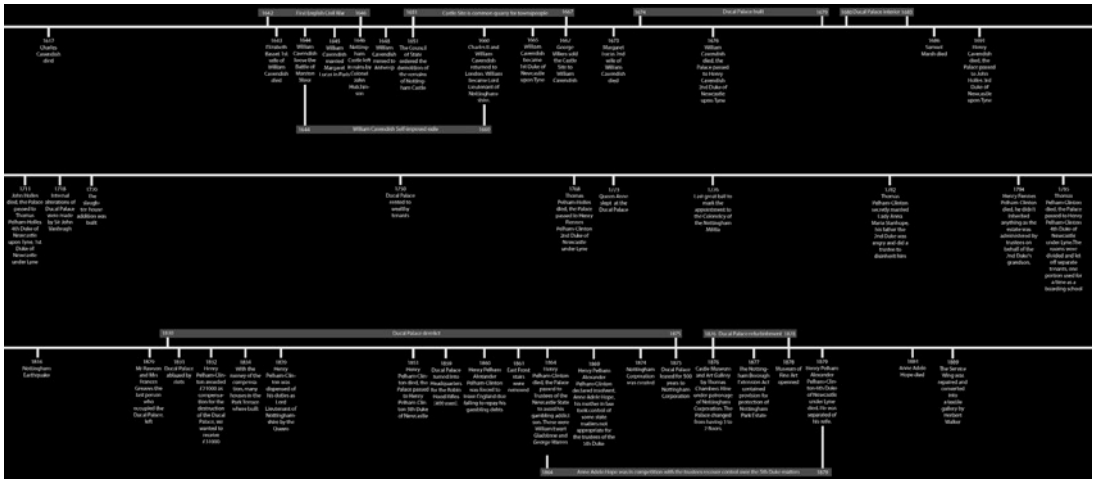

Figure 37: The history of the Ducal Palace in Nottingham (CAUGH)

The full version of this historic narrative is found in Appendix 1. It charts the period from the reign of Charles II until the restoration as the first municipal museum outside London. The palace was constructed in the grounds of Nottingham castle (See Figure 38) by the Duke of Newcastle, was burnt to the ground becoming ruinous, a roofless shell before rising once again (See Figure 39/40).

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Figure 38: Nottingham Castle guarding the bridge on the River Trent (Royal Palaces)

Thomas Hine, a local architect proposed major internal changes and restored the external envelope. The gallery was opened to the public in 1878 by the then Prince of Wales, soon to be King Edward VII, and his wife, under the

directorship of George H. Wallis, Wood & Reese (2016). The Palace remained until 2018 virtually as Hine left it on the completion of the project.

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Figure 39: The ruins of the Ducal Palace after the fire (Picture Nottingham)

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Figure 40: Nottingham Castle as a ruin (Hine, 1876)

The most recent refurbishment, completed in 2021, represents the latest iteration in the history of the Ducal Palace. This renovation eliminated any existing maintenance deficits and removed several previous modifications, allowing the rooms to be restored to their original proportions. Following an

archaeological excavation in the kitchen courtyard to the north of the main building, the area was enclosed to create a new gallery showcasing rebellion.

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Figure 41: Ducal Palace post-restoration new entrance into gallery through tunnel (Nottingham Castle)

This gallery can be accessed via the previously closed Victorian tunnel, which now serves as a new entrance to the palace (see Figure 41). A new lift provides access to the upper levels, where visitors can explore both temporary and permanent exhibition spaces. The stakeholders are now contributing to the intangible history of the castle, which hosts a variety of events including days out, markets, workshops, comedy performances, speakers, and more.

4.12.4 Detail

There were five campaigns undertaken between 2017 and 2022, each resulting from the collaboration between Nottingham Trent University and Nottingham City Council. When Nottingham City Council handed the reins to The Nottingham Castle Trust these continued. The five can be titled as;

a) First Floor Gallery – Permanent and Temporary Exhibition space before renovation

b) External areas – Facades, kitchen courtyard, tunnel, gatehouse and roof areas before renovation

c) Kitchen Courtyard – Archaeology including the arched storage areas

d) Ground Floor Gallery – Temporary Exhibition space after renovation

e) External areas – Elevations only after renovation – Clockwise colonnade to new entrance

The research involved additional staff during the first three campaigns. In each instance, the objective was to obtain accurate, high-quality digital data while minimising instances of occlusion. The scope of the project extended to include areas both immediately internal and external to the working area, serving as a link between internal and external campaigns.

Except for the roof, all campaigns utilised the Leica Scanstation P20 terrestrial laser scanner, mounted on a survey-grade tripod. The roof areas were surveyed using a BLK360 G1 scanner, remotely controlled via an Apple iPad. All stations recorded RGB images captured by the internal cameras. Targets were trialled in external areas to compensate for potential deficiencies in natural targets; however, these proved unnecessary. The most challenging task in the external areas involved establishing a connection between ground-level and roof-level stations. All external campaigns were conducted during the summer months in dry conditions, as discussed further in the analysis section.

The data collection for the first-floor gallery and external areas occurred while Nottingham Castle was open to the public, albeit during a period of low visitor numbers preceding the closure. However, during the final stages of the external areas campaign, preparations for reopening caused some disruptions, such as noise and people walking through the scene, which occasionally necessitated pausing and restarting the scanner. Additionally, the presence of parked and moving vehicles introduced issues of occlusion, which will be elaborated upon in the analysis section.

Final scanning locations were determined on-site to minimise constraints on the quality of the point cloud data. For the external areas, the project was divided into three groups to manage the large digital model. The groups included the roof surveyed using the BLK360 scanner, the kitchen courtyard and tunnel leading to the gatehouse, and the elevations of the Ducal Palace. All locations were documented on a site drawing and numbered according to the automatic system within the scanner.

The general workflow followed a linear pattern, particularly in the Ducal Palace elevations, where the process involved a clockwise circuit around the building, linking the roof at the colonnade, the roof over the kitchen block and the kitchen courtyard. Only in the elevations area were targets employed. The procedure involved setting the scanner on a tripod, levelling the tribrach, and positioning targets on either side, also levelled. The Leica equipment allows the tribrach to remain levelled on the tripod while interchanging the target with the scanner for efficiency, requiring only one tripod to be moved and levelled.

The scanner operates with four batteries, two of which are used during operation, with one serving as a backup and the other as a counterbalance. These batteries can be hot swapped to ensure continuous operation. On the most demanding days, battery replacement was not necessary. The carry handle can be removed during operation to avoid missing a 'cone' of sky or ceiling, but care is needed when reattaching it. Data is stored on the scanner's Hard Disk Drive (HDD), a slower storage system compared to the BLK360's faster Solid-State Drive (SSD). All stations' data is organised into a common file structure within the scanner's memory before acquisition begins, containing files for point cloud data and RGB images.

Data can be downloaded via Wi-Fi, cable connection, or, in the case of the P20, a memory stick, with cable connection providing the fastest transfer speed. This was only necessary post-campaign, as the onboard memory was sufficient for all collected data. Leica Cyclone software is used to import, unpack, unify, clean, and register the point clouds, or alternatively, to export each station in a universal file format compatible with point cloud software. The final processing, including unification, registration, and cleaning, can then be completed in the universal software.

The data acquisition began at the north staircase of the first-floor gallery, progressed through the permanent art exhibition, moved into the temporary ceramic area, and concluded at the head of the south staircase. The resolution was set to 3.1mm at a distance of 10 meters, with the quality set to 2. RGB images were captured at a maximum resolution of 1920x1920, with the white balance set to 'Warm Light.' The files were subsequently imported into Leica Cyclone and automatically registered (see Figure 42).

Figure 42: Ducal Palace First Floor Temporary Exhibition space – Note - the circle on the floor positioning the scanner infilled with data from another station and minor visitor occlusion on the wall (By author)

The data was cleaned and exported into various file formats, serving as the foundation for a VR experience to be integrated into free 4D gaming software. The proximity of the points in the point cloud enabled the creation of a high-quality mesh for the digital model, ensuring accuracy. The research partners provided high-resolution images of the artwork as JPEG files, which were overlaid onto the 3D model, enhancing the representation of the point cloud version. Interactive triggers within the model displayed the title of each artwork both audibly and visually.

This VR setup was tested, as shown in Figure 43. Although it did not achieve gaming-level quality, it successfully demonstrated the concept of disseminating knowledge to a broader audience. Feedback from stakeholders during the workshop indicated a strong desire for additional digital content, as discussed further in the analysis section.

Campaign b) External areas split into three groups, Leica Scanstation P20 elevations, Leica Scanstation P20 kitchen courtyard to main gatehouse and BLK360 roof areas.

The scanning process began at the top of the steps in the northeast corner, with the scanner positioned to overlook the lower kitchen roof. The scanning proceeded along the east side of the Ducal Palace in a clockwise direction.

The RGB settings were configured for a cloudy sky, with a resolution of 1920x1920 pixels and a point cloud resolution of 6.3mm at 10 meters, with a quality setting of 2. The workflow involved leapfrogging the targets and the scanner. The setup included seven stations along the east side, four along the south, nine on the west — due to the area outside the colonnade — and six along the north face, with additional stations on the bridge and the stone staircase landing, completing the circuit at the top of the staircase.

Figure 43: Ducal Palace First Floor Permanent Gallery space VR experience in testing (By author)

On the following day, a new group was conducted utilising a similar survey method starting from the room at the top of the stairs to the caves, including three stations in the courtyard, three in the tunnel, and six down to the gatehouse and through the entrance to the highway. The instrument has the capability to capture point cloud data up to 120 meters, which allowed the inclusion of surrounding contextual data. However, the resultant point cloud model was extensive, and removing distant data proved beneficial.

As is typical with models created using this method, no data was captured at roof level from the ground. Therefore, a Leica BLK360 scanner, controlled with an iPad Pro, was employed to collect additional data. This combination allowed for real-time model construction during data capture, aiding in identifying occluded areas. The BLK360, equipped with a single battery, can

last for over 40 stations, capturing both point cloud data and images. A single battery sufficed for the Palace roof survey. The BLK360's specifications, including a maximum range of 60 meters and a 360° x 300° field of view, make it highly capable at short distances, such as those encountered at roof level. Set to a high resolution with a point density of 5mm at 10 meters, it provided slightly better detail than the P20's setting of 6.4mm at the same distance. The survey began at ground level on the east side to overlap with the P20 data before proceeding to the roof. Targets were strategically placed to assist in merging the two data sets. The compact size and lightweight nature of the BLK360 made it particularly useful in confined areas around the roof, especially behind the parapet.

Figure 44/45: BLK360 G1 scanner on tripod - LHS image Main Roof Southwest immediately to rear parapet and RHS Ducal Palace kitchen roof with North elevation backdrop (By author)

However, the exposed nature of the Palace roof and the lightweight construction of the instrument resulted in unsatisfactory outcomes during the initial attempt. High winds and the fully extended tripod caused movement during data capture, compromising the results, which were subsequently discarded. As the iPad recorded the stations, a predetermined schedule was unnecessary, and adjustments were made as required. The roof's complexity necessitated further modifications after reviewing the initial data. Additionally, large sections of the lead valleys and parapet gutter were

inaccessible due to elevated walkways, which impeded data collection in these vulnerable areas (see Figure 44).

A subsequent attempt at roof level proved more successful, benefiting from insights gained during a careful analysis of the initial effort. The improved conditions, including lower wind speeds and a non-extended tripod, enhanced stability. The scanner's baseplate, allowing for flat-surface mounting without a tripod, further increased stability in exposed locations. An additional issue arose when the iPad overheated due to prolonged exposure to sunlight, despite a recorded maximum shade temperature of only 24°C - within Apple's specified operating range of 0-35°C. This was mitigated by ensuring the iPad remained shaded during scanner relocation and operation. However, due to a risk assessment, the scanner could not be placed directly on the stable parapet walls along the east and south elevations, as the public was present in the Castle grounds immediately below.

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Figure 46: Nottingham Castle Ducal Palace Southwest corner point cloud digital model single group without roof areas (CAUGH)

The lower roof area of the kitchen, accessible from the west elevation (see Figure 45), posed challenges for comprehensive data capture due to the presence of numerous upstands. Eight scans were conducted under cloudy skies in a zigzag pattern, concluding near the gate at the top of the steps, where the main elevation data collection commenced. The proximity of the main roof, which overlooks this area, and the overlapping nature of the elevation scans facilitated the integration of datasets, resulting in a high-quality model. The RGB data captured by the BLK360 employed HDR technology to produce spherical images with a 360° x 300° field of view.

However, on the north elevation, this resulted in a blue hue as seen in Figure 48/49, which will be further examined in the analysis section.

Due to the large file size, the data was downloaded from the scanner using a cable connection, with a backup copy saved. The workstation was equipped with a 4K display in addition to the standard screen, and the video driver was optimised to prevent slowdowns during regeneration. Files were uploaded in batches to the Leica Cyclone software for registration. Extraneous elements were removed, leaving only the Ducal Palace and the immediate surroundings, including paths, trees, and landscaping, as shown in Figure 46. In Figure 47, the dataset is registered but not cleaned. In Figure 48, three groups are merged, with the blue hue from the BLK360 visible, and in the foreground the subterranean vaulted ceiling storage areas can be recognised. The final image in the series, Figure 49, illustrates the northeast corner with the three groups merged, where the blue hue is confined to the roof area. The glass in the windows was removed to eliminate reflections to leave a uniform appearance. Some areas, such as the parapet, windowsills, and window heads, are missing from the scan due to the scanner's inability to capture these surfaces (see Figure 46/47). For the digital model at parapet level, these elements were represented as flat surfaces without texture. Several potential solutions were considered to address this issue, with the most suitable involving a rig to hang the BLK360 scanner (or a camera for photogrammetry) over the parapet. However, the associated costs and public safety concerns made this approach challenging.

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Figure 47: Nottingham Castle Ducal Palace looking west towards gate house - point cloud digital model two groups delivering a high-quality output (CAUGH)

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Figure 48: Nottingham Castle Ducal Palace Northwest corner point cloud digital model showing vaulted subterranean storage areas off the kitchen courtyard (CAUGH)

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Figure 49: Nottingham Castle Ducal Palace Northeast corner point cloud digital model showing roof areas added note blue hue around the kitchen roof from BLK360 data (CAUGH)

It is important to note that the ornate window depicted in Figure 50 is a remnant of the original west entrance door, characterized by a rounded or segmental pediment and columns. An examination of App. Figure 3 (See Appendix) shows a plan indicating steps leading to an entrance where the current colonnade stands, corresponding to the opening visible in the image.

Initial excavation pits in the kitchen courtyard revealed various archaeological finds. Following a comprehensive archaeological dig, which uncovered modern drainage systems and remnants of structural foundations, all artifacts were removed, leaving only the structural remains. A survey campaign was initiated using the Leica P20 scanner, referred to as c) Kitchen Courtyard – Archaeology, including the arched storage areas. The weather was dry but overcast, with damp ground conditions. No targets were necessary due to the abundance of natural features. The scanner settings were configured at

6.4mm resolution at 10 meters with a quality setting of 2, and the RGB images were set to 1920x1920 for overcast conditions. Despite the reflective, closed-cell material surfaces and the irregular nature of the stones, a higher quality setting would not have significantly enhanced the data; instead, it could be determined the images, and their locations were of greater importance.

Figure 50: Nottingham Castle Ducal Palace West Elevation over colonnade - original door opening (By author)

The scanning commenced in the Victorian tunnel and proceeded in a zigzag pattern across the site, concluding in a small room located in the northwest corner. To ensure high-quality data acquisition, numerous stations were established to accurately capture the structural foundation remnants present in the ground, as depicted in Figure 51. During the refurbishment, the archaeological remains were carefully backfilled, and a concrete floor installed to protect them prior to the construction of the new gallery.

The data was downloaded, backed up, imported into Leica Cyclone, and then unified and registered. Minor cleaning was performed to remove artifacts such as people and a barrow from the excavation work, but the overall scene

remained largely unaltered. The file was exported in the E57 format for distribution to the stakeholders.

Figure 51: Leica P20 Scanner on surveying tripod in kitchen courtyard at West end with door to caves in the background (By author)

During the refurbishment, the entrance was reconfigured to include the Victorian tunnel, and the reception, shop, and café were relocated to the new visitors' centre near the entrance bailey. The ground floor changes were documented under the campaign d) Ground Floor Gallery – Temporary Exhibition Space After Renovation. The refurbishment resulted in open areas designated for gallery space, see Figure 52. Before the first exhibition introduced bold colours to the walls, the area was scanned to provide an accurate record.

The scanning process began at the base of the south staircase, following a zigzag pattern through the space with additional scans positioned at the doorways between rooms. The resolution was set at 6.4mm at 10 meters, with a quality setting of 2, suitable for the straightforward nature of the spaces. The RGB images were captured at 1920x1920 with a warm light setting to accommodate the artificial lighting. A higher resolution was deemed unnecessary due to the simplicity of the space, the effective reflection off the white walls, and the lack of intricate details.

Figure 52: Leica P20 Scanner on surveying tripod in the new exhibition space middle gallery (Note use of spider to protect the floor and provide a rigid support) (By author)

In the central space, doors on the east elevation provide external access. To facilitate future integration with the external model, a scanner station was strategically placed in the gallery doorway and on the path immediately outside. The reflective nature of the floor material may cause slight discoloration in the point cloud data. Occasional foot traffic necessitated pausing the scanner to enhance data quality and streamline the registration process. Environmental conditions are maintained by glazed entrances with automatic glass doors at each end of the gallery series.

The scanner data was imported and backed up. The subsequent unification and registration process required minimal cleaning, as the scanner had been paused during data acquisition. However, additional cleaning was needed around the glass lobbies due to reflections and refractions. The files were exported in LAS and OBJ formats for use by the owner (an involved stakeholder) in planning exhibitions. It is noteworthy that the file size was

approximately 900MB, which may present challenges for average computers to import.

The final data acquisition campaign consisted of eighteen stations, designated as e) External Areas – Elevations Only After Renovation – Clockwise Colonnade to New Entrance. Given prior experiences at the site, where target usage was deemed unnecessary, this campaign relied solely on the scanner. Although the roof underwent significant refurbishment, it was not included in the data acquisition due to access constraints. The objective was to document

Figure 53: Leica P20 Scanner on surveying tripod sited on path back to the visitor's centre overlooking the new entrance (by Author)

new areas and interventions to showcase the site's development. As Nottingham Castle was approaching its reopening, eighteen scans were completed, leaving the east and south elevations incomplete. The scanner settings were consistent with the initial scans, at 6.4mm resolution at 10 meters, with RGB images at 1920x1920 under clear skies. The weather was bright with 50% cloud cover. The scanner was paused when people moved through the scene, and at one point, it stopped due to becoming unlevel. On

the north elevation, additional stations were required to capture the newly inserted gallery fully. The route then continued down the hill towards the gatehouse before turning back to the new entrance at a lower level, see Figure 53.

The data was downloaded and securely backed up to the cloud before each station was individually opened and cleaned. This process involved removing residual elements from the construction project, such as parked vehicles and passersby. Generally, any resultant voids from the cleaning were addressed during the registration of the eighteen stations. Significant cleaning was required around the windows; incomplete glass areas and internal artifacts from the glass within the palace were meticulously removed. The shadows recognised in Figure 54 are visibly transferred to the point cloud, highlighting another generalisation in digital data resulting from the scanning process. Extraneous areas outside the scope of the site were eliminated to reduce the file size. The prepared data was then shared in the E57 file format.

Figure 54: Nottingham Castle West elevation colonnade post refurbishment uncleaned note areas of shadow (By author)

The data pertaining to the Nottingham Castle Ducal Palace holds a distinctive position, unobstructed and exposed to the elements on all sides. This exposure allows for the capture of data without interference from flora, water bodies, or highways, facilitating the creation of a high-quality model. The ashlar stone, being neither too light nor excessively dark, permits excellent colourisation and textural detailing, although occasionally bright weather has introduced high contrast. Despite the exposed nature of the site, significant

weathering of the elevations is generally absent, a quality of the stone material.

Local adverse weather conditions necessitated the installation of glass to enclose the colonnade, ensuring that the environmental requirements for the travelling exhibitions are satisfied in the ground floor gallery. This enhancement aligns with the purpose of the Ducal Palace and generates additional revenue for the Nottingham Castle site. The modifications represent a minimal intervention, thereby preserving the historical significance of the asset. Consequently, the development of the Ducal Palace is evident not only in the addition of glazing but also in the integration of a gallery in the kitchen courtyard and the new entrance utilising the Victorian tunnel. Internally, the new temporary galleries restore the space to simple volumes, allowing the understated architectural details to be prominently displayed. The initial campaign did not encompass the entire area; however, at the intersections of the external acquisition, the space immediately inside the East entrance included data. This can be compared to the gallery model to illustrate the development of the space.

Each campaign undertaken on this Grade 1 Listed monument has undergone rigorous scrutiny, enabling iterative improvements in the process. This case study has contributed unique insights into digital modelling, encompassing both data capture and initial processing. The emphasis on quality has fostered a comprehensive understanding of both the internal and external areas, as well as archaeological excavation for documentation and practical use. Building on previous case studies, active research has been advanced.

4.12.5 Analysis

The case study underwent five distinct iterations over the course of the research period, with the synthesis of the action research being thoroughly examined in this section. The emphasis on quality in the research is particularly noteworthy, as it upholds the value of significance as the guiding lens for the final framework. Data acquisition was conducted both internally and externally, with environmental conditions shown to have a measurable impact. A notable difference was observed in the accuracy achieved, calculated using Leica Cyclone software. Typically, following registration, an external campaign involving flora and other movement achieves an accuracy

of approximately 15mm. For internal projects, this figure improves to a maximum of 5mm, likely due to the reduced influence of environmental factors such as flora movement, though this was not further researched.

The initial campaign in the gallery space employed a high-resolution point cloud, enhanced by settings of 3.1mm at 10 meters, which, although increasing capture time, provided greater detail. In subsequent instances, settings were adjusted to 6.4mm at 10 meters, balancing resolution with manageable file sizes and maintaining image and point cloud capture within a 15-minute threshold. This approach was effective in external locations, where it captured detail without producing excessive file sizes, and in simpler internal spaces, where the shorter distances ensured a high level of discernment and quality. Analysis of the point clouds revealed a consistent level of detail throughout, with no requirement for capturing data at higher resolutions. However, for specific features such as the busts in the colonnade, the use of handheld scanners is recommended.

The instrument's capability of capturing data up to a maximum of 120 meters enabled the inclusion of detailed settings, although the focus on the Ducal Palace positioned the site as the central setting. The grounds were documented from the gatehouse bailey to the Ducal Palace, illustrating the procession and revealing the palace in both the second (see Figure 47) and final campaigns. The inclusion of the surrounding setting aligns with the guidelines of Historic England and the NPPF, both of which recognise the physical environment as a crucial contributor to the significance of the asset.

Another critical consideration is the minimum distance required between the instrument and artefacts to obtain accurate data, generally set at 0.5 meters, though this is contingent on the reflectivity of the surface. Within the Victorian tunnel, it required careful attention and the tunnel's rightward bend helped mitigate potential issues. Internally, during the initial project in the gallery space, exhibits placed close to the wall caused occlusions at minimum distances, with the laser's raking across the surface reducing returns over a 70-degree angle of incidence to the perpendicular. As the distance from the instrument increases, the spacing between points also increases, making the careful determination of station positions essential to ensure model quality. The angle of incidence further exacerbates this effect, increasing the distance

exponentially. The final model revealed areas that were not fully captured, particularly beside larger art frames and grand decorative mouldings, which became especially noticeable in the meshed model used for the VR experience. For permanent exhibitions in the Ducal Palace gallery, it is advisable to position the instrument centrally, with regular intervals based on the size of the art frames. Although this approach was not tested as an alternative method, it would be a valuable exercise in future data acquisition. A close examination of Figure 42 suggests that this issue is mitigated to some extent by the spacing between the exhibits.

To prioritise quality, the optimal approach is not to decrease point density but to increase the number of scanning stations. While the P20 scanner offers slightly greater accuracy, it is the resolution that primarily influences the quality of the final output. The P20 has the advantage of shortening the distances between points; however, in smaller spaces and for assets with a resolution of 5.0mm at 10 meters, the BLK360 G1 achieves a resolution of 1.0mm at 2 meters, which is sufficient in many scenarios. Moreover, increasing the number of stations enhances overlap, thereby improving point density. During the registration process, duplicate points can be removed, reducing file size without compromising final quality. The P20 scanner, which requires approximately 18 minutes per scan, including re-levelling time, could be supplanted by faster instruments like the BLK360 G1. This device reduces scan time to six minutes at the highest setting, capturing 65 million points and eliminating the need for re-levelling, thus reducing station time to approximately eight minutes. This reduction in time is particularly advantageous when dealing with dynamic elements such as people and vehicles within the scanning environment, although newer instruments with software that compensates for movement mitigate these challenges. Further investigation is needed to assess any potential impact on quality.

Within the temporary gallery, the presence of glazed lobbies introduced significant challenges in the digital modelling process, leading to confusion within the model. This issue was identified in one of the external models, particularly concerning the glass wall incorporated into the colonnade. Although the artifacts within the gallery were meticulously removed, there remains a concern that the accuracy of the model for gallery planning might

be compromised. Conversely, retaining these elements could introduce complications for users who are less familiar with the space.

In the elevation models for the external structures, it was deemed essential to present a consistent and accurate representation. Consequently, the glass was removed from the openings, although the point cloud still retains traces of the glazing. The internal artifacts present in the building's elevations posed further challenges, as their presence could adversely affect the quality of the merged internal and external clouds. Therefore, these artifacts were carefully excised to maintain consistency across the model.

This issue is also evident in the final project, which includes the glazing in the colonnade. However, there is a necessity to retain some aspects of the glazing for asset management and developmental purposes. Only a few artifacts were identified outside the glazing line, and these were removed. This issue is likely related to the angle of the scanner relative to the glass, a phenomenon that warrants further investigation. The complexity of this issue is considerable, and it appears to be unique to the specific circumstances of any project.

Further research is needed to explore the nuances of this problem, particularly the interaction between the scanner's angle, the light, reflected images and the glass surfaces. Given the potential impact on both the accuracy of the model and its utility in future planning and management, this is a critical area for ongoing study.

The timber floor structure introduced minor movement, which, while not preventing the use of the P20 instrument, could extend capture time. Utilising remote control via mobile devices can mitigate this issue, provided the instrument can be levelled without significant movement during the process. The BLK360 G1, used on rooftops, eliminates the need for manual levelling by incorporating an enhanced internal compensation function. This feature further reduces station time, potentially improving the quality of the model by limiting the impact of human presence and subsequent occlusions. It is proposed that the operational parameters of the scanner significantly influence the outcome, not through accuracy or data collection alone, but through the workflow employed. The latest scanners combine the P20's accuracy with the BLK360's speed, particularly in image capture. A limiting

factor, however, is the image quality, which, while adequate for texturizing the point cloud, may overlook details essential for heritage recording.

During the second campaign, targets were employed with the aim of constructing an external digital model, segmented into three groups. The first group focused on documenting the elevations and immediate site, the second on the journey from the kitchen to the gatehouse via the Victorian tunnel, including the surrounding landscape, and the third on the roof areas. At ground level, stations used targets positioned on either side of the scanner, integrated into the workflow to allow for sequential scanning or 'leapfrogging' of the scanner. However, due to the presence of natural targets, these artificial targets were often unnecessary. An exception occurred in the roof area at the original entrance through the colonnade, where targets were required to ensure consistency between the point clouds. The automatic registration function in Leica Cyclone software successfully unified the cloud without further intervention, suggesting that in urban environments, the need for artificial targets is limited. Operators must assess each situation, particularly the overlap between internal and external campaigns, and the availability of natural features. The skill of the operator, as discussed in archaeological contexts, plays a crucial role in the effectiveness of this process.

This image has been removed by the author for copyright reasons

Figure 55: The Nottingham Castle Ducal Palace accurate point cloud model - at the LHS the Victorian tunnel is visible with the steps over, centrally the colonnade and the roof form (CAUGH)

The ground-level areas exhibited commendable accuracy, with a satisfactory quality of data and an appropriately justified number of scanning stations (see

Figure 55 included here with the permission of the project team showing project outputs). While the images used for colourisation were generally of good quality, an unexplained issue arose with the south elevation porch, where the quality was notably substandard. Images captured with an RGB camera were acquired for integration into the point cloud via the software. Furthermore, as illustrated in Figures 48/49, a distinct blue hue is evident on the North elevation and the roof of the kitchen extension. It is proposed that this anomaly resulted from the HDR function of the BLK360, which likely attempted to compensate for the low natural light conditions, an issue that did not affect the main roof due to the abundance of natural light during capture. The recommended solution involves accessing the image file as a single dome to fine-tune the colours or alternatively, removing the affected point cloud data to allow the P20 data, captured from the ground, to take precedence in that area.

The tunnel was documented using three stations, maintaining consistent quality despite the limited availability of natural light. Although the P20 scanner is equipped with HDR functionality, it was deactivated during this process, yet the model's colour fidelity remains satisfactory.

Occlusions caused by immovable objects presented a challenge, particularly the presence of a skip in the kitchen courtyard and debris in the vaulted subterranean storage areas, which compromised the quality of the data for the rear walls and floors. While the option to region grow the missing data to complete the digital model exists, this approach is coarse and would likely compromise overall accuracy. The strategic selection of station locations in the fifth project, following refurbishment, proved beneficial, particularly in areas where contractor equipment was present. By cleaning individual stations, objects could be effectively removed, and the unification of the point clouds allowed for the closing of voids with infill points. In external areas, the ability to pause the scanner was utilised whenever vehicles traversed the scene, thereby reducing the amount of post-processing required. On occasion, objects adjacent to the asset were temporarily moved and replaced after the scanning at that station was completed.

A level walkway, installed above the roofline, provided a stable platform for accessing all areas, yet it also obscured significant portions of the lead

gutters—an essential component of the roof's construction that requires periodic maintenance and immediate repair when damaged. The omission of data regarding the location of gullies or chutes, which are prone to blockages that can lead to leaks and subsequent internal damage, is concerning. A viable solution would involve manually inserting placeholders into the data to indicate these critical locations.

From an archaeological perspective, the selection of station locations warranted careful consideration. A high-level scan from the bridge was instrumental in aligning the mission with other campaigns, while the approach through the Victorian tunnel dictated the starting point of the linear progression through the space. The determination of station locations could not be accomplished through any method other than an on-site visit, thus placing the responsibility in the hands of the operator and relying on their skill to produce a reliable record. Voids were particularly prevalent on the ground between the remnants of the foundations, where shadows obscured the surface beyond. Notably, some foundations connected to the retaining wall of the kitchen courtyard, revealing the outline of steps that ascended to a section of wall infill at ground level, indicating access prior to the construction of the tunnel. Unfortunately, no archaeological report was received to compare the model with the findings or to insert placeholders for discoveries within the model.

The environmental conditions must be considered in detail, as they can significantly impact data acquisition in exposed locations. Although issues were observed in two instances, evidence suggests that such occurrences are rare and should be noted as exceptions rather than the norm. The roof areas, in particular, posed several challenges that raised concerns about the suitability of the smaller BLK360 instrument. During the initial campaign, high, albeit not dangerously excessive, wind speeds caused movement in the scanner and tripod, which went unnoticed during the initial unification performed via the mobile device. To address this, the acquisition was repeated under calmer conditions, occasionally with the scanner strategically placed on the parapet wall on the West and North sides to ensure overlap with the ground campaign. While this placement carried inherent risks, it also leveraged the roof below as a protective barrier for the public. Additionally,

in locations inbound of the parapet, the tripod was kept minimally extended to enhance the scanner's stability.

Another challenge arose when the mobile device connected to the scanner overheated due to direct sunlight on a bright, clear day, leading to a shutdown when its temperature exceeded operational limits. After cooling the device in the shade, operations resumed, and the device was subsequently kept shaded to prevent further interruptions. Although the scanner can function independently of the mobile device, doing so would eliminate remote control capabilities, potentially compromising stability and introducing occlusions that would require post-processing to remove from the point cloud. These issues underscore the critical role of environmental conditions in the accurate capture of digital model data.

Aligning the roof section with the other groups presented further difficulties, as it was tilted along the North-South axis. While the unification and registration process in the software allows for such adjustments, this added considerable time to the overall process. Additionally, the roof capture failed to include the outer parapet elements, resulting in data voids that detracted from the model's quality and clarity. To address this, a dark monolithic plane was introduced to fill the void in the VR model and subsequent films. Although not an ideal solution, it mitigates confusion within the VR environment. Alternative approaches include the use of photogrammetry software to create a model from photographs, which could then be integrated into the point cloud. Despite potential issues with scale, the accuracy of the point cloud would allow for necessary adjustments. However, cleaning the photogrammetry model around detailed elements, such as baluster shafts, would be essential, making a point cloud solution preferable for preserving accuracy.

The digital model was employed in a short film for stakeholders (See figure 60 included here with the permission of the project team showing the project output) and in presentations alongside the historic timeline (see Figure 36). Although there was limited direct feedback on these outputs, there was a consensus that digital media plays a significant role in heritage preservation, particularly in engaging younger audiences, albeit as a complementary rather than primary attraction. The digital component should enhance the

exhibition, be user-friendly, and remain manageable within the limited resources available to museums. Maintaining historical and archaeological accuracy is paramount. AR/VR experiences should be leveraged to enhance accessibility, especially for stakeholders unable to physically visit Nottingham Castle, including the cave system. Stakeholders also advocated for a digital application that vividly portrays the castle's historical development, thereby enriching visitor understanding and engagement. An accurate digital model of the castle site could serve as a catalyst for such an application.

The model was utilised to generate 3D content and uploaded to YouTube under the Centre for Architecture, Urbanism and Global Heritage (CAUGH) banner. There were three files, Galleries 360HR, Ducal Palace 3D Point Cloud and Ducal Palace GIS and to date views total 750. These required no specialist software to view. The Castle Workshop VR model has also been uploaded and to date has received >170 views. This identifies the potential of simplistic output to engage stakeholders.

Figure 56: A researcher demonstrating the VR walk through the permanent art gallery in Nottingham Castle (CAUGH)

Stakeholders tested the VR model of the gallery formed from the first campaign in a workshop organised by CAUGH , a later questionnaire revealed significant findings (see Figure 56 included here with the permission of the project team showing project outputs). Sixty percent of participants claimed above-average knowledge of the castle's history, potentially driven by their invitation and attendance at the Nottingham Castle workshop. The castle's significance is reflected in stakeholder perception, with 26% considering its importance beyond the UK, aligning with its status as recognised by Historic England. Notably, 95% of respondents believed digital content has a place in heritage, supporting the research's direction. Furthermore, over 60% of stakeholders had experience with VR and AR, and a similar proportion had used mobile applications, with slightly more (70%) engaging with digitised collections.

The feedback on the VR from the Global Heritage Workshop and Seminar: Engaging with Nottingham Castle Future in 2019 held at Nottingham Trent University was generally positive. One participant suggested incorporating a group experience or, at the very least, including virtual visitors, interesting since the digital model had been cleansed of human shapes. Other comments called for a more immersive experience with the artwork, specifically requesting higher resolution to achieve a quality comparable to photographs. This feedback indicates two perspectives: a desire for a more realistic experience or a primary focus on the art itself, this was not explored with the attendees.

Data from the scanned elevations, post-refurbishment, offers a valuable opportunity for comparison with previous campaigns to identify deviations, changes, and interventions over the span of three years. Although this analysis falls outside the current research scope, it is crucial to highlight it as a prospective area for future investigation. The integration of earlier data sets would facilitate a comprehensive understanding of these deviations, enabling a precise identification of areas where interventions have occurred. As previously discussed, existing research on stone defects, additive or reductive changes, structural stability, moisture infiltration, and damage or repair will enrich our understanding of the surface conditions. This, in turn, will provide a nuanced appreciation of surface modifications between data captures, thereby informing the system's capabilities.

The quality of the data was meticulously analysed to determine the optimal parameters for data capture, ensuring the creation of models with sufficient detail to monitor changes effectively. These models are crucial for inclusion in management reporting and strategic planning. As Barber et al. assert, *"The sampling of the point cloud is selected based on the detail required by the final product, with subjects with complex surfaces requiring high levels of sampling and accuracy."* Barber et al. (2006, p.36) A range of comparative analyses was employed, including manual procedures such as slicing through point-cloud data sets or applying incident lighting to meshes to assess shadowing. These methodologies require final assessment and detailed explication before visually revealing the areas of interest for future monitoring or intervention planning. Heat maps are particularly effective in this context, as they assist in identifying and quantifying differences, providing a visual record that highlights areas requiring ongoing monitoring or intervention.

The exploration of data captured in previous campaigns represents a critical area for future research, underscoring the fundamental importance of recording in heritage conservation. The data, stored in both raw and modelled formats, along with detailed records of each campaign, presents a unique opportunity for continued study. Specifically, the use of these datasets in new operations focused on the monitoring of building fabric is a particularly promising research avenue, especially when concentrating on key elements such as the façade, which is often considered the most significant aspect of the structure.

4.12.6 Summary

The case study highlights a number of key points which emphasise contributions to the quality of the digital models and issues emanating from the main contributors to the data capture including the methodology and the skill in the operative. The case study underwent five distinct iterations, thoroughly examining the synthesis of action research, with a strong emphasis on maintaining quality as the guiding principle for the final framework.

The ability to return to the site over five campaigns provides an action research opportunity in the single case study. However, not all acquisitions are directly comparable. When starting to plan an acquisition the output

requirement should be determined. In each situation the purpose of the model was known, the archaeological and gallery model were for record. The gallery moved into the realm of basis for a VR experience which shows versatility with an accurate comprehensive model. The temporary gallery model required a high level of quality to export for planning purposes. Finally, the post refurbishment data was to repeat the original external model for comparison. Whilst this is beyond the research focus it did highlight the inclusion of features in the asset and the setting which develops a new iteration in the history timeline.

Data acquisition, conducted both internally and externally, revealed that environmental conditions significantly impacted accuracy, particularly in external campaigns, where flora and movement reduced precision to approximately 15mm. Internal projects achieved greater accuracy, with deviations capped at 5mm, likely due to the controlled environment. The initial gallery campaign employed a high-resolution point cloud with settings of 3.1mm at 10 meters, enhancing detail but increasing capture time. Subsequent campaigns adjusted settings to 6.4mm at 10 meters, striking a balance between resolution and file size.

The P20 instrument's capability of capturing data up to 120 meters facilitated detailed site documentation, including the Ducal Palace and its surrounding grounds. Challenges posed by the impending public opening and access constraints limited comprehensive data collection. Internally, the placement of scanning stations was critical to avoid occlusions, especially in areas with complex architectural features. Increasing the number of scanning stations, rather than increasing point density, emerged as the preferred strategy to enhance quality. The study suggests that while newer instruments like the BLK360 G1 offer faster scanning times and sufficient resolution, further research is needed to assess their impact on data quality, particularly when the software is removing dynamic objects.

The digital modelling process in the temporary gallery encountered significant challenges due to the presence of glazing for example lobbies and the colonnade wall, leading to model inaccuracies. While internal artifacts were carefully removed to preserve model accuracy, this deletion could complicate the model’s usability for gallery planning. Conversely, retaining these

elements might confuse users unfamiliar with the space. In external elevation models, consistency was prioritised, leading to the removal of glass from openings, although traces remained in the original point cloud. Internal artifacts in window areas identified complications in merging of internal and external clouds, necessitating careful excision to maintain quality.

In the final project, the inclusion of colonnade glazing presented similar challenges, requiring a balance between accuracy and the needs of asset management. The issues, likely related to the scanner's angle relative to glass, light, reflections all highlight the need for further investigation for a high-quality solution. The timber floor structure introduced minor movement, which extended capture time, though remote control via mobile devices mitigated this issue. The BLK360 G1's internal compensation function improved model quality by reducing time at each station and reduced occlusions. The second campaign's use of targets revealed that, in urban environments, natural features often rendered artificial targets unnecessary, underscoring the importance of operator skill in achieving effective digital modelling.

The case study highlights significant challenges and insights in digital modelling, focusing on the use of scanning technology to capture and integrate data for heritage sites. Ground-level scans exhibited commendable accuracy with appropriate station distribution, but issues arose with colourisation, particularly with the south elevation porch. Furthermore, a blue hue likely due to the HDR function of the BLK360 G1 scanner is observed in the North facing elements of the Ducal Palace. The recommended solution involves either colour adjustment or prioritising data from alternate scans.

The tunnel scans maintained consistent quality despite low light conditions, but immovable objects such as skips, and debris compromised data quality. The strategy of carefully selecting station locations and cleaning individual stations improved model accuracy. In external areas, pausing the scanner to avoid moving vehicles minimised post-processing.

A level walkway installed above the roofline, while providing access, obscured essential components like lead gutters and gullies, risking data omission. This type of localised problem would not be simply resolved yet is typical impacting on the quality and usability of the model. The importance of station placement

was emphasised, particularly in archaeological contexts where again operator skill was crucial in avoiding data voids.

Environmental conditions, including wind and sunlight, posed additional challenges, affecting scanner stability and device functionality. Roof alignment issues required complex adjustments, and voids in the model led to the use of fills as a temporary solution, though point cloud data was preferred for accuracy. More research is required in this area.

At a workshop the VR model of Nottingham Castle's gallery was tested, yielding significant insights. A post-workshop questionnaire revealed that 60% of participants had above-average knowledge of the castle's history, and 95% supported the integration of digital content in heritage preservation. Feedback on the VR model was generally positive, with suggestions for a more immersive experience and higher resolution for artwork. Stakeholders' familiarity with VR, AR, and digital collections was high, with over 60% having prior experience. Online content showed a healthy engagement underscoring the benefit to engagement. This supports the notion that accurate digital models support stakeholder involvement.

Additionally, recent data from the refurbished elevations offer a vital opportunity for comparative analysis with previous campaigns to identify deviations and changes over the years. This investigation, although outside the current research scope, is crucial for future studies. Detailed data analysis ensured models with sufficient detail for monitoring changes, essential for strategic planning and management reporting. The continued exploration of historical data sets in future operations is vital, particularly focusing on key structural elements for example façades.

Revisiting the voids in the point cloud model particularly at high level, contemporary alternatives include using the recently released BLK2GO or BLK2FLY scanners, which employ SLAM technology and are effective at short range. These devices, capable of rapid data capture, do not require a rig to support over the parapet. For example, the handheld BLK2GO can be tethered to the operator, mitigating risk to those on the ground. The BLK2FLY is a UAS combining a scanning head with a quadcopter to complete autonomous data capture over elevations and roof areas. Alternatively, scanning could be performed early in the morning or late in the evening, outside crowded

periods, to eliminate risks. Given the high accuracy of the elevation point cloud, the less precise data obtained from SLAM scanners often can be integrated to enhance the model with small scale adjustment. This is an area for future research to determine a robust workflow.

This constituted the most comprehensive campaign undertaken, encompassing five distinct data acquisition excursions across the site. The initial internal survey engaged a diverse array of spatial configurations, varying in both scale and content, thereby offering valuable learning opportunities through problem-solving exercises aimed at constructing an accurate and holistic model despite inherent challenges. The subsequent external survey built upon insights gleaned from the first case study and was notably expansive, incorporating a full contextual mapping of the site - including, unusually, the roof area. This significantly reinforced the framework presented in Figure 58 – Considerations for a LiDAR Campaign, particularly in relation to the dimensions of Environment and Artifact.

Historical data were actively sought for the Ducal Palace, culminating in the appended Historic Narrative (pp390-399), which served as a comparative reference against the detailed digital model. This juxtaposition yielded critical insights that permeated subsequent dissemination activities, including seminars, exhibitions, and related events, with feedback from these engagements informing the development of the final framework.

Innovative elements were introduced, such as the deployment of smaller instruments to access the roof and peripheral equipment. The integration of these outputs into the digital model necessitated novel solutions that extended beyond previously encountered methodologies. The archaeological geometric model, informed by Case Study Two, facilitated the testing of these approaches within a more controlled and limited spatial context.

The final two campaigns afforded the opportunity to revisit earlier environments and scenarios, thereby reinforcing prior knowledge and enabling a more nuanced appreciation of solution variability. This iterative process served to refine the methodology and critically evaluate the considerations for a LiDAR campaign outlined in Figure 58.

4.13 Strategic Analysis from Case Study Outcomes

The following section synthesises the insights derived from the three case studies, offering a cohesive understanding of the processes and outcomes involved. In each case, the data was meticulously unified into an accurate model. Additionally, historical data was unearthed and employed to inform and highlight significant aspects of each heritage asset.

In the Arkwright case study the outputs aligning seamlessly with historical records. The second case study, however, faced challenges due to the geometric data being generated by a third party, which led to complexities in achieving a comprehensive understanding. The final case study involved five iterations of data capture to ensure a holistic comprehension of heritage project data acquisition, encompassing external, internal, archaeological, and artifact data. This case study also included the development of an asset timeline that traced the construction and occupancy of the building, thereby enhancing the understanding of its historical significance. In the latter two studies, historical data was leveraged to produce outputs that effectively engaged stakeholders. The digital model served as the foundation upon which additional layers were developed using gaming software, ultimately resulting in a VR experience. Stakeholders responded positively, indicating that the knowledge was effectively disseminated, and a deeper understanding was achieved.

Environmental conditions impacted two of the three case studies. For the pyramid case study, the specific environmental conditions during data capture were not documented. The location's consistent weather patterns with minimal precipitation should be acknowledged yet high temperatures posed a potential risk to the accuracy of the instruments. For more extensive campaigns, it would be advisable to provide shading for both the equipment and the operators to mitigate potential overheating. The castle's exposed location experienced extreme weather events, with squalling winds during the first roof campaign destabilising the scanner and corrupting the data. In a subsequent campaign, direct sunlight caused the mobile device to overheat and shut down. These incidents underscore the need to carefully assess the suitability of equipment and implement measures to counter environmental

effects, not only in terms of equipment selection but also regarding operator safety and efficiency.

In the Arkwright case study, careful consideration of station locations and scanner settings yielded a reliable model, though variances in colourisation due to diurnal lighting were observed. Similar issues were encountered in the second and third case studies, where intense sunlight resulted in high contrast, and internal spaces illuminated by artificial light posed additional challenges (see Figure 42). The instrument's adjustment capabilities are coarse, making it difficult to compensate for fluctuating external conditions. An alternative approach could involve colourising the model using images from a remote camera, allowing for greater adjustment. However, this method requires a highly skilled photographer to ensure uniform conditions. Mismatches between point clouds and colourisation can result in inaccuracies, particularly at material boundaries, such as timber appearing as stone. Reflective materials also present challenges, as alternative colours may be introduced, especially when the photographer cannot be excluded from the shot. Software tools could be employed to retouch the image for more realistic texturisation before merging it with the point cloud, though this would add additional stages to the workflow.

The type of material used in the Hawara Pyramid and Nottingham Castle case studies significantly influenced the quality of the resultant data. In the Hawara study, the adobe mudbrick was found to absorb the laser, which diminished the quality of the returns and, consequently, the output. To address this issue, additional scans were proposed to identify the most suitable approach. It was determined that increasing the overlap of scans would enhance point density, and reducing the angle of incidence would further improve this density. Additionally, decreasing the distance between scanning points could potentially increase the returns. However, these solutions would require extended time in the field, thus increasing exposure to extreme temperatures. Night scanning, when temperatures are lower and humidity rises, was also suggested as a potential area for future research.

In the Nottingham Castle project, reflective surfaces, particularly glass, presented well-known challenges. While increasing point density was one potential solution, reducing the angle of incidence emerged as a more

effective approach, allowing for refraction rather than reflection and revealing objects behind the glass. This phenomenon was notably observed in the Arkwright case study, where the ornate staircase in the main entrance could be seen through the north-facing windows with minimal reflection of the external scene, thereby rendering the staircase more prominent (see Figure 17). Extensive cleaning was required in the glass lobbies of the temporary gallery, although the recently installed glazed wall in the colonnade had a lesser impact (see Figure 54).

The use of targets was explored in both the Hawara Pyramid and Nottingham Castle case studies. At the Hawara Pyramid, the organic nature of the monument and its surroundings necessitated the use of targets. High-quality outputs depended on multiple targets to accurately tie the vertices in the point clouds, and these targets had to be positioned away from the asset to avoid data obscuration. When stations operated in a circuit around the pyramid, a minimum of three targets needed to remain in position to connect the first and last stations, thereby accounting for drift in the errors. Spherical targets proved ideal in this context, as they are accurately visible from all directions, as demonstrated in the field. If UAS data is to be used to fill voids at higher elevations, ground control points (GCPs) are essential for scale and accurate unification, thus combining targets with GCPs would be the most effective solution. These targets and GCPs should remain in position throughout both campaigns.

The urban setting of Nottingham Castle and the presence of 'natural' targets in the scene provided an excellent opportunity for automatic unification. However, limited overlap between point clouds at different stations necessitate the inclusion of targets. This issue could be partially mitigated by placing a station within the immediate vicinity of the overlap, as seen in the temporary gallery and the Victorian tunnel during the kitchen yard archaeological iteration of the case study. In the campaigns that spanned the roof and external areas, there was a risk that the overlap might not include points with sufficient definition. Therefore, targets were strategically placed within the scene and scanned at both ground and roof levels. These targets were crucial for verifying the accuracy of the unification process, although horizontal alignment of the roof plane remained a challenge.

Operator efficiency and campaign duration, while not central to this research, were secondary to the primary objective of producing high-quality models that accurately support the significance of heritage assets. Although operational challenges did not reach extreme levels, the emphasis on time in the field was minimal in comparison to the priority placed on data quality. For instance, in the Arkwright case study, the deployment of sixteen scanning stations resulted in an output of such high fidelity that it required minimal cleaning and post-processing. Conversely, the difficulties encountered during the pyramid campaign suggest that operator expertise significantly influences the final product. Despite meticulous planning, unforeseen circumstances — such as environmental conditions — can disrupt operations. The surveyor's ability to adapt and resolve such challenges in the field is therefore crucial for maintaining the desired quality.

In the Nottingham Castle case study, the diversity of situations encountered highlighted areas for potential improvement. While increasing the resolution of the point cloud delivered a high-quality outcome, it is likely that the introduction of additional scanning stations would have further reduced voids and enhanced overlap, thereby improving resolution by default. Although this would increase the time required on site, the duration at each station could be minimised, thereby balancing the overall campaign time. Moreover, the use of the BLK360 G1 scanner, with its shorter capture time, becomes feasible for such shorter distances, potentially offsetting the time needed for additional stations. Additionally, reducing capture time may decrease the incidence of transient artifacts, which would subsequently lessen the need for post-processing. This iterative, active research approach thus contributes valuable insights that can inform future methodologies.

The Arkwright Building at NTU, which suffered a direct hit from a World War II bomb, provides a compelling example of how accurate scan data can reveal subtle historical details. The images captured show the extent of the damage, and the subsequent reconstruction of the West corner — undertaken during a period of material and skill shortages — reflects the intangible heritage of that era. The high-quality scans were able to capture these variances, which remain concealed in the landscape behind trees and shrubs, and clearly illustrate the differences between the original structure and the post-war

repairs. The symmetry of the original building's details makes these discrepancies easily detectable.

Both the Hawara Pyramid site and the Ducal Palace served as precise foundations for the creation of immersive VR experiences, wherein historical narratives were overlaid onto the digital models. The VR experience of the Ducal Palace allowed stakeholders to explore the gallery, interact with tagged paintings, and access factual information. To enhance this experience, visual elements were superimposed onto the point cloud data, with additional audio-visual notes designed to disseminate knowledge effectively. In contrast, the pyramid was transformed into a simplified interactive game, enabling players to revisit the site and learn about the archaeological excavations. While some artistic license was taken to simplify the details for the game, stakeholder feedback in both case studies was overwhelmingly positive. These examples underscore the effectiveness of digital content in fostering knowledge-building and engagement, illustrating the transformative potential of such technologies in the preservation and interpretation of heritage sites.

While there has been no formal documentation of the Arkwright case study's outcomes, the shared imagery has sparked significant discussion among students and stakeholders at the University. In contrast, the other two case studies elicited formal feedback during structured sessions, which strongly supported the conclusion that the digital models were effective in engaging stakeholders and enhancing their understanding, particularly with respect to historical knowledge.

An important observation across all case studies is that digital content was primarily accessed via equipment provided at organised events. Expanding this access to allow users to interact with the content on their own devices could deepen the research insights. This issue was partially addressed in the Nottingham Castle project through the release of 3D YouTube experiences. However, the Hawara project faced restrictions on publication due to constraints imposed by other partners. The need to identify secure solutions for data output, protected storage, and future retrieval for ongoing monitoring remains outside the current research scope. Nevertheless, considerations related to digital archiving and the choice of software - particularly with regard to export capabilities - should be briefly acknowledged.

There are established standards for data recording and sharing within the HER, as recognised and endorsed by local authorities and the MIDAS Heritage UK Historic Environment Data Standard, provided by the Forum on Information Standards in Heritage (FISH). According to English Heritage "*The MIDAS Heritage Vision is sharing the knowledge of the past. The intention of the MIDAS Heritage is not to control the content of an inventory. Only to provide a common framework within which information systems should develop.*" English Heritage (2012, p.5). Adhering to these standards is essential, particularly when considering the integration of data into BIM. Although BIM represents the natural platform for utilising such data, the current process of converting raw data into objects within BIM environments is neither fully automated nor comprehensive. This conversion process is time-consuming, requires highly trained personnel, and may compromise data accuracy, as noted by Bosche et al. (2015). Nonetheless, significant advancements are being made in this area, especially as efforts converge to integrate different types of survey data — both metric and observational — into BIM. This integration is crucial for supporting the management of heritage buildings throughout their lifecycle. As Brumana et al. assert, *"The main peculiarity of BIM applications is the capacity to link various types of data and information to the 3D Objects, favouring the preservation plan and the retrieval of the information gained during the life cycle management (LC)."* Brumana et al. (2017, p.559)

These observations highlight the evolving landscape of digital heritage management, underscoring the potential and challenges of integrating digital tools with traditional heritage conservation practices. As digital methodologies become increasingly integral to heritage studies, the ability to seamlessly combine different data types within a unified framework will be essential for the effective preservation and management of historic assets.

4.14 Conclusion

The three case studies presented a sophisticated and progressive understanding of the research problem, revealing both the potential and inherent challenges of employing digital modelling for the sustainable management of historic assets. These studies underscore the critical importance of meticulous attention to environmental conditions, careful

selection of equipment, and the seamless integration of historical data. The impact of lighting on digital models can introduce interpretative challenges, while the material properties of heritage sites may inadvertently compromise data quality. Although precision-enhancing targets are available, their necessity is often mitigated in urban environments, where natural reference points may suffice. The operator's expertise is paramount; while thorough planning is essential for high-quality outcomes, the ability to review and make iterative adjustments in the field is crucial to achieving optimal results. Instrument choice plays a key role in the data capture workflow, with the specifications of selected equipment directly influencing output quality. However, if multiple instruments are available, they can be strategically integrated into the workflow to achieve synergistic effects. Newer instruments, with their faster capture rates and marginal variations in accuracy, have the potential to surpass more precise scanners when used expertly, leading to enhanced overall quality. A skilled operator adopts a holistic approach, carefully considering all variables to determine the most appropriate solution. Ultimately, the data acquisition process must be driven by the overarching goal of preserving the cultural significance of these historic assets, ensuring that digital models serve as a robust foundation for their ongoing conservation and management.

The methodology employed in this research argued convincingly for the suitability of case studies conducted within an action research framework, reflecting the industry standard of continuous iterative improvement. The qualitative insights generated through this approach have yielded practical solutions, highlighting key contributors to achieving high-quality outcomes. Each case study places heritage at its core, with the process of action, observation, reflection, and recording shaping a deeper understanding. The literature review provides a theoretical foundation, which was rigorously tested in the case studies, thereby advancing practical knowledge and contributing to the development of innovative procedures grounded in established comprehension.

Therefore, the case studies have successfully fulfilled the research objective of providing a robust foundation for the development of a framework that facilitates the integration of digital models into the sustainable management of heritage assets. This framework is pivotal in ensuring the retention of

cultural and historical significance while embracing modern technological advancements. By addressing the complexities of heritage preservation through digital innovation, the research underscores the potential for a more efficient and effective approach to managing and safeguarding heritage assets for future generations. The findings contribute significantly to the evolving discourse on heritage conservation in the digital age.

Chapter 5.0 Theoretical Framework

5.0 Introduction

This chapter begins at the conceptual framework as the outcome of the literature review elucidating the key pillars and their relationship with the digital model at its core (See Figure 14). The generation of the theoretical framework will follow an inductive path to meet the aim of this research using LiDAR as a data capture with virtual modelling technology to present that record for the management of historic building data in sustainable preservation and management of heritage assets to support informed decision-making to retain significance by all stakeholders.

The conceptual framework as an output of the literature review, see Figure 14, evolved through the empirical work being the three case studies into the theoretical framework. This framework focuses on conservation as the philosophical bedrock for the approach to heritage asset management to ensure the retention of significance and sustainability. The unique nature of each heritage asset ensures a single proposition is insufficient to capture all eventualities and hence the framework solution.

The initial literature review produced the conceptual framework 'bins', elucidated in the next section yet becoming too intent on this agenda can limit the value of the case study to provide the requisite theoretical effectiveness. The conceptual framework identified four key domains, management, policy/ethics, asset significance and stakeholders. The literature review covered a wide range of topics to frame and ground the problem and determined the contribution to knowledge. Existing knowledge shapes and informs the empirical investigation to answer the research questions thereby building into the theoretical framework. Flexibility allows the shift in the researcher and research, identifies components in the theory or employed to interpret the data. Theoretical postulation in research means there is an explanation as to how and why things work the way they do, elucidating a reality, Ngulube (2018). Budiman, Wati & Norhidayat (2019), propose a 5R adaption framework covering timing, location, device, user and content however this is focused on the capture of data to improve organisational performance in the creation, sharing and use of knowledge.

Sustainable management relies to some extent on interest in the artefact, conservation is an ethical approach required for heritage assets to maintain prominence for all generations.

The action research, conducted through detailed case studies, constitutes the empirical backbone of this study, enriching the theoretical insights derived from the literature review and synthesised here. For instance, the research acknowledges the significant impact of legal and ethical principles on the management of heritage assets, which, in turn, shapes the development of the framework. Throughout the empirical investigation, both the research and the researcher undergo transformative shifts between the conceptual and theoretical frameworks, necessitating iterative revisions in the data collection process and the construction of the digital model. Recognising these shifts is crucial to deriving a solution free from bias; these emergent, unanticipated developments prompt the research to adopt a more investigative and adaptive approach.

Taking the stance the conceptual framework supports the initial position of the research, it is important to reflect on the contribution to knowledge, the proposal is to determine the theoretical framework shaping the consummate specific model. Additionally, to progress from a static to a dynamic proposition in pursuit of proactive heritage management supporting the policymakers' requirement for sustainable conservation management in reducing any loss of significance. This aligns with the stakeholder determination of the importance of the heritage asset, social responsibility, conservation policy and future development. The lack of integration and sharing of data mapping the lifecycle devalues the asset especially when interventions are required. In Chapter 4, the three case studies utilised active research to cyclically improve understanding of the process of geometric data capture and heritage data timelines, and hone the design of the theoretical framework, the nature of heritage assets as autonomous, individualistic, and specific, with dissimilar epochs requires a flexible solution.

The initial case study underscores the critical connection between geometric and historical data, with the physical fabric of the asset adding a supplementary dimension. While the fabric defines spatial parameters, it cannot be fully verified without invasive exploration, thus presenting a

limitation. As projects for intervention progress, this detailed data element expands, culminating in the development of robust information. The chapter proposes an initial iteration of the framework, introducing theoretical links that are further developed through the second and third case study. These two ran concurrently with interlinked exploration of the processes, feedback continually sought analysed and reapplied in the action research methodology.

The Hawara case study, in its purest form, serves as an exploratory foundation for a future dewatering project. The mechanics of subsoil water removal may risk destabilising the remnants of the pyramid, potentially leading to partial or total collapse. To mitigate this risk, the digital model will be iteratively strengthened, incorporating layers of point cloud data and models to monitor ground movement and assess collapse potential. This baseline model allows for clash detection by comparing data from future campaigns, identifying deviations that may indicate structural shifts.

The final model, developed through five distinct campaigns at Nottingham Castle, positions the digital model at the centre of the research problem. These campaigns encompass all stages of the project - pre-intervention, intervention, post-intervention, and subsequent use - thereby providing a comprehensive framework. The resultant framework not only identifies the key pillars but also integrates the final links necessary to formulate a robust solution. While this marks the conclusion of the framework’s development, it also draws upon the considerable depth of digital modelling work, which is incorporated into the final framework.

The establishment of the final framework is underpinned by a fundamental intent: to place significance at the forefront of heritage decision-making. Significance is the primary lens through which heritage assets are managed, and the proposed framework, with the digital model at its core, is designed to enhance this decision-making process. Immediate access to accurate data enables a profound understanding that serves as the foundation for informed and robust decisions. Sustainable heritage management hinges on maintaining the significance of assets as the central focus. Interventions, whether driven by conservation needs, development pressures, or other factors, require a deep understanding of the asset's inherent qualities, which

are embedded within the digital model. These interventions should also generate data that is reintegrated into the model, particularly when previously undetected materials or technologies are revealed during the process. Given the often-irreplaceable nature of heritage fabric, efficient access to data that encapsulates the asset's significance is crucial, especially in the event of disasters or when planning applications are submitted. This data supports the preparation of effective design and access statements, conservation plans, and heritage impact assessments for submission to relevant authorities. Stakeholders - whether directly involved or peripheral, including owners, users, professionals, and the public - play a pivotal role in the decision-making process.

Case studies consistently demonstrate that stakeholder engagement fosters a deeper understanding and generates feedback that leads to well-considered decisions. There is little value in developing a resource that remains underutilised; engaging stakeholders in the decision-making process instils confidence in the solutions proposed and reinforces the ethical integrity of the outcomes. Collaboration revolves around the data housed within the digital model. Moreover, providing access to this data can uncover additional information, including previously unrecorded history or artifacts, which can then be incorporated into the model. By democratising access to data, the asset itself is brought further into the public domain, promoting broader engagement and appreciation.

Given the financial challenges often faced in heritage management, the introduction of efficiency and effectiveness into all interventions yields significant benefits. The model’s accuracy supports precise decision-making, enabling swift action, reducing downtime, and shortening project lifecycles. Furthermore, the accuracy of the data enhances the development of educational tools and games, adding a dimension of realism that enriches the learning experience. Research grounded in accurate models can inform future studies and add considerable value to heritage assets. The framework’s intent holds great potential for significantly enhancing the value and preservation of heritage assets.

This chapter thus synthesises the grounded literature review and empirical research to address the research questions, achieving the objectives in alignment with the overall aim of the study.

5.1 Digital Model

The concept of the digital model is a central theme within this contemporary heritage management framework. This model integrates historical and geometric data to enhance decision-making processes related to the conservation and management of historic assets. The empirical research conducted explores the methodologies employed in data collection, emphasising iterative knowledge generation through direct engagement with both data types across different case studies.

In the second case study, historical and geometric data were predominantly sourced from third parties to construct a VR experience. This scenario closely mirrors situations where building owners or management organisations commission external entities to gather necessary data. Each case study underscored deficiencies in the commissioning processes for geometric data, revealing that the resulting model necessitated significant refinement to meet satisfactory standards. Additionally, the acquisition of historical data proved challenging due to the dislocated nature of artifacts, which also predominantly pertained to later periods. It is important to note that this case study was deliberately selected for its complexity and inherent difficulties. Despite these challenges, the VR output achieved a high quality and provided a compelling experience as validated by stakeholders during the seminar.

The findings from each case study reinforce the fundamental concept that digital models, which synthesise heritage and geometric data, can effectively support decision-making for the sustainable management of heritage assets, thereby ensuring robust outcomes. This is evidenced by the model outputs, which included both 2D and 3D representations derived from geometrically accurate models, with the fourth dimension – time -incorporated into the historical content. However, a notable limitation lies in the artifact data pertaining to the materials and technologies obscured beneath the asset's surface. While some information is retrievable from existing records, its accuracy remains uncertain until physical intervention exposes it. This has

led to generalised assumptions, with some proposing that complete demolition is the only way to fully uncover the data needed to emulate a new-build model - an approach contrary to current policies and ethically indefensible for heritage conservation.

The literature review illuminated the various pressures exerted at local, national, and international levels through policy and ethical considerations, impacting all stakeholder actions connected to the asset and its context. These pressures extend to digital models, where accuracy is paramount, and quality must be meticulously integrated. Moreover, any conjectural elements in the output must be transparently articulated.

The compilation of historic data should be grounded in all known, reliable evidence. As new data emerges, it must be rigorously tested against the existing dataset and revisions made as necessary to ensure the most comprehensive and accurate version is utilised in decision-making processes. Failure to do so would contravene best ethical practice.

Similarly, geometric data must maintain a high degree of accuracy, with LiDAR technology being renowned for this precision. The resolution must be appropriate to the asset in question, but ultimately, it is the overall quality of the data that is of utmost importance. This quality not only includes resolution but also extends to the completeness of surface coverage. The empirical investigation highlighted challenges in capturing surfaces obscured from direct laser exposure, particularly those at elevated levels. Despite exploring various solutions, areas such as parapets, the tops of cornices, and window details often remained outside the model's scope. While the importance of these surfaces could be debated, it falls outside the research's scope. Nonetheless, advancements in UAS equipped with SLAM technology combined with LiDAR offer potential solutions, albeit at reduced accuracy.

In the first case study, the geometric data validated existing knowledge by revealing changes to the fabric of the original structure. This analysis extended beyond the loss of detail to encompass material alterations; for instance, damaged timber frame windows were replaced with Crittall steel frames, a change supported by historical records of material shortages during WWII. Although photographic evidence from the time documented the damage, the restoration process was not thoroughly recorded. The

geometric model partially compensates for this gap in documentation.

The integration of newly discovered and revised data into the model fosters the development of a dynamic digital model. Superseded data remains archived within the model as a historical record of its evolution, thereby serving as a valuable resource that not only highlights discoveries but also documents the methodologies employed to achieve these findings. As this knowledge is revisited, additional insights may be uncovered in similar contexts, potentially leading to a deeper understanding. In this way, the digital model evolves concurrently with the physical asset, becoming an integral part of its history.

To maximise its utility, the digital model must remain up to date. Newly discovered information should be rigorously tested against existing model data before being integrated or discarded. Revisions to the narrative should only be made based on sound, well-reasoned justification, applicable to both geometric data and, when available, new artifact information. Timely updates enhance the model's dynamism, ensuring that the most informed and robust decisions can be made.

Finally, it is crucial to encourage all stakeholders to engage with the digital model at various levels. Each case study provided opportunities for such interaction, and in each instance, the outcomes were positive. Stakeholders recognised the value of the digital model across multiple applications. As exhibition material, its accuracy provided assurance of validity, and the exported 3D model served as a foundation for exhibition planning. In the third case study, the art gallery model represents a record of the gallery's arrangement immediately preceding refurbishment, while the accurate depiction of the archaeological findings in the kitchen courtyard now serves as a valuable resource for further study.

In the realm of geometric data modelling, point clouds are generally sufficient for most applications, with vectorisation being applied selectively to address specific problem areas. However, vectorisation is a resource-intensive process that can potentially compromise the inherent accuracy preserved within the point cloud. Similarly, meshing—particularly when automated—can exacerbate inaccuracies by introducing errors, especially when not overseen by specialists with a deep understanding of the original survey data.

This issue was evident in the empirical research, where stakeholders expressed criticism of the raw outputs of the digital models for the Nottingham Castle project. Notably, the Hawara project, which utilised gaming and archaeological data to recreate period details, was accepted as achieving an appropriate level of quality, as it successfully captured the essence of the historical period. Yet, the basis of this data was conjecture, whilst cemented in similarity was the figment of the game developer's 'eye'.

To address these challenges, the proposed strategy involves isolating the specific components requiring analysis from the point cloud, thereby concentrating resources on vectorising or meshing only the essential object(s). Non-visible entities would remain in the digital model as point cloud data. A subsequent targeted scanning campaign would then focus on the same element group, facilitating comparison through specialist software to detect changes such as movement, loss, or weathering. This comparison, in conjunction with historical data, informs interventions that are both proportionate and sensitive to the historical significance of the elements involved. A heat diagram would be utilised to guide a balanced response, ensuring that any actions taken are appropriate. Moreover, conducting multiple scanning campaigns enables the monitoring of 'change over time,' allowing for timely interventions and providing ample data to reverse any interventions should the intended outcomes not be realised. The final case study portrayed the concept well with the output utilised at all stages in the fabric lifecycle.

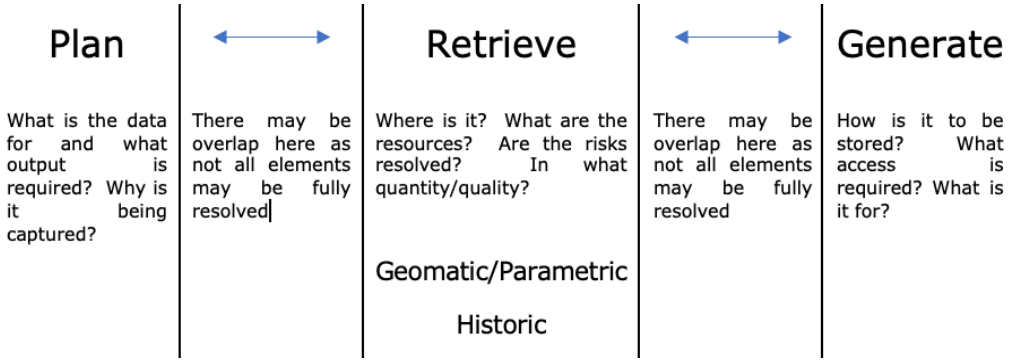

Figure 57: Basic workflow for data acquisition (By author)

There are three stages for the development of the digital model, Plan, Retrieve and Generate for output (see Figure 57). These sit below the requirement for heritage asset data gathering, management and sharing,

and contain the concepts which form the minutia. Each stage comes with specific demands, yet the overarching feature is to define the purpose of the data, the appropriate quality, suitable quantity and the intended output. In each stage, questions are posed that drive the solution therefore a need to break down each stage with key influences. The stakeholders were included in a consultation process to ensure extensive understanding and encourage interaction. This review will form a reflective phase to determine iterative revisions in the plan stage. It should be noted from the empirical research once in the retrieve stage site nuances caused dynamic revision of the plan in an action research cycle to ensure the highest quality output.

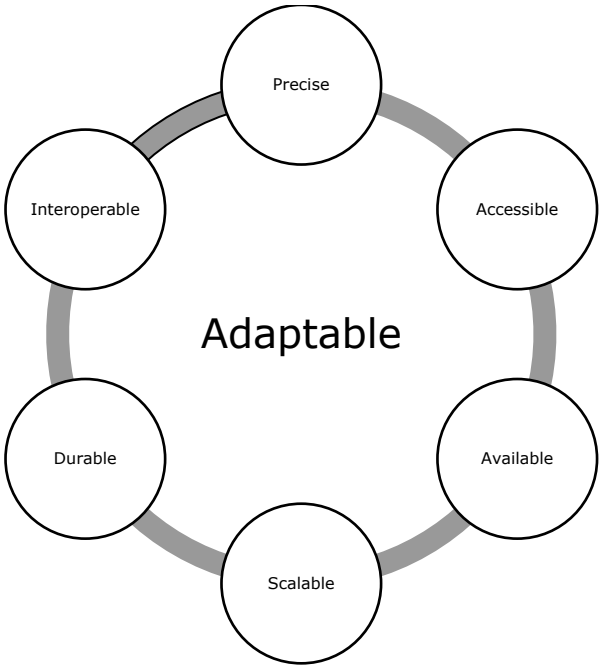

Figure 58: Attributes required in a digital model to support sustainable heritage management (By author)

In the initial stages even before the planning phase a visit to the heritage asset is strongly advised yet, this may not be an option, (see the Hawara case study). Even with a visit in the planning stage, aspects of the data retrieval stage may change, the quality however remains a constant. In the empirical research stage of Case study one and three all retrieve periods were completed in the summer thereby reducing the environment impact yet at this time the flora in full leaf may cause issues for example. Applying the construction industry iron triangle of Cost/Quality/Time then either time or cost will be revised in conjunction with the stakeholders. Considering the Nottingham Castle the remnants of the refurbishment caused additional time to be expended, furthermore environmental conditions are an unknown at

the planning stage. This resulted in time expenditure cutting short the campaign at the expense of data retrieval towards the entrance. The imminent opening of the attraction to the public left the model incomplete.

At this juncture, it is essential to underscore the critical importance of the digital model within heritage conservation. Although this research does not encompass every attribute required for an adaptable digital model, it is necessary to acknowledge these attributes in Figure 58. These attributes are vital for developing a model capable of meeting the unique demands of heritage assets, particularly those that lack standardisation or share limited commonalities with other structures.

The requirements evolve into the planning requirements when approaching a campaign and are generated in the empirical stage of the research. As with any digital model the very first requirement is to determine why the data is being acquired. This has repercussions throughout the campaign, importance cannot be stressed sufficiently especially as it will impact the success of the project.

Accepting the artifact data comes generally from an intervention stage and is to some extent outside this research, notwithstanding the second case study where the mudbricks impacted on the campaign. There are two tranches of data geometric and historic, requiring consideration in the plan and retrieve stage, see Figure 59. These are broken down in the table as found in Appendix 2. There are multiple links acknowledged, for example the weather patterns in the summer months can create an improved environment leading to efficiencies yet these may bring forth higher temperatures and subsequent instrument outside operating parameters or greater foliage which inhibit efficiency. Access appears in more than one of the geometric elements, there is access to the artifact, in the case of Nottingham Castle it was denied during the works for all but the archaeology. There is access to the locale, the P20 and peripheral equipment is particularly heavy to carry for any distance, a single operative is inappropriate except in the most accessible location. Personal Protective Equipment (PPE) is in the equipment column yet is dependent on the people involved and the safety aspect of the artefact, the environment conditions and the locale. Figure 59 illustrates the most robust interconnections, positioning the artefact at the

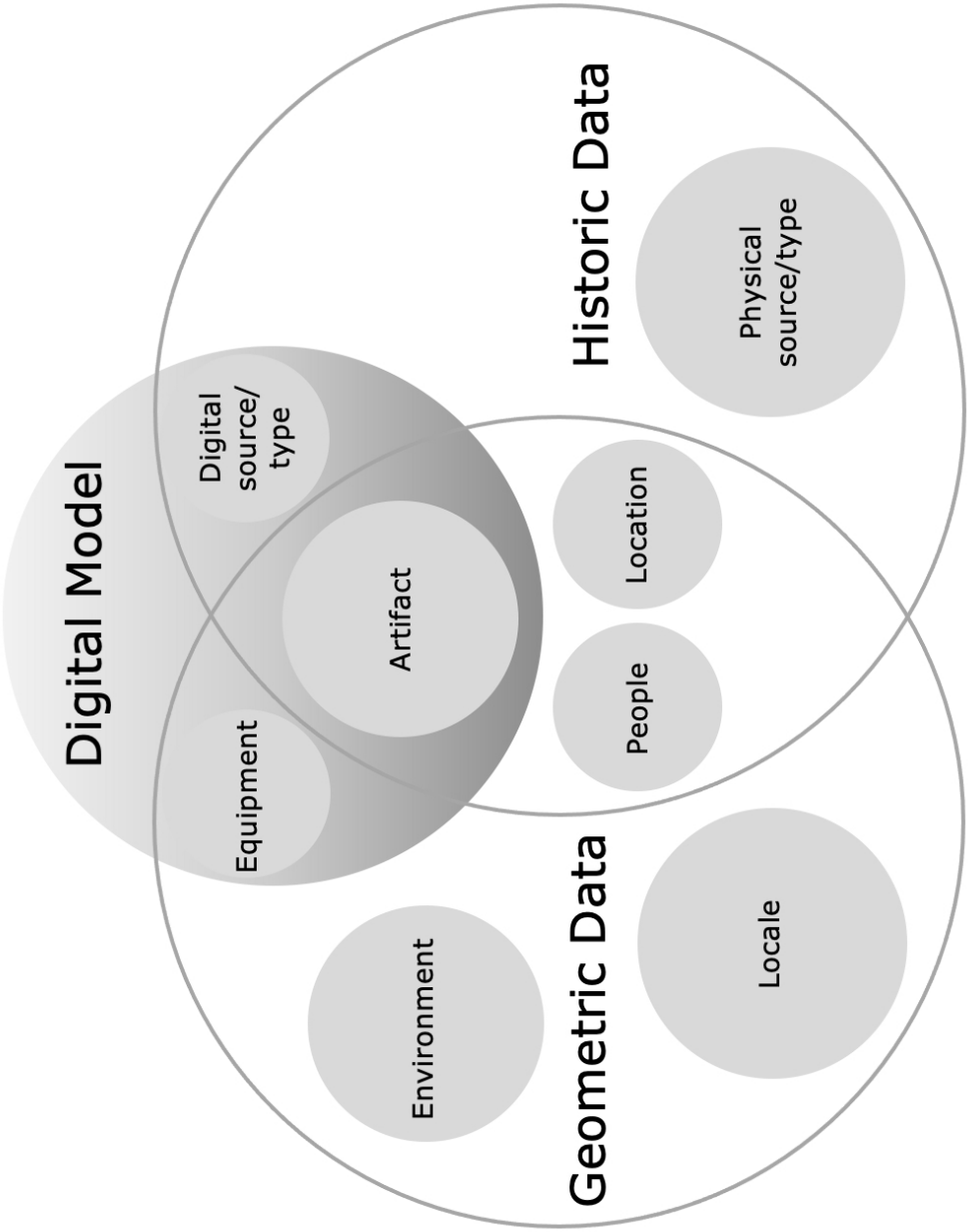

Figure 59: Considerations for data campaigns (See Appendix 2 for tabular format)

centre as a pivotal linchpin around which the domains of model and data revolve. While certain thematic elements recur across multiple domains, others remain uniquely confined within a single domain.

Each case study significantly contributed to the overall understanding, highlighting key environmental and logistical challenges such as the intense heat of the desert in Hawara and the high wind speeds at Nottingham Castle. The necessity for peripheral equipment was evident, with specific requirements such as target placement in Hawara and the need for access to alternative instruments like the BLK360 G1 scanner at Nottingham Castle. In every scenario, adaptability proved crucial, with a strong emphasis on quality necessitating the addressing of specific requirements - for instance, in the Arkwright case study, the need to traverse the elevation twice, both proximate the asset and at a distance using the highway. The Nottingham Castle case study, whether at roof level or within the archaeological dig, demanded meticulous on-site planning to minimise data voids while limiting the number of stations.

Excessive number of stations leads to large data volume posing significant challenges in post processing. In the archaeological context, the decision to deprioritise the detailed documentation at the base of the trench, due to the absence of discovered objects, underscores the need for focused attention on foundational artifacts, which require meticulous documentation. The acquisition of extensive and precise geomatic data can be overwhelming, necessitating high-specification hardware and software for specialised manipulation. The proposition advanced here challenges the argument for the indiscriminate collection of extensive, high-quality data, advocating instead for a proportionate approach to data capture, as outlined in the theoretical framework and as proposed by the NPPF.

Considering this reinforcement, the intent behind a project must be clearly established before any conservation efforts are undertaken, in accordance with heritage asset policy, which often leaves heritage managers without adequate support. Here the digital model takes centre stage. Beyond parametric data and associated imagery, historic data, a detailed development timeline, and comprehensive documentation must be considered to support a thorough understanding. The historic value of an

asset is a prerequisite for any project and is determined not by monetary value but by evidential, historical, aesthetic, and communal significance, which, in some cases, is recognised by statutory designation. It is crucial to note that a heritage asset does not need to be officially listed to be of significance; many assets, as Historic England (2016c) notes, contribute to the heritage landscape, such as conservation areas. Most heritage assets operate with limited financial resources, relying on grants and donations for day-to-day survival, which constrains the allocation of funds for such ventures. However, this financial limitation should not impede data capture but rather necessitate a carefully planned acquisition strategy, dependent on factors such as the asset's significance, quality, quantity, condition, and the need for immediate or future interventions.

The rationale for data capture should be articulated in the planning process, with each variable aligned with the requirements for a future digital model. The primary purpose of data collection is to serve the intended use, whether in new construction, where information is first tested in a virtual environment, or in assessing existing structures, where LiDAR capture techniques provide surface details that are often only superficial. The research aimed to reverse-engineer the digital model, incorporating sufficient detail about the immediate physical context to enhance knowledge, deepen understanding, and facilitate the design of solutions. The concept of significance is central to this process, ensuring that the level of detail captured is adequate to maintain the asset's robustness for the future and to support decisions concerning when and to what extent interventions are necessary. For example, surface degradation may detract from aesthetic appreciation, yet it often serves a protective function, as seen with rust on steel.

To anticipate future needs effectively, it is crucial to develop a highly detailed digital model of the utmost quality, capable of capturing the nuanced surface features of the asset. Conversely, simple shapes with limited ornamentation can be modelled with more frugal data quantity yet maintaining the quality. However, even with the less complex assets there is an argument for maintaining the high level of resolution brought by the LiDAR instrument revealing previous elements for example doorways, picture rails, dado rails etc. Creating a model of this calibre necessitates a comprehensive

understanding of the asset, including its historical data. However, challenges arise due to the complexity of materials, difficult-to-access areas, the extensive time required, and the sheer size of the resulting model. These factors may still result in an incomplete representation, thereby raising concerns about cost-effectiveness. An alternative may be to build a high-quality, high-resolution model of the feature and crop it out of the point cloud as a separate file leaving a low-definition element in the model as a placeholder. A link in the model would take the user to the file containing the high-definition model.

The issue in determining data quantity was explored by Donato, Biagini, Bertini, and Marsugli (2017), who found that although the accuracy of their model exceeded what was necessary for structural purposes, it was well-suited for capturing information pertinent to maintenance and renovation projects throughout the asset's lifespan, including future interventions. Figure 59 offers valuable insights into the process of data acquisition aimed at constructing a high-quality digital model. The implication is that meticulous planning is a critical initial step, encompassing numerous dimensions that often require revision during the retrieval stage. The expertise of those involved plays a pivotal role in achieving the appropriate quality and quantity of data, which underpins decision-making regarding the asset, particularly its significance.

Point cloud quality emerged prominently in the examination of the materials presenting significant challenges in obtaining sufficient data to create a high-quality model. Materials such as glass, and other highly reflective surfaces, demand higher density scanning to ensure precise data capture yet with careful consideration issues related to reflectivity became less pronounced. According to Historic England (2018), the point density (resolution) should be at least twice as fine as the smallest feature to ensure accuracy in the final model. The desired output scale often dictates the ultimate size of the model. Tommasi, Achille, and Fassi (2016) emphasise that a target output model at a scale of 1:50 can frequently result in illegible and inaccurate details. They also highlight challenges such as large file sizes, partial lack of interoperability between survey data and the model, and complications in model elaboration. Although this particular research does not explore digital entity models as utilised in the BIM domain, it is crucial to consider the

potential need to export data to an object-based model in the future.

Further considerations arise when transitioning digital models into object-based packages. Heritage buildings inherently possess a degree of flexibility that allows them to function even when structurally distorted. A well-known example is the Tower of Pisa, a free-standing bell tower built on soft ground that has since been stabilised. However, modelling the tower in BIM would likely result in a vertical interpretation, potentially misrepresenting the current structural reality. For structural modelling and analysis, point cloud data would provide a more accurate representation of the tower's present condition. Similar, though less publicised, cases exist; for instance, when a WWII bomb struck near the Arkwright building as in case study 1, the resultant pressure wave affected the opposite side of the street. During recent refurbishments, it was discovered that the University Hall's main space is trapezoidal at the roof level. Modelling this feature as square would result in a representation that fails to capture the building's true form, thereby diminishing its future utility. In the Hawara case study, despite the challenges posed by the mudbrick material, the organic shapes of the structure complicate accurate modelling. Meshing introduces further inaccuracies; hence, retaining the unified and registered point cloud ensures the highest data quality. Consequently, it is argued that maintaining the integrity of the unaltered point cloud digital model provides the most robust data for heritage preservation and analysis.

BIM compliance involves adherence to several critical components, including the Employer's Information Requirements (EIR), the Common Data Environment (CDE), and standards such as BS 1192 and Classification systems. The effort required to develop a parametric BIM model for a historic asset from a point cloud is considerable, with only partial automation currently available. Heritage buildings, which often feature flexible construction techniques with greater tolerance levels compared to modern structures, present unique challenges. On the positive side, the formation of objects allows historic data to be integrated with geometric and artifact data, creating a single source of truth. However, this obscures an issue: the highest quality data is required for heritage assets, yet the intricacies, deflections, and higher levels of understanding this generates are lost in the smoothing process. For example, if structural analysis is to be successful, all

deflections must be accounted for and included to provide a complete picture and subsequent specification for the resolution. Moreover, future reviews of the intervention or monitoring will require a detailed model, not one that has been overly simplified.

Retaining the initial point cloud is essential; its accuracy represents the finite asset, and any data corruption during manipulation allows for reverting to the baseline model. As point clouds cannot be clashed to identify issues, a workflow should be established to extract elements of interest for modelling, mesh one, and clash with the second point cloud. Finally, applying a heat map can quickly identify problem areas. Returning any intervention to the original state is part of the requirements set by policy bodies. Having the original data allows for reverse engineering the solution. Contemporary project management software enables 2D drawings to form the basis of a digital model, tagging data to specific locations. Furthermore, facilities management software may provide solutions for elements outside this research, but it is an area for future investigation.

Moreover, the absence of intelligent object libraries further complicates the digital modelling process, as noted by Turco, Mattone, and Rinaudo (2017). Successfully integrating such models would require the availability of experienced personnel, as well as sufficient computing capacity and storage to overcome these obstacles. A critical consideration is that most heritage asset owners and managers may lack awareness of the technicalities involved in BIM requirements, often relying on the professional project team to determine these needs. This situation can lead to reports of extensive costs and reluctance to invest, particularly when BIM is integrated as part of the data collection process, as identified by Kineber, Othman, Famakin, Oke, Hamed, and Olayemi (2022).

Beyond the initial data capture and subsequent creation of a digital model, effective data management is essential; however, this requirement is often lacking within the sector. For the digital model to be truly effective, all historical data should be underpinned by the most resilient evidence available, with any new discoveries systematically incorporated into the model. This continuous integration necessitates regular reviews to ascertain whether newly acquired data necessitates a revision of current

interpretations or if the existing understanding remains valid. Additionally, any interventions conducted should generate new data, which should then be incorporated into the model to enhance and refine the understanding of the asset, allowing for comparisons with existing information.

It is through a rigorous cyclical process of discovery, collection, processing, storage, evaluation, significance assessment, comparison, review, and deployment that the data's integrity and robustness are enhanced. Consequently, the management of the model is both fundamental and dynamic, playing a crucial role in supporting informed and robust decision-making.

Similarly, the geometric information associated with the heritage asset should be continuously updated. This information undergoes a parallel iterative process of capture, processing, storage, evaluation, comparison, review, and deployment, where the review stage may prompt further interventions. The dissemination of updated data to relevant stakeholders is vital for the effective management of the heritage asset. Whilst the accuracy is a consideration it is the resolution and the overarching quality which will drive a suitable model.

Upon initial construction, the data must undergo thorough verification and review to ensure it is fit for purpose. Any areas where the data is insufficient or where there are concerns regarding its reliability should be revisited to validate and enhance the dataset. While the establishment of a robust model provides a strong foundation, it should not be considered exhaustive or final. Through subsequent interventions and ongoing research campaigns, gaps in the data will be progressively filled, thereby enhancing the comprehensiveness of the model. This iterative process strengthens the model, making it more robust and adaptable for future applications. Case study three perfected this iterative process providing data for specific purpose yet allowing model development.

In each case study, the digital model serves a critical purpose by engaging stakeholders with the heritage asset and providing them with valuable knowledge. Both formal and informal events have utilised the data to actively involve stakeholders, and in every instance, the outcome has been positive, enhancing both illumination and understanding.

In the Arkwright case study, displaying the model in a 2D format enabled stakeholders to engage in simple visual comparisons that highlighted the asymmetry of the building's elevation. This interactive approach, akin to a basic gaming experience, prompted stakeholders to seek further clarification and they were astonished to learn the historical reasons for the irregularity. This revelation fostered a deeper connection to the history of the asset.

In the second case study, a seminar and exhibition event in Cairo featured a VR experience constructed from the digital model, which was based on historical data and artefacts found at the site. This immersive experience allowed attendees to visualise the complete pyramid, and the labyrinth purported to be located south of the site. Although language barriers prevented the collection of detailed feedback, the experience generated significant interest and captivated the audience, who expressed their gratitude.

Finally, in the third case study, a workshop titled 'Engaging with Nottingham Castle Future: Virtual Platforms & Public Engagement with Nottingham Castle User Groups', brought together a diverse range of stakeholders, including the owner, local authority, conservation officers, and various interest groups. A short questionnaire was employed to gather feedback on the entire programme, with specific questions focused on the digital content. The responses indicated strong support for the integration of digital content in heritage settings, with 95% of participants affirming its value and 62% having previously experienced VR/AR in such contexts. Participants praised the content for being highly accessible, convenient, enjoyable, and immersive, though there was some criticism regarding the tailored content aimed at younger audiences and concerns about reliability. A key requirement identified was that digital content must be accurate, with clear distinctions made where artistic interpretations have been included.

Summarising the section, the digital model is a vital concept in contemporary heritage management, integrating historical and geometric data to enhance decision-making processes for conserving historic assets. However, a complete model would include artifact information outside the research focus. Empirical research highlighted the challenges and deficiencies in commissioning and collecting geometric data, particularly when sourced from

third parties, necessitating substantial refinement for accurate VR representations.

Historic data acquisition also posed difficulties due to the displaced nature of artifacts. The study emphasises that digital models, combining accurate heritage and geometric data, are crucial for sustainable asset management, supporting robust outcomes. However, limitations exist in accurately modelling unseen materials and technologies. It is essential for data to be rigorously tested and validated, maintaining high accuracy standards, particularly adept when using LiDAR. Continuous engagement with stakeholders ensures the digital model remains current and valuable, providing accurate records and insights that facilitate decision-making and serve multiple applications which came out of the empirical research such as exhibition planning and historic reconstruction.

In geometric data modelling, point clouds typically suffice, with vectorisation selectively applied to specific issues. However, vectorisation and automated meshing can introduce errors and compromise accuracy, particularly when not overseen by specialists. This was evident in the Nottingham Castle project, where raw digital model outputs were appraised. Conversely, the Hawara project was deemed successful in capturing historic essence, despite being based on conjecture. A proposed strategy focuses on vectorising or meshing only essential components of the point cloud to conserve resources and maintain accuracy. Changes would then be monitored through specialised software and multiple scanning campaigns, ensuring sensitive interventions. The digital model development involves three stages: Plan, Retrieve, and Generate, with stakeholder consultation to refine the process and achieve high-quality outputs.

As seen in the section, an initial visit to the heritage asset is advised but may not always be feasible. Changes in data retrieval can arise during the planning phase. Quality remains constant, but environmental conditions and cost/time constraints can impact project completion. When planning a heritage data acquisition campaign, it is crucial to first identify the purpose of data collection, as this decision influences the entire process. There were two primary data types to consider: geometric and historic. Artifact data provides support in interventions yet comprehensive data only emanates

from interventions. Environmental conditions can impact data quality and efficiency, while logistical challenges, such as equipment transport and access, further complicate operations. Adaptability is essential to address specific requirements and to ensure data quality, especially when dealing with difficult materials like mudbrick or reflective surfaces as found in the case studies. Comprehensive planning is necessary to capture sufficient detail for a high-quality digital model. Reiterating, the model's intended use determines data quantity and quality, which should be carefully balanced to support future interventions and maintain the asset's significance. Heritage asset managers must navigate financial limitations, underscoring the importance of a well-considered acquisition strategy tailored to the asset's unique attributes.

Transitioning digital models of heritage buildings into object-based packages like BIM presents challenges, as these buildings are often flexible, accommodating structural distortions. For example, BIM modelling could inaccurately represent the Leaning Tower of Pisa or the trapezoidal roof of University Hall if forced into standard geometric shapes. Accurate heritage modelling requires maintaining the integrity of the original point cloud, as meshing and object creation can distort the structure. While object-based models allow for historical and geometric data integration, they often oversimplify intricate details necessary for accurate structural analysis for example. Accurate data management is vital for integrating new discoveries and revising models accordingly. Effective heritage asset management requires iterative processes of data capture, review, and update, ensuring robust models that facilitate informed decision-making. Engaging stakeholders with digital models enhances understanding and connection to heritage assets, as demonstrated through various interactive experiences, including VR exhibitions and workshops.

5.3 Heritage Frameworks

The framework cannot act independently, there are a range of key contextual examples requiring integration as elucidated in the literature review. This research adopts a conservation-focused approach to global heritage, prioritising sustainability aligned with the global heritage manifesto. Managing heritage assets under the proposed framework, especially with a

sustainability focus, is complex, requiring the integration of environmental, economic, and social considerations. UNESCO (2021) highlights challenges such as typologies, climate change, and vandalism. The framework extends beyond technical aspects to include education, planning, and tourism, aligning with the United Nations 2030 Agenda. The agenda's heritage goals are rooted in the five 'Ps': people, planet, prosperity, peace, and partnerships, underscoring their critical importance for humanity and the planet.

Retaining outstanding universal value demands effective asset management, a plan to maintain and protect it for future generations. This involves continuous preparation, implementation, monitoring, and adaptation, considering environmental, social, and economic factors, and addressing broader heritage trends and interventions. A thorough assessment of the asset's significance and condition should guide decisions, exploring alternatives and assessing impacts on OUV. Safeguarding OUV, especially against disasters and climate change, requires comprehensive documentation, informed by national and international comparisons, and continuous monitoring. This documentation requires to be robust, poor data leads to poor decisions. The UNESCO promotes skills required in the heritage arena and utilise experiential learning as an efficient and effective approach to protect a heritage asset.

In the UK Historic England, Cadw, Historic Scotland and Historic Environment Division Northern Ireland contribute to the policy supporting heritage assets along with the NPPF. The importance of the shared resource, stakeholder involvement, place significance, value management, decision making, and documentation form the basis of the principles applied. In alignment with this research, change management directs the question of sufficient information to understand impact, sustainability, effect on authenticity and integrity, reversibility, comparing options, mitigation and monitoring and evaluating outcomes. A conservation requirement considered as a framework for heritage assets is to manage all physical aspects starting with maintenance and following up in the specific order repair, renew, restore, replace. Historic England (2016) use the basic framework of Identify, Plan, Manage, Implement and Review. The NPPF as the overarching planning framework provides a foundation of four measures, Foresight, Strategic

Threat Assessment and Resource, Recognition and Identification of the Potential Resource, and Assessment of Character and Significance. However, there is no action plan for the management, it is a policy for legal implementation of heritage protection.

Historic Environment Scotland provides the PIC Asset Management Tool which contains a range of consistent data to provide a current condition building on regular surveys, yet it identifies digital content as immature, HES (2018). CIOB (2020) extend the understanding of heritage assets to include non-listed traditionally constructed buildings. The skills level required is beyond the understanding of modern equivalents, part of a golden thread running through conservation understanding and ethically respecting the importance of an asset thereby managing significance. Feilden and Jokilehto (1998), recommend evaluating value should first document its history and existing condition before proposing intervention, and any valuation should include the intangible elements. The knowledge gleaned through the process of assessment and recording of the asset, and the subsequent understanding revealed in analysis of the data contributes to appreciation of significance.

BS 7913-2013 serves as a foundation for building conservation, emphasising the protection of heritage through evidence-based research. The Conservation Process Flowchart integrates strategic and operational management, ensuring decisions are informed by the asset's significance. Conservation management plans, essential for both strategic and daily administration, should regularly assess significance, vulnerabilities, and necessary interventions. Best practice includes monitoring the asset every four to five years, updating records, and ensuring all involved understand the asset’s value to support informed decision-making.

Moving towards a micro position Management plans integrate conservation, use, and development, balancing protection with stakeholder consent, legal policy, and professional ethics. Data collection is foundational, involving maps, reports, and advanced techniques like LiDAR and photogrammetry to ensure comprehensive and accurate information. This stage includes documenting site conditions, erosion, structural deformations, and historical context, all crucial for understanding significance. Frameworks emphasising historical, aesthetic, scientific, and social values, integrating digital models

to visually represent these aspects, which are crucial for conservation practices and guidelines.

The section explored existing frameworks and workflows in heritage conservation, emphasising the need for digital processes to generate extensive data and downstream repositories for effective management. This knowledge underpins the development of the theoretical framework, aligning with UNESCO's emphasis on sustainable development and the criteria for Outstanding Universal Value. Competency frameworks aim to address skill gaps through experiential learning. UK policy and organisations like Historic Environment Scotland and CIOB/RICS highlight the importance of robust management plans, strategic planning, and condition monitoring. The section concludes a lack of structured data and collaborative frameworks hampers effective heritage management, digital models would go some way to prioritise tasks and guide sustainable interventions.

Recognition must be given to the management theory that emphasises the inclusion of strategic, intermediate, functional, and emergent stages to ensure robust decision-making processes. Neglecting to implement all stages of planning relegates decision-making solely to the emergent stage, resulting in reactive solutions that can lead to premature failure, substantial material loss, and a diminished perception of the asset's value. Moreover, hastily undertaken repairs often lack proper consideration, thereby compromising quality. Adequate preparation, on the other hand, facilitates access to the necessary materials and skills for effective intervention, minimising the impact and preserving the asset's significance, ultimately fostering a sustainable approach.

Managing heritage assets entails a heightened level of responsibility and complexity due to the ethical considerations that are fundamentally underpinned by policy pressures at local, national, and international levels. Stakeholders involved in determining the significance of these assets scrutinise them rigorously pressuring strict compliance with policies. This dual obligation introduces further challenges, as increased public access not only complicates management efforts but also accelerates wear and tear. As heritage sites gain popularity, the pressure to balance preservation with public engagement becomes increasingly pronounced, demanding meticulous

planning and robust management strategies to safeguard these assets for future generations.

This highlights the necessity for an integrated and comprehensive approach to managing heritage assets, emphasising sustainability and by extension significance, and aligning with global and national frameworks. It underscores the importance of including strategic, intermediate, functional, and emergent stages in management processes to ensure robust decision-making. This approach considers environmental, economic, and social dimensions, as outlined by UNESCO and the United Nations 2030 Agenda. Key challenges, such as typologies, climate change, vandalism, and the impact of increased public access, complicate heritage management, necessitating a balance between preservation and accessibility.

The framework extends beyond technical conservation to encompass education, planning, tourism, and robust documentation, including advanced digital techniques like LiDAR and photogrammetry, to manage assets effectively. It also stresses the importance of continuous preparation, monitoring, and adaptation to protect the OUV of assets, ensuring they are preserved for future generations. The significance of heritage assets is evaluated through a comprehensive assessment of their historical, aesthetic, scientific, and social values, with a focus on both tangible and intangible elements.

The research points to a need for robust data and structured management plans, supported by organisations such as Historic England and Historic Environment Scotland, to address current skill gaps and improve strategic planning. The integration of conservation, use, and development within management plans is essential for balancing protection with stakeholder consent and policy requirements. Ultimately, effective heritage management requires a holistic, well-documented approach that fosters sustainable interventions and upholds the significance of heritage assets.

5.4 Theoretical Framework

The proposed theoretical framework, developed through both literature review and empirical research, serves as a foundational element that binds complex themes in this study. It bridges the gap between theoretical postulation and practical application, ensuring a comprehensive explanation

of reality as suggested by Riggan and Ravitch (2011) and Ngulube (2018). The framework's advancement marks a significant contribution to knowledge, particularly through the creation of a dynamic digital model of heritage assets. This model integrates current geometric data with historical and contemporary records, offering a time-bound, editable, and manageable conservation tool. However, current limitations include a lack of public engagement, which inhibits broader decision-making capacities, as highlighted by Jeffrey (2015).

The framework's flexibility allows for periodic updates and strategic decision-making, ensuring the digital model's data remains current and relevant. The earlier section elucidated the digital model components, content and the link with the empirical research. Regular reapplication and the inclusion of new historical data can enhance the model's accuracy and utility, aligning with the need for high-quality digital facsimiles, Kenderine (2018). The proposed framework centralises significance emphasising conservation as a critical factor in heritage management, contrasting with other models that focus primarily on economic and organisational performance as elucidated by McGibbon, Abdel-Wahab and Sun, (2017).

Heritage skills are a sector wide issue, the aging workforce are not being replaced by a younger contingent and with the retirees a raft of experience is being lost. The loss of experiential knowledge leaves the assets vulnerable; information sharing brings valuable understanding and reduces the susceptibility to loss or undermining of significance. Furthermore, the framework supports interdisciplinary collaboration by providing a visual interface that bridges gaps between owners and users, tradespeople and professionals, potentially using augmented reality as output in the empirical research. Ultimately, this framework offers a robust, ethical approach to heritage conservation, ensuring the preservation and socio-economic benefit of heritage assets for future generations.

In advancing the theoretical framework, the literature review contextualised and clarified existing conservation theories and frameworks to address the current challenges in heritage management. These have been summarised in an earlier section of this chapter. A critical issue is the diminishing significance of heritage assets, often due to unfounded or delayed

management decisions, particularly in routine maintenance and repairs.

The proposed framework emphasises a dynamic, adaptable model for heritage management, designed with future needs in mind and evolving with the asset's understanding. Influenced by heritage policies, digital tools, and stakeholder input, the framework integrates management strategies, documentation, and maintenance while remaining flexible in software choices (excluded from the research). As a digital repository, it will centralise historical knowledge, becoming a key reference for strategic, operational, and utilisation levels of asset control. The research incorporates feedback loops and performance indicators, though not the research primary focus.

Drawing on theories defined by Varpio and Paradis (2020), the framework supports data capture and dissemination, particularly in addressing conservation interventions and repairs. It bridges theoretical concepts with practical application, enhancing understanding through literature and empirical work. Crucially, the framework addresses the current gap in public engagement, expanding its utility beyond professionals. By facilitating continuous updates, high-quality digital facsimiles, and augmented reality interfaces, it enhances collaboration and preserves historical knowledge. Unlike previous approaches, this framework integrates conservation as a fundamental requirement, ensuring future socioeconomic benefits. It serves as a novel contribution to heritage management by uniting tradespeople and professionals, users and owners, ensuring the asset's long-term preservation and enrichment.

The development and introduction of the theoretical framework provides the basis of data capture and dissemination for inclusion in the conservation management plan. The robust plan provides the lynch pin in the deliberation of interventions and when faced with a requirement for immediate repair (temporary or permanent) after damage (accidental or vandalism). The appreciation of the stages in management previously discovered proposed the three standard, strategic, intermediate and functional, and the additional emergent issues. The framework has generalised the concepts within the quality lens applied. The concepts were identified in the literature review and tested during the empirical work with the case studies. The final framework provides the linkage of these concepts into theories to develop

understanding.

The fundamental situation is shown Figure 65 where the digital model, located inside the conceptual framework, in championing heritage management forms the central region between the key features. In support of the term heritage management van Vollenhoven proposes *'.. the application of management techniques to conserve and develop cultural resources so that they remain part of a cultural heritage with long-term value and benefit for the general public.'* van Vollenhoven (2018, p.346). The framework for managing heritage assets Historic England (2017) takes this to include 'Identify', to comprehend the asset, with deficient information a barrier to effective management recognising that gathering and maintaining data is resource intensive. The section after the contextualising the framework summarised the literature review, providing an overview of the macro and meso, the international and the national.

This basic model can be melded into the digital model with the inputs as data capture for geomatic, historic and artifact elements which moves the understanding forward. A link between the historic, the geomatic and the artifact data has to be acknowledged where elements of greater significance focus the depth of geometric accuracy and where observations in the geometric data can reveal a historic narrative. This was seen in rich detail in the Arkwright Building façade case study where the historic and geometric data concurred, the chain of events evidenced in the images and the isometric point cloud image from the geometric data included revisions to the detail.

The detail contained in the digital model according to NPPF diktat should be proportionate to the importance of the asset. If the observation focuses on the economic, the model likely contains only sufficient quantity and quality of data to support the intended intervention whether to protect, sustain or enhance. Sustainable solutions require all pillars in harmony to be compliant, the social focus complements the inclusion of the stakeholders and the environmental may be addressed through the light touch of any intervention utilising knowledge from the model, a proactive approach. Yet English Heritage (2023), propose a long-term strategy to address the risk factors which end in disrepair hence the notion that to record beyond the minimum

level is the norm as a baseline for that approach. This would lead to the capture of data for the whole asset along with the setting as the '*… research can reveal more about the past whilst finding solutions for the future.'* English Heritage (2023, p.3). In doing this the digital model is aptly positioned to support the management decision making. Strategic planning includes the whole of the asset and setting as intra and inter-linked elements with the significance interdependent with a synergetic relationship hence a moderate digital solution has adverse future implications.

The data flow into the digital model should not be understood as a unidirectional process; rather, it should exhibit bidirectionality, where interventions generate data that contribute to the development of new insights or the amendment and enhancement of existing records. The digital model, which encapsulates historical data, plays a crucial role in elucidating the asset's significance. Asset management processes involve the extraction of information from this model, facilitating the transformation of data into knowledge and thereby fostering understanding that informs decision-making. In turn, the outcomes of these decisions are reintegrated into the model, contributing to its historical narrative and ensuring the geometric model is consistently modernised with contemporary data. This reciprocal relationship is aptly illustrated by the directional arrows labelled 'Defines' and 'Informs,' which signify the dynamic interplay between stakeholders and the evolving significance of the asset.

Stakeholders, in their assessment of an asset's significance, actively contribute to its definition, as indicated by the directional flow towards the asset. The asset's importance is established at the highest levels by heritage bodies, whose evaluations are further refined as historical context and new discoveries are interpreted. This ongoing appraisal process, once robust, determines the asset's significance, which subsequently informs asset management strategies. This was seen in the elevation of the Arkwright building from Grade II to Grade II* on completion of the refurbishment including demolition of the lecture theatre and reordering the spaces. Countering this example are the listed buildings carefully dismantled when building the Channel Tunnel link to London St Pancras station. These were repositioned and upon completion of the rebuilding exercise were delisted.

There is a compelling argument for maintaining a feedback loop wherein asset management could potentially influence the asset's significance. This is feasible; however, provided that policy and ethical standards are rigorously upheld, the asset should not fall into disrepair or a state of maintenance deficit. Under these conditions, the asset's quality will inherently justify its significance. Any deviation from this standard would undermine the integrity of the policy and ethical charters. That said, unforeseen situational or incidental challenges may arise, occasionally leading to delays in problem resolution due to a lack of skills or materials. In such instances, the intent behind actions serves as a mitigating factor, ensuring that any impact on the asset's significance remains marginal. The inherent importance remains. A solution to uphold these ideals would be to enact protective measures to ensure minimum impact, the theft of lead from an ecclesiastical building would lead to extensive water damage. The use of temporary covering to withhold the water allows the rectification work to incorporate skilled operatives and appropriate materials at a suitable juncture.

Furthermore, the feedback from geospatial data is integral to the model, continually enhancing its accuracy and relevance. Once new information is incorporated into the model, it is immediately archived as historical data. This dynamic process captures the evolving condition of the asset, documenting changes resulting from factors such as weathering and vandalism, which are indicative of emergent situations. As the asset undergoes interventions - whether repair, renewal, restoration, or replacement - each action alters its state, effectively transitioning the asset from one iteration to the next.

An essential requirement is that data derived from these interventions be rigorously documented within the digital model, thereby constituting an integral element of the artefact's dynamic narrative. Such meticulous record-keeping facilitates the ongoing evaluation of the intervention's long-term efficacy. Moreover, the data enables the implementation of adjustments or, if necessary, the reinstatement of the asset to its original condition, ensuring adherence to established policy and best practices.

Stakeholders influence asset management practices through the flow of information, while policy and ethical considerations shape their perspectives,

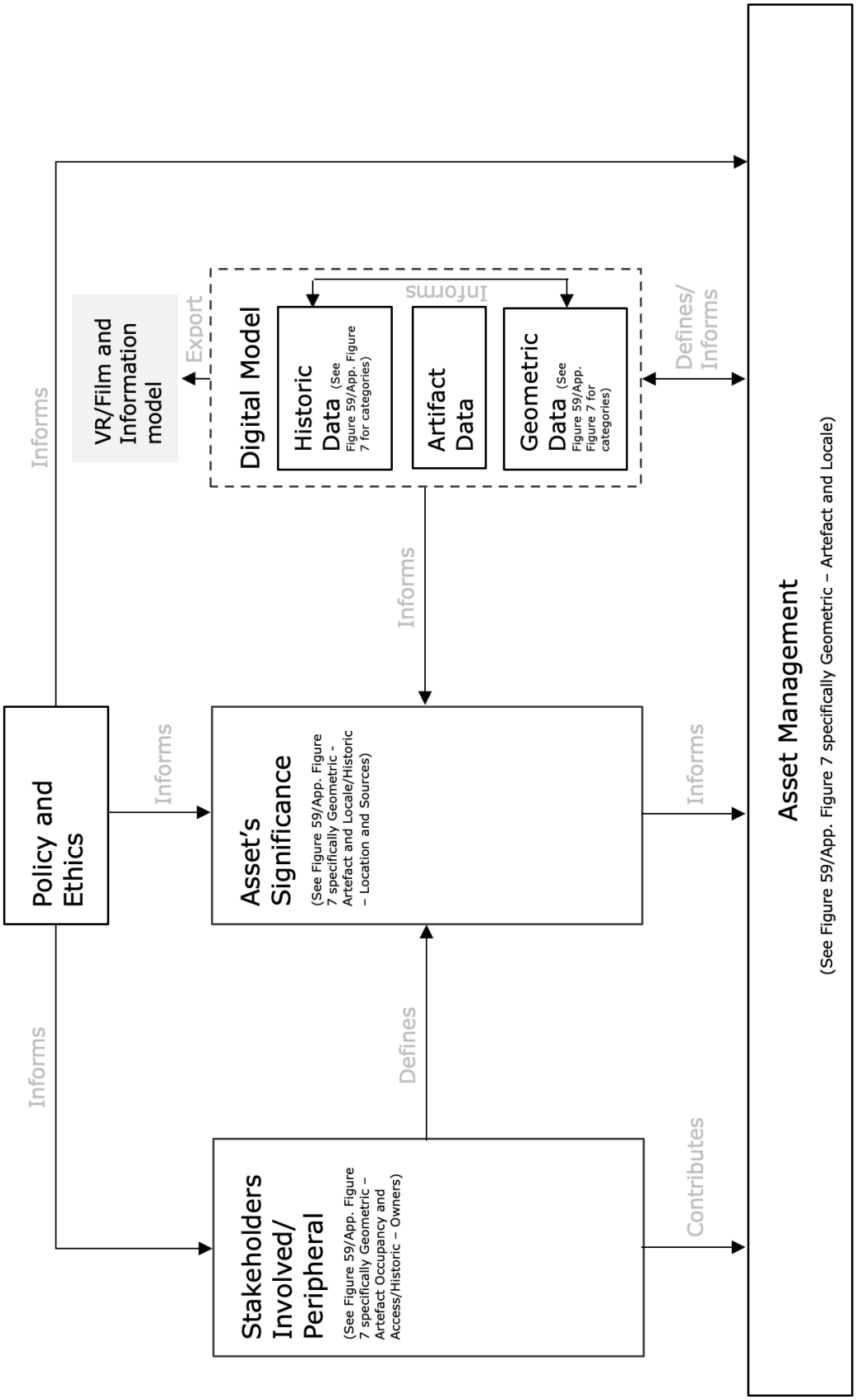

Figure 60: Asset Management Theoretical Framework showing links between the elements

guiding both management decisions and the assessment of an asset's significance. This continuous interplay between theoretical principles and practical implementation helps to develop a coherent theoretical framework.

A notable gap exists between policy, ethics, and the digital model, with the data used in the model being curated and gathered by stakeholders, establishing only an indirect link between these elements. Other indirect relationships also emerge, mediated through management and the perceived significance of the model. Stakeholders and managers oversee data collection within the model, guided by managerial objectives and the model's perceived importance. However, as highlighted in the Hawara case study, it is essential that instructions are fully understood to ensure effective implementation.

The risk of misinterpretation or an incoherent specification is significant when stakeholders face communication barriers or lack clarity regarding the requirements. While policy bodies propose frameworks that can influence the digital model, particularly in the context of advocating for conservation management plans, these frameworks have an indirect impact. The literature review further emphasises this need. A known limitation in the industry is no standard exists for geospatial data.

Stakeholder access to the digital model will be carefully regulated by the asset's management systems, ensuring that the level of detail provided aligns with the specific needs of each stakeholder, particularly when their involvement extends beyond a peripheral interest. The digital model is capable of exporting data to various software platforms, enabling the creation of images, films, or virtual reality experiences. Additionally, any revisions made within the digital model can be integrated and stored on the platform, serving as a repository for multimedia content. Engaging stakeholders through shared access to the model not only facilitates knowledge exchange but also dismantles barriers and enhances social value by making the content accessible on common platforms. For instance, a planning application for listed building consent would require a comprehensive plan, whereas a researcher focusing on a specific historical aspect would need access to more targeted data. In each case, the resulting data would need to be reintegrated into the model. While the asset's management acts as the gatekeeper to the digital model, stakeholders and relevant policies indirectly shape the model's

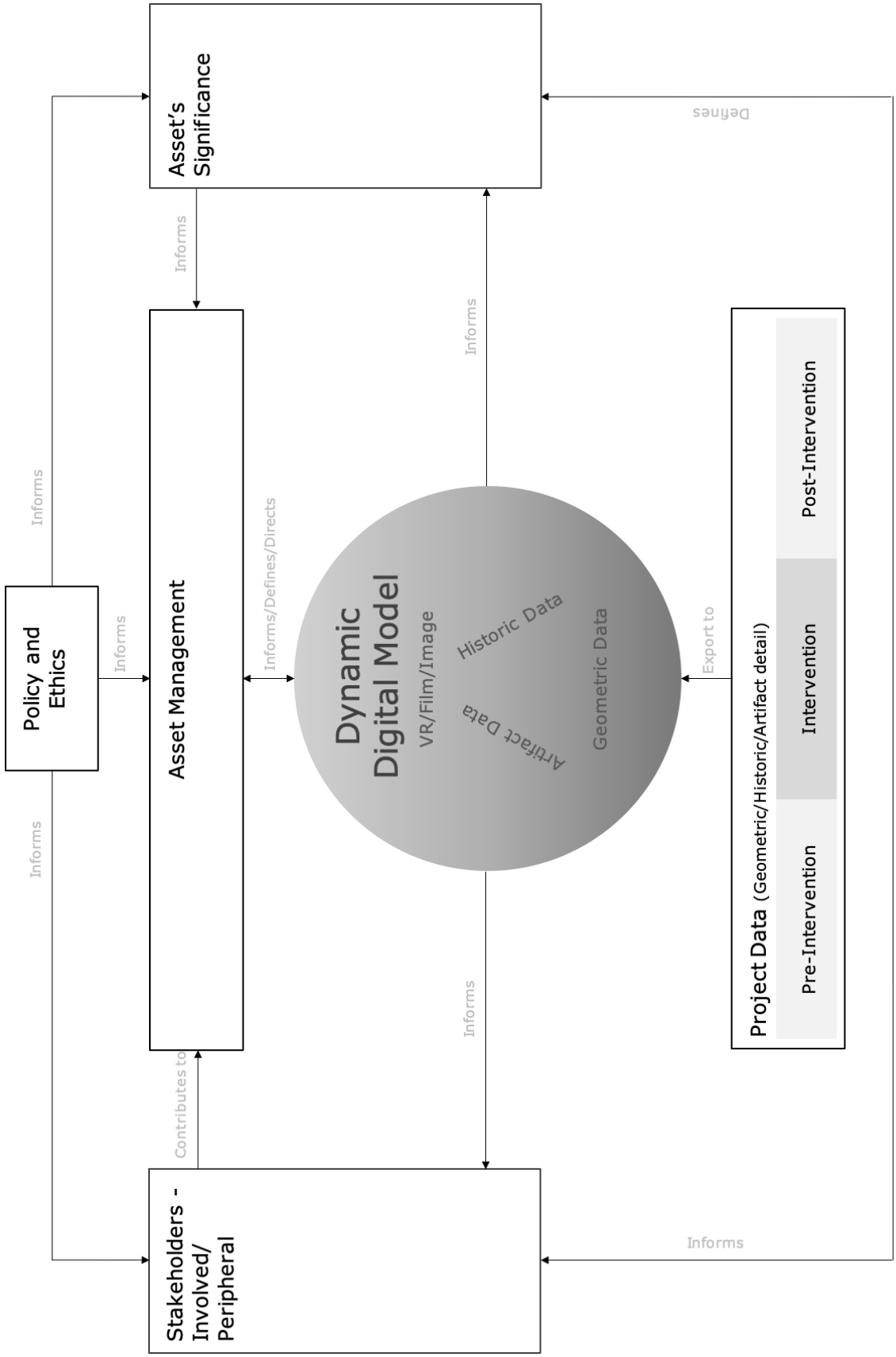

Figure 61: Final Historic Asset Management Theoretical Framework

evolution. The insights gained from empirical research drive the transition from conceptual understanding to theoretical development, as illustrated by the evolving links in Figure 60.

The subsequent phase involves integrating the outcomes from Case Study Three at Nottingham Castle, marking a pivotal shift in the digital model's role from a supportive tool to a central, dynamic asset, as illustrated in Figure 61. In this context, the digital model functions as a living document, continuously capturing and synthesising data throughout all stages of the project, pre-intervention, during intervention, and post-intervention. Data from each phase, including historical records, geometric information, and artefactual findings gathered during the intervention, is systematically incorporated and preserved within the digital model. The Construction Leadership Council (CLC) (2024) issued guidance for accountable persons, the golden thread contains the information about the asset and management systems. The requirement is for the information to be accurate, understandable, accessible and current whereupon Figure 58 demands the model is adaptable to allow flexibility for all types, sizes and locations of the asset.

Several key elements have undergone refinement; notably, stakeholders such as surveyors, researchers, and contractors are now actively engaged in

both retrieving and contributing data. This active involvement creates a direct link between the asset's cultural and historical significance and the stakeholders themselves, facilitating a mutual understanding and enabling more informed decision-making. This collaborative exchange deepens respect for the heritage asset, which is subsequently integrated into the asset's management strategy. The significance of the asset guides the data collection process, dictating the scope and depth of information required in alignment with the NPPF principle of proportionality.

The foundational elements of this model are shaped by policy and ethical considerations, which determine the operational framework of its key concepts. Stakeholders, both directly involved and, on the periphery, play a crucial role in defining and understanding the asset's significance. Their esteem for the asset is informed by this significance, establishing a bidirectional flow of knowledge and influence. While the historic data embedded within the model provides foundational insights, it is the

comprehensive digital model itself that offers stakeholders a deeper understanding, through the rich repository of knowledge and data it contains. The model's outputs, including images, films, 3D models, virtual reality simulations, and other media, are centrally maintained and can be utilised to engage and inform stakeholders through accessible and varied formats. Finally, the ongoing, dynamic collection of data serves to enhance both the accuracy and relevance of the digital model over time.

The framework provides a comprehensive understanding of the processes and interactions involved with the digital model of historic assets. These interactions are facilitated by management systems specifically designed to uphold the asset's significance. Interventions are informed by the digital model, serving as a pivotal reference to generate the necessary understanding for executing the most suitable actions. Historically, the sector has been plagued by inaction stemming from a lack of data to support decision-making. The introduction of the digital model fundamentally alters this dynamic by fostering a proactive approach. It enables precise timing for interventions, which becomes standard practice, thereby optimising the preservation of original materials. As a result, replacements are made only at the point of inevitable disintegration, rather than prematurely, in an effort to maintain the asset's integrity. Alternatively, post-failure interventions, which leave the asset vulnerable to weathering and erosion, are minimised. This approach mitigates the loss of material and, consequently, prevents the degradation of the asset and its historical significance.

5.5 Application of the Framework

The theoretical framework delineates essential components in policy and ethics, significance, stakeholders, and management systems, all of which are integral to decision-making processes facilitated by the digital model. This framework clearly maps out the flow of influence and information, ensuring comprehensive coverage of all aspects. Continuous data streaming in and out of the digital model fosters dynamism, rendering it a contemporary resource capable of supporting asset management and maintaining both the significance and sustainability of the asset.

Empirical research serves as a foundation for testing this theory. The initial case study integrated geometric data with historical records to capture the

current state of the asset and its surroundings. A comparative analysis revealed synergies that highlighted historical modifications resulting from an aerial assault. Moreover, the imprecise nature of the subsequent rebuilding distinctly marked the areas of impact and, equally importantly, encapsulated intangible history due to the lack of available resources. The framework communicates these findings to stakeholders through straightforward 2D resources, uncovering significance that might otherwise remain hidden.

The Hawara case study, preceding an intervention involving site dewatering, amalgamated key historical data with precise geometric information. The resulting virtual reality models, informational 3D films, and point cloud models significantly contribute to the dissemination of history. This accessible evidence not only enhances the site's significance but also provides a baseline model to monitor the site during dewatering activities. Stakeholders engaged in planning activities around the site can thus identify critical areas beyond the perimeter of the edifice. Both central and ancillary activities related to the dewatering can be strategically located to minimise impact on sacred areas. Furthermore, an understanding of the data acquisition process enables stakeholders to replicate it during the project, ensuring that accurate models are available for comparative analysis.

Furthermore, in the second case study, capturing precise geometric and geospatial data revealed issues related to mudbrick materials. Understanding these issues within a model before the project's commencement allows for efficient workflow determination, equipment procurement, and onboarding of skilled operatives. Although project planning can be an extended and costly process, the framework supports stakeholders in comprehending key dynamics, while the digital model provides robust evidence on which to base plans.

The Ducal Palace, protected by the walls of Nottingham Castle, exemplifies how the digital model's dynamism supports all stages of a refurbishment project. Initial models were integrated into the offer during the site's closure, allowing stakeholders to virtually access the main gallery through a combination of 3D film and VR experiences. This provided a foundation for subsequent campaigns and identified a specific historical point of interest. Documenting the archaeology before reburial beneath the new gallery floor

has resulted in an accurate record, which future research will likely reference for insights into the concealed artifact. During the research phase for this thesis, an image of a painting depicting the steps from the kitchen courtyard, used before the Victorian tunnel was built, was discovered. Data from the campaign corroborates the location of the stair base, with a blocked opening visible in the wall above.

The post-refurbishment campaigns documented the new temporary galleries, situated on the ground floor's east side, which occupied the space previously used for the entrance, shop, and start of the exhibition. These rooms were stripped back before the installation of new services capable of accommodating the environmental conditions required by touring exhibitions. The accurate digital model was exported in a commonly used format for exhibition designers. Addressing universal challenges, such as space availability, exhibit placement, visitor flow, and staff positioning, the precise 3D model answers these questions effectively. Objects representing the exhibits can be arranged, visualised, and visitor flow modelling can be conducted to optimise the experience.

A campaign to document the external environment identified new information points on the site and interventions during the refurbishment. Although not extensive due to the property's Grade I listing, this model nonetheless charts the asset's evolution. The kitchen courtyard, infilled with the gallery, could potentially be restored to its original state, supported by the pre-refurbishment model. Similarly, the glazed colonnade could be reopened to the elements, as it was during the late 19th-century refurbishment. An external building condition record exists, providing a baseline for future interventions similar to case study two. Future campaigns should include areas such as the offices, plant rooms, and roof to complete the model. Although these areas are currently considered of lesser importance, a comprehensive digital representation would provide enhanced support for all components.

The framework, embedded with the digital model enriched with historical and geometric data, could enhance protection for the asset's significance through the accessibility offered by VR experiences and 3D films. Stakeholders do not require an exhaustive collection of drawings and photographs; instead,

inclusive media can deliver valuable insights. Areas of greater importance can be identified through heat mapping, ensuring that invasive intrusions are minimised, thereby elevating and disseminating the significance of the asset's components. The model has the capacity to store pertinent current data and be augmented with new discoveries, thereby maintaining a valuable, accessible resource.

Each case study consistently demonstrates the framework's applications and content. The integration of stakeholders, guided by policy and ethical considerations, supports the preservation of significance in management and ensures sustainable responses through applied systems. The flexibility within the framework allows for its application across various assets, shaping the digital model's content. Through iterative action research, the framework has been refined and strengthened, emerging as a valuable tool. This section has illuminated the practice where the framework meets identified requirements, with inclusion beginning with clear objectives to guide content development.

5.6 Conclusion

The proposed theoretical framework serves as a cornerstone for integrating complex themes within heritage management. Developed through a rigorous literature review and empirical research, it bridges the divide between theoretical concepts and practical applications. This framework introduces a dynamic digital model that amalgamates current geometric data with historical records, serving as an adaptable tool for conservation. A critical issue it addresses is the historical lack of public engagement, which Jeffrey (2015) identified as a barrier to broader decision-making.

Stakeholders play a critical role in shaping an asset's significance through their assessments, which influence asset management strategies. The asset's importance, initially defined by heritage bodies, evolves with new interpretations and discoveries. This dynamic was evident in the empirical research case study Arkwright building's elevation from Grade II to Grade II* after refurbishment. A feedback loop between asset management and significance is crucial, provided policies and ethics are strictly adhered to, preventing disrepair. The digital model continuously incorporates geometric data and intervention records, preserving the asset's evolving narrative and

supporting informed decisions. Although stakeholders indirectly influence the digital model, management decisions are vital in determining data collection, ensuring relevance to the asset's perceived importance.

The framework is designed for flexibility, allowing for continuous updates and data integration, thereby enhancing its accuracy and utility. It prioritises conservation over economic factors, distinguishing it from other models that focus primarily on financial and organisational performance, as noted by McGibbon, Abdel-Wahab, and Sun (2017). By fostering interdisciplinary collaboration and leveraging digital tools, including augmented reality, the framework enhances public engagement and knowledge sharing, mitigating the loss of experiential knowledge due to an ageing workforce.

Misinterpretation and unclear specifications pose significant risks in heritage management, especially when communication barriers exist among stakeholders. While policy frameworks indirectly influence digital models by advocating for conservation management plans, there remains a notable absence of standardisation in geometric and geospatial data. Stakeholder access to digital models is regulated by asset management systems, ensuring data relevance to their needs. This model supports exporting data to various platforms, fostering knowledge exchange and enhancing social value by making content accessible.

Empirical research and case studies, such as those at Nottingham Castle, have shifted the digital model's role from supportive to central, emphasising its dynamic nature. The model, as a living document, captures data at all project stages and adapts to changes, aligning with guidelines from the CLC (2024). This approach enhances the accuracy, accessibility, and relevance of the model.

Active stakeholder engagement in data retrieval and contribution links cultural significance to management strategies, fostering mutual understanding and informed decision-making. The digital model integrates historical data with new findings, supporting a proactive approach to conservation. This ensures that interventions are timely, minimising material loss and preserving the asset's integrity and significance, which are fundamental to heritage management and policy compliance.

It has been shown that the theoretical framework integrates policy, ethics, stakeholder management, and decision-making through a dynamic digital model. This model supports asset management by providing precise data for historical and geometric analysis, enhancing understanding, planning, and preservation efforts. Case studies demonstrate its application in capturing and disseminating significant information, guiding interventions, and fostering sustainable practices. The framework's flexibility and comprehensive data support make it a valuable tool for maintaining the significance and sustainability of cultural heritage assets.

Ultimately, this framework offers a robust, ethical approach to heritage conservation, facilitating informed decision-making and ensuring the preservation and socio-economic benefits of heritage assets. It represents a novel contribution to heritage management, emphasising the significance of assets and the necessity of a proactive, data-driven approach.

Chapter 6.0 Conclusion

6.0 Introduction

This research has investigated the multifaceted subject of heritage management during a period of significant change. The knowledge base in this field is diminishing due to an aging workforce and the associated loss of skills, which is a well-known issue in the sector. The importance of both tangible and intangible heritage cannot be overstated, as these elements form the foundation of contemporary life. While the loss of heritage should not be accepted, the challenge of preserving it amidst the pressures of modern societal existence is considerable.

Effective heritage management requires a proactive strategy to safeguard assets and their environments, with the goal of retaining their significance for a sustainable future. This process begins with a comprehensive understanding of the fundamental components of heritage, but it is complicated by the interdisciplinary nature of conservation practices and the support systems that underpin them. Stakeholders play a crucial role in shaping the future of heritage management; their unique relationships with heritage assets drive both the value of these assets and influence their condition. All of these considerations must operate within the boundaries of ethical practice and policy at local, national, and international levels.

The gradual loss of physical fabric due to weathering processes diminishes the significance of heritage assets by diluting their physical attributes. However, the memories held by stakeholders often maintain these assets in high esteem. Uncontrolled factors such as conflict, vandalism, poor maintenance, and inadequate repair further erode the physical integrity of heritage sites, diminishing their quality and significance. Engaging with digital models can help reverse community detachment by providing detailed documentation in an accessible format, thereby facilitating a thorough understanding of heritage assets and supporting informed decision-making to retain and enhance their significance.

LiDAR, as a non-invasive procedure, captures accurate geometric data that can be used to create three-dimensional models. When augmented with historical data, these models provide a foundational dataset for objective

decision-making. Recognising the evolution of heritage assets and their settings allows for a valuable catalogue of changes, contributing to an appreciation of their significance. Static databases, however, often fail to adapt to new understandings that emerge through contemporary discoveries. Additionally, the effects of weathering and invasive processes, which deteriorate the quality of heritage assets, need to be quantified as part of their historical narrative to enable proactive responses. A dynamic digital model, centralised within a comprehensive framework, plays a crucial role in recording events and informing present decisions based on all available data, with a focus on preserving significance for a sustainable future.

The research identified three case studies: the Arkwright Building, the Hawara Pyramid, and the Ducal Palace at Nottingham Castle. Each case study provided unique insights, with the latter studies building upon the findings of the former to enhance the framework's development. Through an iterative process of reflection, these case studies allowed for the development of robust solutions, leading to the creation of high-quality digital models. Each iteration was tested with stakeholder participation, both informally and formally, through seminars and workshops.

The final framework integrates the digital model with four cornerstones: policy and ethics, significance, management, and stakeholders. The model is initially populated with essential data, including dimensional, historical, and, where available, artefactual information. Artefactual data, which includes material and technical details, generally remains outside the scope of this research, as it typically becomes available only after conservation interventions and is thus often overlooked. While craftspeople may possess valuable local knowledge, this information is frequently siloed and is diminishing alongside the loss of traditional skills.

This chapter delineates the process through which the research objectives were fulfilled, critically evaluating the contribution of each constituent element to the overarching aim, culminating in a unified outcome. It also identifies limitations and suggests areas for refining the framework. While this research has contributed to the field by developing a new framework, further research is necessary to enhance and sustain the management of historic assets, ensuring their significance is preserved for future generations.

6.1 Meeting the Objectives

The initial investigation systematically gathered relevant literature to establish a solid foundation for the research and to refine the aims and objectives. During this phase, a preliminary conceptual framework was devised that encapsulated the digital model. Further analysis and exploration of gathered resources led to the development of an expanded framework, represented as a tetrahedron encompassing the digital model at its core (see Figure 65). This unique geometric configuration allows each cornerstone to be centrally aligned when the shape is rotated and viewed from a specific perspective. Within this framework, the digital model supporting management is contextualised by four key components: policy/ethics, significance, stakeholders, and management. When the element of 'significance' is placed at the forefront, the supporting elements then comprise management, policy/ethics, and stakeholders. The versatility of the framework is enhanced by its capacity to incorporate the universal nature of a historic asset and its setting. This ensures that the framework is adaptable to any monument, regardless of its size, type, or location. Furthermore, within the framework, 'management' is conceptualised as an active process (a verb), with the manager's role being integrated into the 'stakeholder' cornerstone.

The empirical research employed three case studies to refine the conceptual framework into a more comprehensive theoretical model. Each case study facilitated the integration of geometric and historical data into a singular digital model. The outputs from these studies included various resources designed to engage stakeholders, such as images, films, 3D films, and virtual reality models. These resources, grounded in precise data, illuminated historical events and constructed timelines that underscored the significance of the assets.

The final framework evolved iteratively from the conceptual model by adding interconnections between its components. In this refined model, the digital component occupies a central position, flanked on either side by 'stakeholders' and the 'significance' of the asset. 'Management' is supported by the model, with ethical principles and heritage policies serving as overarching guidelines. Additionally, to maintain a dynamic model, newly discovered data is continuously integrated to enhance the model's development.

Stakeholder engagement, facilitated through organised events, was instrumental in disseminating knowledge, shaping understanding, and fostering stakeholder buy-in. The underlying premise is that active stakeholder involvement in the asset enhances the relevance of the historic site, thereby ensuring its sustainability. Furthermore, the digital resources, readily accessible in a centralised repository, are democratised and available to stakeholders, thereby fostering knowledge-sharing, particularly in relation to interventions. This accessibility mitigates, to some extent, the loss of local expertise, dismantling knowledge silos and compensating to some extent for the depletion of skills.

Utilising the outputs from the digital models - including images, films, 3D films, and VR models - in seminars, workshops, and lectures effectively engaged stakeholders by demonstrating how the immediacy of the content could captivate and inform users. While the data was stored locally, this does not preclude the possibility of adopting a cloud-based solution, especially when using mobile devices. In such a scenario, the model could become more dynamic, with updated material being immediately accessible to those with appropriate access rights. However, it is important to note that a web-based solution was not tested within the scope of this research, particularly in relation to the intervention process, representing a limitation of the study.

In conclusion, the research has successfully developed a robust theoretical framework that integrates a digital model central to managing and interpreting historic assets. Through iterative refinement, the framework highlights the dynamic interplay between significance, stakeholders, management, and ethical policies, demonstrating its adaptability across diverse contexts and assets. The empirical case studies effectively validated the framework, illustrating how digital resources can enhance stakeholder engagement and sustain the relevance of historic sites. Moreover, the potential for adopting cloud-based solutions was recognised, though further investigation is needed to explore their application fully. Overall, the research underscores the importance of a flexible, data-driven approach in heritage management, ensuring the sustainable preservation and accessibility of historic assets for future generations.

6.2 Achieving Objective 1

Critically analyse the methods, methodologies and practices involved in recording, retrieving and updating information for a heritage asset, focused on aligning these processes with contemporary conservation practice

The literature review highlighted the multifaceted nature of heritage asset management, encompassing the diverse requirements set forth by local, national, and international bodies such as ICOMOS, the UK Government, and local planning authorities. A critical aspect of this complexity lies in the role of stakeholders, whose involvement is essential in imparting significance and relevance to these assets. Each heritage asset is unique, possessing distinct attributes related to its materials, construction, style, setting, and location. These characteristics contribute to the asset's historical narrative, which may or may not be formally recognised through listings. While historic assets are inherently valuable, they must also be allowed to evolve to remain functional and financially sustainable. This necessitates a flexible approach that accommodates change without imposing undue constraints. Furthermore, to uphold the asset's significance, information about it should be disseminated to all stakeholders, whether directly involved or peripheral.

An accurate survey is considered the essential first step in the process of decision-making making to inform the management and use of buildings. Accurate records are necessary for applications for listed building consent, typically included in a Design and Access Statement, and for the development of a conservation plan before any changes are made to the asset. Many existing data sources, especially those of a historical nature, are still in physical formats, often stored in repositories at various levels - local, national, or even international - as highlighted by the Hawara Pyramid case study. When planning interventions, research is undertaken to identify and collate this information to support applications. However, few assets have readily available repositories for consultation or for planning future developments. Moreover, there is often limited or no access to these repositories for craftspeople involved in the conservation process.

The construction industry increasingly recognises the transformative potential of digital technology across various domains, including sustainability, health

and safety, record-keeping, clash detection, material management, modelling, and building management. Modern building management frameworks often rely on accessible information through mobile technology. HBIM is an emerging research area, with several projects exploring its application, although standardisation remains an issue. While high levels of detail are crucial for heritage assets, obtaining comprehensive data of the required quality can be prohibitively resource intensive. Unlike models of new buildings, which are typically standardised, heritage models gain from incorporating discovered data, which enhances their richness and robustness. Digitised historical data can also be integrated into these models to provide a more comprehensive understanding of the asset's relevance. Simple solutions like tagging within the digital model or implementing basic search functionalities can facilitate timely access to information. Integrating ICT into heritage management not only streamlines processes but also supports innovative conservation and dissemination strategies, fostering dynamic and interactive engagement with cultural heritage.

The opportunity exists to consolidate information into an accessible knowledge model based on LiDAR data, which can significantly aid the decision-making process. Such a model should encompass four key areas of knowledge: artefact, lifecycle, investigation practice, and stakeholders, all of which should be accessible, editable, and manageable within the conservation process. This technology can seamlessly integrate historical records and newly discovered artefacts, providing a comprehensive understanding of a site's historical and contemporary contexts. By embedding heritage data within these information models, the management and conservation of heritage assets are greatly enhanced. Comprehensive, accessible digital records support informed decision-making and help preserve the significance of historical structures. This integrative approach promotes sustainable management practices, ensuring that the cultural and academic value of heritage assets is maintained and appreciated.

In the realm of heritage conservation, integrating digital models preserves the significance of historical structures by facilitating informed decisions and sustainable management practices. These models offer comprehensive digital records that assist in the maintenance, repair, and refurbishment of heritage assets, ensuring their cultural and academic value is upheld. Access to such

data empowers stakeholders to manage heritage assets effectively, balancing utilisation with preservation. Thus, digital technology not only transforms modern construction practices but also enhances the conservation and appreciation of historical assets, contributing to the retention and amplification of their significance.

Therefore, it is seen that Objective 1 has been thoroughly explored and grounded in the literature review. By providing accessible and comprehensive digital records, a contemporary approach ensures that heritage sites remain relevant, appreciated, and protected for future generations.

6.3 Achieving Objective 2

> *Evaluate the existing systems and processes in heritage asset management for administering information identifying best practices and limitations within the current frameworks*

This objective was comprehensively addressed in the literature review, which underscored the complexity and multifaceted nature of heritage asset management. The continuous evolution of monuments over time, intertwined with stakeholder engagement and the dynamic socio-cultural contexts they inhabit, reinforces the imperative of ongoing adaptation and relevance. Best practices in heritage management emerge at the convergence of meticulous fabric conservation, sustained stakeholder involvement, and the principles of sustainability. Effective management strategies must be designed to honour and embody these values, ensuring that heritage assets remain meaningful and accessible while preserving their cultural and historical significance for future generations.

The management of traditional heritage assets is a complex process, reflecting a diverse array of materials, technologies, and site-specific adaptations developed over millennia. These complexities present contemporary practitioners with significant challenges, often requiring costly and intricate decisions to ensure the preservation of these assets. An integrated approach necessitates balancing diverse requirements, aligning them with strategic and operational practices.

Across the globe, aging urban development face a limited inventory of

heritage assets, many of which lack comprehensive repositories for proactive management. This absence often leads to reactive rather than strategic interventions, further complicating conservation efforts. It is widely acknowledged that managing heritage assets involves additional layers of complexity beyond those found in modern assets. These include philosophical, regulatory, and community-driven requirements that are unique to each heritage site. Proactive management is crucial in maintaining the significance of these assets, focusing on pre-emptive measures to mitigate risks and recording changes to ensure informed, planned interventions rather than reactive responses.

The management of historic places now extends beyond mere technical requirements; it incorporates sustainability principles that address environmental, economic, and social well-being. This comprehensive approach requires a careful balance between maintaining the authenticity of heritage assets and adapting them to contemporary requisite. The principle of documenting the existing fabric, uses, associations, and meanings of a site prior to any alterations highlights the importance of thorough recording and analysis to support sustainable heritage management practices. Engaging stakeholders - ranging from local communities to government bodies and conservation professionals - is vital for fostering a shared understanding and commitment to preserving heritage values.

Heritage management plans advocate for a proactive approach grounded in objective surveys and thorough research. This approach emphasises strategic organisation and decision-making that considers multiple stakeholders, aiming to achieve sustainable development outcomes. Such plans are dynamic and must be adaptable to both internal and external forces, including evolving stakeholder requirements and environmental changes. Effective communication and collaboration mechanisms are essential to ensure all stakeholders are aligned, contributing to well-informed, consensus-driven decisions. This enhances the robustness of the decision-making process and ensures that diverse perspectives are integrated into final solutions.

Digital models can play a pivotal role in heritage management, particularly in delineating the current state of conservation and planning future interventions. These models should record changes to the asset, including

the rationale behind decisions and the outcomes of revisions. Maintaining the significance of historical assets requires a highly detailed and fine-grained model that supports precise documentation and facilitates effective maintenance, repair, and preservation activities. Proceeding without comprehensive investigatory data risks suboptimal decision-making, particularly if stakeholder engagement has been inadequate, potentially compromising the asset's importance. The integration of digital technology into heritage management practices has transformed the field, particularly through tools like BIM. This facilitates the efficient management and sharing of vast amounts of interconnected data via a graphical interface, revolutionising project management, procurement, construction, and operational workflows. In heritage conservation, digital models can preserve the significance of historical structures, facilitating informed decisions and sustainable management.

Knowledge management is critical in improving performance through the creation, sharing, and use of information in decision-making. However, broad access to all information can sometimes negatively impact the OUV of heritage sites, though it can also enhance and develop a site's identity. Management must consider the diverse interpretations of discoveries, especially given the less-than-objective nature of historic information. Flexibility in managing data flow into and out of the model is essential as projects progress and as new insights emerge over the lifetime of the asset.

Conservation management plans are vital documents for both strategic and day-to-day administration. They typically follow four steps: identifying what is present, understanding why it is significant, recognising vulnerabilities, and determining how any impact can be mitigated. Guidance stresses that conservation is not merely about applying rules but about understanding the building through detailed knowledge and research, supporting intervention decisions. A Conservation Management Plan, prepared and adopted by stakeholders, is crucial for the asset's future. Discoveries made during a project should be accessible to all interested parties, ensuring transparency and inclusivity in the conservation process. A clear vision, strategic aims, and objective statements supported by all stakeholders should underpin the management plan. However, assembling a comprehensive understanding of heritage assets is time-consuming and requires meticulous effort to interpret

content accurately. Variability underscores the inherent challenges in creating uniform digital models for heritage conservation. Bringing data to the forefront would substantially enhance asset management, supporting more informed decision-making and sustainable practices. In terms of planning, alterations and new interventions are generally sanctioned only when they have minimal or no impact on the asset's significance, are reversible, and when no other viable alternatives exist. Central to this is a dynamic system that relies on consistent data, gathered through regular surveys tailored to the site in question, forming a comprehensive digital record. When made accessible at each location, this record facilitates ongoing monitoring of asset condition in relation to the documented significance data. This approach ensures that all stakeholders have access to up-to-date, reliable data, thereby supporting informed decision-making and promoting effective conservation practices.

Visualisation in heritage management involves data collection, storage, processing, analysis, and dissemination, which can include current features, eroded or revised elements, or elements that have been removed. Consistency across all parts of the model is essential to ensure credibility and usefulness for all stakeholders. However, there are always inherent challenges in balancing new technologies, the needs of current asset users, and the demands of conservation practice. Achieving an appropriate balance is crucial for sustainable heritage management, requiring continuous evaluation and adaptation of strategies and tools to meet evolving needs.

Frameworks for heritage management must incorporate flexibility, especially at the strategic level, to adapt to the evolving policy and technological landscape. These guidelines advocate for comprehensive management plans outlining how OUV will be sustained, ensuring effective protection for current and future generations. Effective management involves a continuous cycle of preparation, enactment, monitoring, appraisal, and feedback, ensuring that heritage assets are preserved and adapted sustainably. There is a general understanding that the skills and knowledge required for managing complex systems in the heritage sector are often lacking, leaving assets vulnerable to the erosion of their OUV. Heritage asset management requires an integrated, multidisciplinary approach to preserve the significance of historical structures while adapting to contemporary existence. By incorporating sustainability

principles, engaging stakeholders, utilising digital technologies, and fostering a comprehensive understanding of heritage values, practitioners can ensure the long-term preservation and adaptive reuse of these irreplaceable cultural assets. This approach aligns with broader sustainability goals, promoting inclusive governance and collaborative efforts to safeguard our shared heritage for future generations.

In summary, sustainable heritage asset management requires a proactive, holistic approach that balances traditional conservation methods with modern technologies and practices. By prioritising significance, engaging stakeholders, and utilising advanced digital tools, practitioners can ensure the long-term preservation and adaptive reuse of heritage assets, contributing to the sustainability of the cultural legacy.

6.4 Achieving Objective 3

> *Analyse the benefits and challenges of adopting digital models in the management of historic buildings*

In contemporary heritage management, the integration of digital technologies has revolutionised the documentation, conservation, and interpretation of cultural heritage assets. The use of 2D images, 3D models, and VR platforms has enhanced the presentation and analysis of these assets, enabling more dynamic engagement with stakeholders. The empirical research conducted following the initial literature review explored these digital platforms, all of which relied on precise geometric data enriched with historical context. This digital information was subsequently tested with stakeholders through seminars, workshops, and direct presentations, ensuring its accuracy and relevance.

The literature review highlighted the intricate nature of heritage assets and the critical need for accessible, accurate and comprehensive contemporary data to inform robust decision-making processes. The primary requirement for such data is that it must be thorough, pertinent, and current to address the complex and often unstructured nature of heritage management issues. The role of experience in evaluating and acting upon heritage data is significant, and digital platforms serve as invaluable tools in this process, allowing less experienced individuals to contribute meaningfully to heritage

conservation efforts.

BIM is increasingly recognised as a DSS in heritage management, offering comparative evaluations over time for asset development. BIM's ability to store, retrieve, and analyse plans, models, and research data makes it an essential tool for managing heritage assets. However, concerns about outdated or incomplete documentation have been raised, as these can lead to suboptimal decisions and negatively impact the asset's OUV. The management, storage, and dissemination of heritage data have been significantly enhanced by advancements in ICT. ICT integration in heritage management streamlines processes and fosters innovative approaches to conservation and engagement, enabling a more dynamic interaction with cultural heritage. The trend in building management is increasingly focused on the accessibility of information via mobile technology, allowing any authorised user to access detailed information about objects within the built environment to support maintenance, repair, performance, or refurbishment.

Despite the benefits, developing an accurate model with comprehensive data is challenging without extensive records, intrusive surveys, and capable infrastructure. There are fundamental issues, such as the need for consistent terminology and definitions, and output compatibility across different software platforms. Critical factors like data security, potential data corruption, infrastructure scale, accessibility, and compatibility must also be addressed. The model should synthesise parametric, material, technological, and historical data to enhance understanding of the asset's lifecycle, guide conservation efforts, and inform evolutionary design. However, historical information can often be subjective, and the digital model must be seen as a 'best fit' basis for decision-making rather than a definitive guide.

The dual nature of heritage artefacts - comprising aesthetic and historical dimensions - complicates their management, as perception is often subjective and influenced by external factors. The tangible fabric of the artefact is what can be conserved, while its intangible qualities are continuously developed. Digital models assist in understanding these complexities by integrating spatial and temporal dimensions, facilitating access and analysis. The lifecycle of a heritage building, from construction through modification, conservation, and potential loss or addition of elements, is inherently linear. Digital models

can record these transformations, providing a comprehensive history and guiding future interventions. A cloud-based, regularly updated, interactive tool serves as an effective DSS in heritage management, providing access to information, analysis, and decision guidance. The use of technologies is increasingly preferred for data collection due to its efficiency, safety, and accuracy compared to traditional methods. The ToC methodology promotes an iterative refinement process throughout an asset's lifecycle, allowing for continuous revisions and improvements that incorporate new stakeholder input and adapt to changing policy or contextual factors.

Digital models are beneficial not only in initial data collection but also in monitoring and evaluation stages. They help assess the effectiveness of actions and contribute to the sustainability of the asset. As these models evolve into management plans, they reveal the full complexity of heritage administration, fostering a deeper understanding among stakeholders and ensuring coherence across management activities. By promoting collaborative and interdisciplinary engagement, heritage management plans can adhere to best practices while fulfilling broader social objectives of sustainable heritage management. Implications of digital models are the need for clear industry policies and a strategic adoption process at the stakeholder level. Digital models are intricate constructs designed to facilitate the aggregation and dissemination of relevant data, emphasising both quantity and quality to ensure effective communication and data integrity. A well-constructed digital model serves as an evolving repository that preserves the asset's values, highlights its significance, and ensures that necessary interventions retain the asset's importance. The range of stakeholders involved in heritage management presents challenges in developing digital models that are accessible to all. The data must be presented in a way that is understandable to both professionals and laypeople, without compromising on technical accuracy. Any inaccuracies can quickly erode confidence in the model, making it essential to ensure that data capture and representation are accurate and authoritative.

3D LiDAR scanning technology integrates seamlessly with historical records and discovered artefacts, contributing to a comprehensive understanding of a site's historical and contemporary contexts. Managing heritage assets effectively requires balancing continued use with the impact on significance.

Digital data consolidated in a single location can help manage this balance by providing efficient and effective access to essential information. Ensuring consistency in the quality and uniformity of historical data for digital models presents challenges. While some data is readily available in heritage records, much relevant information often remains inaccessible, particularly for less renowned assets. Addressing these challenges requires a systematic and collaborative approach to developing robust digital representations that enhance preservation efforts and deepen our understanding of cultural heritage. Authenticity remains a critical issue in 3D/4D representations, as the integration of historical data into digital models introduces a fourth dimension that often relies on incomplete evidence or conjecture.

The future of digital models lies in integrating diverse datasets from archival to contemporary sources. Digital documentation techniques, such as laser scanning and photogrammetry are becoming common although BIM has yet to become a standard in heritage projects. Given the iterative nature of digital model development, starting with clear parameters and a comprehensive understanding of limitations can provide a solid foundation for building a robust repository of heritage asset information. This approach ensures that the model evolves over time, adapting to new insights and technological advancements while supporting effective heritage preservation strategies.

The rigid schemas embedded within proprietary software and employed in IFC data exchange frameworks limit their application to heritage assets, which often require more flexible, ad hoc systems. Adapting these systems to accommodate the unique characteristics of heritage assets can enhance management and preservation efforts. Current technological limitations, time constraints, and costs make achieving high levels of accuracy in digital models challenging. A hybrid approach, combining a macro view of the 'as built' environment with micro-models of specific features, offers a viable solution.

For any information repository to be effective, it must be intuitive and allow all stakeholders to interact with the data on multiple levels. A common interface that is accessible to all stakeholders will enhance engagement and ensure that relevant data is available when needed. The use of LiDAR surveys, combined with historical research, can precisely document heritage assets, creating clear narratives about their development. However, the

research is often open to interpretation, introducing a degree of inaccuracy that must be addressed. Maintaining current, robust data is essential for managing and preserving the asset's significance, although the considerable investment required for this process may be prohibitive for some assets.

It is advocated retaining geometric scan data in its original point cloud format to ensure both accuracy and transparency, especially in models incorporating hypothetical reconstructions. The integration of historical evidence with point cloud data has the potential to enrich interpretative insights; however, such integration must be approached with meticulous care to prevent any contradictions with established conservation principles.

The case studies outlined in this research utilised LiDAR data as a fundamental source for exploring historic environments, supported by precise historical information. While both data sources are of equal importance, their integration allows for a nuanced understanding of heritage assets, revealing historical changes and the impacts of past events. Each case study presented unique challenges and opportunities in digital heritage management, highlighting the complexities of data acquisition, processing, and interpretation.

The investigation into the Arkwright Building, which suffered partial destruction during World War II, exemplifies how digital technology can enhance our understanding of historical events. The digital model serves as a precise contemporary facsimile that is anchored in the present but also reflects historical revisions, providing insights into the social history of the period. The repairs made to the building, influenced by the skills of masons and metalworkers, available materials, and financial constraints, are effectively captured in the model, contributing to the sustainable management of heritage assets.

The case study of the Hawara Pyramid presented a different set of challenges, particularly in terms of data quality and acquisition. Here, research conducted by third parties was amalgamated into VR experience, aimed at digitally recreating the site. The case study underscores the importance of establishing clear objectives and ensuring high-quality data acquisition from the outset of any digital heritage project. The initial failure was attributed to an overestimation of the local team's expertise and inadequate use of targets

during data capture. Moreover, the environmental conditions and the physical characteristics of the mudbrick material further complicated data acquisition. The Hawara case study thus illustrates the complexities of remote data capture and the need for careful planning and quality control.

The final case study focused on Nottingham Castle's Ducal Palace, where multiple data capture campaigns were conducted over time. This iterative approach allowed researchers to build a dynamic digital model that incorporated a historic timeline, capturing changes and interventions over several years. The study highlights several key considerations in digital heritage management, including the impact of environmental conditions on data quality, the importance of skilled operatives, and the limitations of current technology. One of the main challenges encountered during the Nottingham Castle study was the presence of data voids due to features being out of sight, which can significantly impact the accuracy of digital models, particularly for applications such as VR. The use of contemporary SLAM technology could potentially address these gaps by capturing data in previously unseen areas. By rescaling the data using terrain-based equipment, researchers could achieve the highest possible quality in the model, ensuring its utility for conservation management and other applications.

Across all three case studies, the importance of data quality and accuracy in digital heritage projects is evident. The quality of scan data is primarily assessed based on the completeness of the point cloud, with minimal non-data zones indicating a high-quality capture. Accuracy, however, is a multifaceted concept that encompasses both internal and external measures. Internally, accuracy can be assessed by comparing point clouds representing the same object or by examining the precision of point placement within a single plane. Externally, accuracy is evaluated by referencing a measured physical object. Resolution, another critical factor, refers to the ability to discern features within the point cloud and is influenced by point density.

The complexity and uniqueness of an object's surface can also affect the amount of data required for accurate representation. For example, reducing the distance between points in a scan increases data quality but also results in longer capture times and larger file sizes. This trade-off must be carefully

managed, particularly when dealing with large, simple areas versus detailed, intricate objects. The case studies demonstrate that data capture parameters must be tailored to the specific requirements of each heritage asset to ensure comprehensive and accurate documentation.

The outputs of digital heritage projects can take various forms, each serving different purposes. Fly-through videos generated from point cloud data can provide engaging narratives for tourism or educational purposes, enhancing public engagement with heritage assets. Record images, on the other hand, offer detailed knowledge that can be integrated with historical data to build a thorough understanding of a site. The ability to slice data thinly in any plane allows for the construction of accurate plans and sections, which can be further refined for archival purposes. Additionally, the detection of movement in objects over time through repeated scans can provide valuable insights into the structural stability and conservation needs of heritage assets.

Despite these capabilities, current software does not yet allow for a seamless transition from point cloud to solid object-based models. While some elements, such as floors, walls, and standardised features like pipes, can be automatically recognised, the irregular nature of many heritage assets limits the effectiveness of such automated processes. External data capture is further complicated by environmental factors, such as vegetation and seasonal changes, as well as internal challenges like the presence of furniture.

In summary for Objective 3, effective heritage management requires comprehensive and up-to-date data, accurate digital models, and an inclusive approach. The integration of digital technologies has transformed heritage management, providing new tools for documentation, conservation, and interpretation. However, challenges remain in ensuring data quality, model accuracy, and stakeholder engagement. By addressing these challenges and leveraging the benefits of digital models, heritage managers can enhance the preservation and understanding of cultural heritage assets for future generations.

The case studies of the Arkwright Building, Hawara Pyramid, and Nottingham Castle's Ducal Palace illustrate the diverse challenges and opportunities in digital heritage management. They highlight the importance of high-quality data acquisition, careful planning, and skilled operatives in producing accurate

and useful digital models. As technology continues to evolve, the potential for more sophisticated and comprehensive digital heritage applications will grow, offering new ways to document, preserve, and interpret our cultural heritage. However, it is essential to recognise the limitations of current tools and to approach digital heritage projects with a clear understanding of the specific needs and challenges of each site. Doing so ensures that digital technologies are used effectively to enhance understanding and appreciation of the past by all stakeholders thus contributing to the management of significance in heritage assets.

Therefore, effective heritage management relies on accurate and comprehensive data, digital models, and stakeholder engagement. The integration of digital technologies has been shown to significantly enhance documentation, conservation, and interpretation, as demonstrated by the case studies. While technological advancements offer new opportunities, it is crucial to address challenges related to data quality and model accuracy. By doing so, heritage management can sustainably preserve and interpret cultural assets for future generations.

6.5 Achieving Objective 4

> *Develop a comprehensive framework for the integration of digital models in heritage asset data management*

The research adopted conservation as its primary philosophical lens, examining heritage assets with a focus on their intrinsic value and significance. While this approach prioritises conservation, it also considers other perspectives, including surveying, materiality, and technology, as essential components in understanding and managing heritage. The classification of significance is central to this framework, integrating policy, ethics, and stakeholder roles to create a comprehensive approach to heritage preservation. To develop a framework, the research draws on key contextual examples discussed in the literature review and aligns with the global heritage manifesto, which emphasises sustainability in heritage management. Challenges such as climate change, vandalism, and the need for adaptive reuse are critical factors in this context. Competency frameworks promote experiential learning, essential for developing the skills needed to manage heritage assets effectively. Policy underscores the importance of recording

and preserving heritage assets, particularly in the face of development pressures.

Effective asset management requires comprehensive plans to maintain OUV and protect heritage assets for future generations. This involves not only preserving the physical fabric of these assets but also maintaining their cultural significance, authenticity, and integrity. The research examined existing frameworks and workflows in heritage conservation, emphasising the need for digital processes to generate extensive data repositories that support effective management.

The development of the framework followed an iterative process, consistent with an active research approach. The initial conceptual framework, derived from the literature review, identified four key components centred around the digital model: Management, Asset Significance, Stakeholders, and Ethics/Policy. The model is represented as a rotating tetrahedron, illustrating the dynamic interrelationship of its principles. This representation emphasises the need for a holistic approach to heritage management, where all aspects, from planning to implementation, are underpinned by ethical and policy considerations.

These components form the foundation of the framework, guiding the empirical research and the subsequent development of a more dynamic model. In the empirical phase, the research focused on linking these components to the digital model, initially through a single campaign that provides a foundation for comparative analysis. The second iteration of the framework introduces a dynamic model, where the digital repository is centralised within the management system. This evolution reflects the need for flexibility in the framework, allowing it to adapt to new data and insights as the research progresses. The data generated provides a crucial link between heritage value maintenance and enhancement frameworks. In the context of building management, the model emphasises the importance of accessibility, allowing any authorised user to access detailed information about any object within the built environment, enhancing maintenance, repair, performance, or refurbishment. The proposed framework adds structure to the digital model without imposing undue rigidity, allowing flexibility as required by the complexity of sustainable heritage asset

management. This flexibility is essential in a field that must respond to external environmental pressures and internal risks, as well as the changing policy and technological landscape.

Central to this discussion is the challenge of ensuring consistency in the quantity, quality, and uniformity of historical data incorporated into these models. While various sources of historical data offer significant value, assembling a comprehensive and coherent understanding of heritage assets can be time-consuming and requires meticulous interpretation. This difficulty is particularly evident in less renowned assets, where relevant information may be sparse or missing entirely. Consequently, creating uniform digital models for heritage conservation becomes inherently challenging. Despite these hurdles, aggregated knowledge significantly enhances the comprehension of a model's relevance, facilitating timely dissemination throughout the stages of a project. Furthermore, any significant discoveries can be integrated back into the model, enriching the record and supporting continuous improvement that enhances the asset's significance.

The development of digital models for heritage conservation typically involves three stages: planning, retrieval, and generation for output. Meticulous planning is a critical initial step that encompasses multiple dimensions and often necessitates revisions during the retrieval phase. These stages are foundational to the processes of heritage asset data gathering, management, and sharing, and they encapsulate the underlying concepts that form the core details of the model. Each stage has distinct requirements, but the overarching objective is to define the purpose of the data, ensure its quality and quantity are appropriate, and determine the intended output. The expertise of those involved is pivotal in achieving the requisite quality and quantity of data, which underpins decision-making about the asset, particularly regarding its significance.

Beyond initial data capture and the subsequent creation of a digital model, effective data management is vital, although it is often lacking in the heritage sector. For a digital model to be genuinely effective, all historical data should be based on the most resilient evidence available, with any new discoveries systematically integrated into the model. This continuous integration demands regular reviews to determine whether newly acquired data requires

revising current interpretations or whether the existing understanding remains valid. Additionally, any interventions conducted should generate new data, which should then be incorporated into the model to enhance and refine the understanding of the asset, allowing for comparisons with existing information. For impromptu or enduring management decisions the model should be consumed, change actioned, and the outcome recorded back, i.e., dynamic. Disseminating updated data to relevant stakeholders is essential for the effective management of the heritage asset. While accuracy is crucial, it is the resolution and overall quality of the data that will drive the development of a suitable model.

The visualisation of data collection, storage, processing, analysis, and dissemination can encompass current features, whether whole or partial, eroded, or revised/removed elements, adding a layer of complexity. Achieving consistency across all parts of a digital model is challenging. The initial model generated in software, collected through a defined process, can be parametrically accurate, but areas with limited textural content may be obscured. If the model is a deficient representation, it undermines confidence. Much attention is paid to data capture and creation, less focus is placed on maintaining data in the long term and establishing stable points of access. As models become data-rich and evolve from visual representations to integrated datasets of synergistic material, maintaining accessibility and ensuring long-term usability will become increasingly important. Current digital models are technically oriented, but the future lies in integrating extensive heterogeneous datasets, from archival records to contemporary societal data.

Ensuring the model's accuracy within the parameters of data capture and the objects it represents is paramount. The LiDAR point cloud method excels in this regard, as it retains visible voids where data is missing, allowing for precise identification and subsequent correction. Point cloud technology can facilitate geometric modelling, object identification, and quality inspection. Each heritage asset is unique, and consequently, each project must also be distinctive, hence frameworks are necessary if digital models are to become customary. The management of heritage assets is grounded in the conservation principles of enduring maintenance with minimal intervention for maximum preservation, which must form the foundation of any framework.

Given the uniqueness of each asset, the management approach must also be tailored, focusing on custodianship and exposition.

In current information model frameworks, IFCs serve as repositories for data exchange, readable by modelling-associated software. However, applying these standards to heritage contexts often requires multiple iterations to become serviceable. Moreover, achieving consistent data classification in heritage contexts necessitates adherence to standardised protocols and naming conventions. Implementing such standards poses significant challenges, primarily due to the unique and diverse nature of heritage assets. For accuracy, interoperability, and search facilities, the terminology needs to be consistent across the whole model, including directly and indirectly linked data.

Engaging stakeholders in the process of building the model allows for a greater understanding of the required parameters and potential future extensions. Any information repository and reference system should be intuitive, enabling all stakeholders to interact with the data on multiple levels. Specific stakeholder access will need a common interface and operability to provide accessibility and should highlight the location of, if not the actual data. Developing a timeline that offers stakeholders an insightful narrative into the intricate evolution of an asset is advantageous, yet the need to express elements of uncertainty remain. Employing layers and colourisation within the point cloud can serve as indicators of data validity, and toggling these layers can illustrate the asset's chronology.

A LiDAR survey, when coupled with historic research, can precisely document assets to construct intelligible narratives regarding their development. Nevertheless, such research often remains open to interpretation, introducing a level of inaccuracy, whereas the point cloud, even after registration, can achieve millimetre precision. The point cloud captures only the current state, which may include artefacts from the past, but without supplementary historic data - such as photographs, maps, and drawings - it cannot be fully interpreted. Furthermore, the information inventory for heritage assets should encompass a wide range of data, including asset condition, usage, descriptions, maintenance records, materials, technologies, risks, and significance. The considerable investment in time and capital required for this

process may be prohibitive for many heritage assets. Nevertheless, the necessity for a sound basis for decision-making cannot be overstated. In such cases, prioritising accurate, high-quality data over comprehensiveness may be essential to achieve effective asset management. Considering the advanced theoretical framework, currently public engagement with the digital model is absent, the lack of 'aura' limits consumption to professional actors thereby inhibiting the decision-making capacity.

This model should be shared with all the actors before and during all stages of any planning or works and should be consulted to define the significance of the whole and the parts before the intervention even in the event of an unforeseen demand. Temporary works can cause interventions that impact significance, and by interrogating the model, a strategy design can limit undue fabric damage. A known issue in disseminating knowledge and building understanding between the tradesperson and the consultative or professional person exists; a digital model can provide insight in visual terms with instant access to plug the gap, thereby aiding collaboration. Augmented reality can provide the interface between the model and the asset with little training for all stakeholders.

The comprehensive framework emphasises an active model, wherein the initial content is constructed with future requirements in mind, developed in tandem with the evolving understanding of the asset. Heritage policies, digital tools, and stakeholder input significantly influence the resultant framework. Nevertheless, the content must remain adaptable, and the digital tools employed should not be so specific as to constrain the choice of software packages. The framework provides the basis of data capture and dissemination for inclusion in the conservation management plan in the deliberation of interventions and when faced with a requirement for immediate repair (temporary or permanent) after damage (accidental, in conflict or vandalism). The framework generalises the concepts within the conservation lens applied, in this approach elements may have been left unconsidered. The final framework provides the linkage of these concepts into theories to develop understanding.

The theoretical framework is a fundamental component of heritage management, serving to integrate and bind together complex, multi-layered

themes within the field. This framework is not static; rather, it evolves from the conceptual framework and draws on theories from existing literature or empirical research. These theories form the foundation of any project, providing essential explanations for how and why various elements function as they do. Importantly, such the framework must be adaptable, incorporating feedback loops and performance indicators to ensure it remains dynamic and relevant over time. A central theme within this contemporary heritage management framework is the concept of the digital model. This model is a sophisticated tool that integrates historical and geometric data, thereby enhancing decision-making processes related to the conservation and management of historic assets.

The findings from the case studies reinforced the fundamental concept that digital models, which synthesise both heritage and geometric data, are effective tools for supporting decision-making aimed at the sustainable management of heritage assets. This conclusion is evidenced by the outputs of these models, which include both 2D and 3D representations derived from geometrically accurate models, with a fourth dimension—time—incorporated into the historical content. However, a notable limitation is the incomplete artifact data concerning the materials and technologies obscured beneath the asset's surface. While some information can be retrieved from existing records, the accuracy remains uncertain until physical intervention exposes it. As such, the compilation of data should always be based on all known, reliable evidence. New data, as it emerges, must be rigorously tested against the existing dataset, and revisions should be made as necessary to ensure the most comprehensive and accurate version is utilised in decision-making processes. Failure to adhere to these practices would contravene best ethical standards.

The theoretical framework proposed, serves as a foundational element that binds together the complex themes explored in this study. It effectively bridges the gap between theoretical postulation and practical application, ensuring a comprehensive explanation of reality. The framework's advancement marks a significant contribution to knowledge, particularly through the creation of a dynamic digital model of heritage assets. This model integrates current geometric data with historical and contemporary records, offering a time-bound, editable, and manageable conservation tool.

The proposed framework emphasises a dynamic, adaptable model for heritage management, one that is designed with future needs in mind and evolves alongside the deepening understanding of the asset. A significant issue facing the heritage sector is the decline in heritage skills, exacerbated by an aging workforce and the failure to replace retiring experts with younger contingents. This loss of experiential knowledge leaves heritage assets vulnerable; thus, effective information sharing becomes critical in bringing valuable understanding to the field and reducing the risk of loss or undermining the asset's significance. A key challenge is the diminishing significance of heritage assets, often due to unfounded or delayed management decisions, particularly in routine maintenance and repairs.

As noted, the detail contained in the digital model should be proportionate to the importance of the asset. If the focus is primarily economic, the model is likely to contain only sufficient quantity and quality of data to support the intended intervention, whether to protect, sustain, or enhance. Sustainable solutions require harmony across all pillars of sustainability to be compliant; the social focus complements stakeholder inclusion, while the environmental aspect may be addressed through the light touch of any intervention utilising knowledge from the model - a proactive approach. Yet, a long-term strategy to address risk factors that lead to disrepair, hence the notion that recording beyond the minimum level should be the norm, establishing a baseline for that approach.

The data flow into the digital model should not be understood as a unidirectional process; rather, it should exhibit bidirectionality, where interventions generate data that contribute to the development of new insights or the amendment and enhancement of existing records. The digital model, which encapsulates historical data, plays a crucial role in elucidating the asset’s significance. There is a compelling argument for maintaining a feedback loop wherein asset management could potentially influence the asset’s significance. This is feasible provided that policy and ethical standards are rigorously upheld, ensuring that the asset does not fall into disrepair or a state of maintenance deficit.

The dynamic process captures the evolving condition of the asset, documenting changes resulting from factors such as weathering and

vandalism, which are indicative of emergent situations. As the asset undergoes interventions - whether repair, renewal, restoration, or replacement - each action alters its state, effectively transitioning the asset from one iteration to the next. It is essential that data from these interventions are meticulously recorded in the digital model, serving not only as a historical archive but also as an intrinsic component of the artefact's evolving narrative. This comprehensive record-keeping enables continuous assessment of the intervention's long-term effectiveness. The proposed digital model functions as a living document, continuously capturing and synthesising data throughout all stages of the project - pre-, during, and post-intervention. Data from each phase, including historical records, geometric information, and artefactual findings gathered during the intervention, is systematically incorporated and preserved within the digital model.

Noteworthy is the conspicuous lack of direct connections between policy and ethics and the digital model. The data employed within the model is curated and obtained by stakeholders, resulting in an indirect association between policy, ethics, and data acquisition. Finally, stakeholder access to the digital model will need to be carefully regulated by the asset's management systems, ensuring that the level of detail provided aligns with the specific needs of each stakeholder, particularly when their involvement extends beyond a peripheral interest.

The foundational elements of this model are shaped by policy and ethical considerations, which determine the operational framework of its key concepts. Stakeholders, both involved and peripheral, play a crucial role in defining and understanding the asset's significance. Their esteem for the asset is informed by this significance, establishing a bidirectional flow of knowledge and influence. While the historic data embedded within the model provides foundational insights, it is the comprehensive digital model itself that offers stakeholders a deeper understanding through the rich repository of knowledge and data it contains. The model's outputs, including images, films, 3D models, virtual reality simulations, and other media, are centrally maintained and can be utilised to engage and inform stakeholders through accessible and varied formats. Finally, the ongoing, dynamic collection of data serves to enhance both the accuracy and relevance of the digital model over time.

Meeting the objective, the framework proposed offers a versatile and multifaceted approach to heritage management, designed to meet contemporary challenges and opportunities. It provides a robust mechanism for determining, managing, and disseminating data, enabling informed decision-making by stakeholders to retain or enhance the significance of heritage assets. By aligning with international standards and guidelines, the framework emphasises sustainability, ethics, and stakeholder engagement as core principles in heritage management.

Integrating advanced digital technologies, the framework addresses key challenges in heritage management, including climate change, development pressures, and the need for adaptive reuse. It serves as a comprehensive platform for storing and managing accurate data, identifying the critical information needed for achieving desired outcomes, and outlining methodologies for data collection and collation. This approach not only supports the sustainable preservation of cultural heritage but also contributes to the broader discourse on heritage management by offering nuanced insights and comprehensive perspectives.

The integration of digital models within heritage conservation presents both significant opportunities and challenges. Effective digital models have the potential to revolutionise how heritage assets are understood, preserved, and managed, ensuring that their significance is maintained or even enhanced. However, realising this potential requires careful planning, robust data management, and a flexible theoretical framework that can adapt to the unique and evolving nature of each heritage asset. By focusing on the quality and relevance of data and fostering collaborative engagement among stakeholders, digital models can become invaluable tools for heritage conservation, ensuring that cultural heritage is preserved for future generations.

The proposed theoretical framework delineates essential components such as policy and ethics, significance, stakeholders, and management systems, all of which are crucial to the decision-making processes facilitated by the digital model. It effectively maps out the flow of influence and information, ensuring comprehensive coverage of all aspects of heritage management. The continuous streaming of data in and out of the digital model fosters a dynamic

and contemporary resource capable of supporting asset management while maintaining both the significance and sustainability of the asset.

By embedding a digital model enriched with historical and geometric data, the framework enhances heritage management, offering protection for the asset's significance through accessible formats such as virtual reality experiences and 3D films. This innovative framework bridges the gap between theoretical concepts and practical applications, promoting an ethical, proactive, and data-driven approach to heritage conservation. Ultimately, it represents a significant contribution to heritage management, ensuring the preservation and socio-economic benefits of cultural assets for future generations.

6.6 Achieving Objective 5

> *To continuously evaluate, through action research, the proposed framework's impact on stakeholder engagement and the effective management of heritage assets*

The research successfully met the objective by actively involving stakeholders in both formal and informal settings, providing a comprehensive foundation for effective heritage asset management. Through the creation of precise digital models, the research offered three distinct propositions to stakeholders, each of which was rigorously tested and found to be insightful. These models highlighted the crucial role of sustainable management in maintaining the prominence of heritage assets for future generations. This approach aligns with stakeholders' recognition of the importance of these assets, emphasising social responsibility, adherence to conservation policies, and consideration for future developments.

A significant challenge identified is the lack of integrated data sharing throughout the lifecycle of heritage assets, which can devalue these assets, particularly when interventions are necessary. All stakeholders - ranging from owners, users, professionals, to the public - should be central to the decision-making process. The literature review underscored the various pressures exerted by local, national, and international policies and ethical considerations, all of which significantly influence stakeholder actions related to heritage assets.

Empirical research findings from the case studies reinforced the foundational concept that digital models synthesising heritage and geometric data can effectively support decision-making for sustainable heritage management. The model outputs, including 2D and 3D representations derived from geometrically accurate data, incorporated a temporal dimension by integrating historical content. This dynamic modelling approach demonstrated robust outcomes across different settings.

In one notable case study, the LiDAR campaign showcased the importance of stakeholder involvement in capturing geometric data, highlighting the necessary skills, expertise, respect for the asset, and adaptability required to move plans forward while ensuring data quality. During the planning phase, stakeholders determined the campaign's purpose and methodology. The rationale for data capture must be clearly articulated to align with future digital model requirements at the very beginning of a campaign. Meticulous planning is thus identified as a critical initial step, encompassing multiple dimensions that may need revision during data retrieval. The expertise of those involved is paramount to achieving high-quality data, which underpins decision-making regarding the asset’s significance.

A critical issue addressed by the research is the lack of technical knowledge among many heritage asset owners and managers regarding BIM requirements, often leaving these responsibilities to professional project teams. This situation can lead to reports of high costs and reluctance to invest. A rigorous cyclical process of discovery, collection, processing, storage, evaluation, significance assessment, comparison, review, and deployment enhances data integrity and robustness, underscoring the need for comprehensive stakeholder inclusion in the decision-making process.

Across all case studies, the digital model played a vital role in engaging stakeholders with the heritage asset and imparting valuable knowledge. Both formal and informal events used the data to involve stakeholders actively, consistently yielding positive outcomes that enhanced understanding and interest.

Stakeholders play a critical role at each development stage of the theoretical model. The conceptual framework, depicted as a tetrahedron (see Figure 65), highlights the key attributes that support the four stages of management,

with stakeholders as one of the central components. Managing heritage assets entails a heightened level of responsibility and complexity due to the ethical considerations fundamentally underpinned by policy pressures at local, national, and international levels. Stakeholders involved in determining the significance of these assets rigorously scrutinise them, enforcing strict compliance with policies.

The issue of heritage skills is a sector-wide concern. The ageing workforce is not being replaced by younger talent, leading to a loss of experiential knowledge and leaving assets vulnerable. Information sharing fosters valuable understanding and reduces the risk of losing or undermining an asset's significance. The framework also supports interdisciplinary collaboration by providing a visual interface that bridges gaps between owners and users, tradespeople and professionals, potentially utilising augmented reality as demonstrated in the empirical research.

The proposed framework advocates a dynamic, adaptable model for heritage management, designed to evolve with future needs and deepen understanding of the asset. Influenced by heritage policies, digital tools, and stakeholder input, the framework integrates management strategies, documentation, and maintenance. Crucially, it addresses the current gap in public engagement, extending its utility beyond professionals. Sustainable solutions require all pillars to harmonise to ensure compliance; the social focus complements stakeholder inclusion, while environmental considerations may be addressed through minimal intervention, using knowledge derived from the model as a proactive approach.

Stakeholders actively contribute to defining an asset's significance, as indicated by the directional flow towards the asset in the framework. The asset's importance is established at the highest levels by heritage bodies, whose evaluations are refined through historical context and new discoveries. This ongoing appraisal process, once robust, determines the asset's significance, which subsequently informs asset management strategies.

During instructional sessions, architecture students were introduced to a 2D point cloud image to elucidate the operation and workflow of LiDAR technology. This presentation aimed to disseminate knowledge about the advantages of integrating precise geometric data with historical records. The

students demonstrated a high level of engagement with the material, expressing astonishment at the depth and comprehensiveness of the historical details revealed. This exposure led them to recognise the unique value of the point cloud as a singular record of isolated impacts, prompting further inquiry to deepen their understanding. Additionally, a 'spot the difference' exercise was employed to provide stakeholders with an accessible means to explore and comprehend historical details, thereby enhancing their appreciation of the data's significance.

A case study model serves as the foundation for plans to dewater the site, establishing a critical baseline survey of both the pyramid structure and the surrounding terrain. Furthermore, the digital model, based on accurate survey data, served as the foundation for a 3D VR experience. This experience combined the meshed model with archaeological data from museums and repositories worldwide, employing artistic impressions to visualise the data on a gaming platform. The VR was showcased at events in the UK and Egypt to educate and provide a realistic understanding of the site. The model was meticulously developed after individual point clouds had been received and cleaned, manually aligned, and registered. Subsequently, it was exported to modelling software for detailed analysis. At this stage, archaeological research outcomes were incorporated, with findings guiding the modeller. Objects from the same period were constructed using Blender, and elements of archaeologist Petrie's account, who discovered the tomb, were utilised to recreate the journey from the entrance. The virtual reality experience was showcased at the International Seminar and Exhibition "Hawara - From an Ancient Marvel of the Middle Kingdom to the Future of Tourism in Egypt" on 28 March 2022.

For the Ducal Palace at Nottingham Castle, the research initiates a resource charting the building evolution using archival material, records, and surveys within a current, accurate digital model. The occupier managing the asset collaborated to develop a research-led digital offer, an open resource with additional use in interpretation and education. The 3D films were uploaded to YouTube, with views indicating stakeholder interest and demonstrating the potential of such outputs. A workshop tested the VR output to gauge stakeholder interest. The model focused on two areas: the first-floor gallery, where the gamer interacts with the art, and the external areas in a 3D film.

Maintaining historical and archaeological accuracy is paramount. AR/VR experiences should be leveraged to enhance accessibility, especially for stakeholders unable to physically visit Nottingham Castle, including the cave system. Stakeholders advocated for a digital application that vividly portrays the castle's historical development, thereby enriching visitor understanding and engagement. An accurate digital model of the castle site could serve as a catalyst for such an application. The Castle Workshop VR model has also been uploaded and has received over 170 views to date. This indicates the potential of simplistic output to engage stakeholders. Feedback on the VR from the Nottingham Castle Gallery workshop was generally positive. One participant suggested incorporating a group experience or, at the very least, including virtual visitors, interesting since the digital model had been cleansed of human shapes. Other comments called for a more immersive experience with the artwork, specifically requesting higher resolution to achieve a quality comparable to photographs. The feedback indicated two perspectives: a desire for a more realistic experience or a primary focus on the art itself, this was not explored with the attendees.

In conclusion, the research demonstrates the vital role of stakeholders in heritage asset management and the potential of digital models to support informed decision-making. By integrating accurate geometric data with historical context, these models facilitate robust and sustainable management strategies. The dynamic, adaptable framework proposed for heritage management, supported by empirical findings, underscores the importance of stakeholder engagement, interdisciplinary collaboration, and public accessibility in preserving cultural heritage for future generations.

In the first case study, the model in a 2D format allowed stakeholders to make simple visual comparisons, revealing the building's asymmetrical elevation. This interactive approach, reminiscent of a basic gaming experience, encouraged stakeholders to seek further clarification thereby fostering a deeper connection to the asset's history.

The second case study featured a seminar and exhibition event where a virtual reality experience allowed attendees to visualise the complete pyramid and a labyrinth reportedly located south of the site. The positive experience of the stakeholders was acknowledged.

The third case study, a workshop brought together a diverse range of stakeholders, including the owner, local authority, conservation officers, and various interest groups. Participants praised the content for being highly accessible, convenient, enjoyable, and immersive, although some criticism was noted regarding content tailored for younger audiences and concerns about reliability. A key requirement identified was that digital content must be accurate, with clear distinctions made where artistic interpretations have been included.

Limited stakeholder engagement seems to be impeding the effectiveness of decision-making processes; however, in the three case studies, the presentation of accurate, accessible models effectively countered this issue. The digital representations served as an intermediary, facilitating a deeper understanding of the heritage assets. A crucial consideration, however, is ensuring that these digitally driven resources are not only accurate but also comprehensive and reflective of the most current information available.

The objective was achieved across each case study through both formal and informal approaches, primarily via the creation and dissemination of precise digital models. These models garnered significant interest from both primary and peripheral stakeholders, highlighting their recognition of the asset's value and their support for its sustainable management.

6.7 Meeting the Research Aim

> *To develop a framework for utilising LiDAR and virtual modelling technologies in the management of historic building data to support the sustainable preservation and management of heritage assets*

The objectives of this research have been comprehensively met, as evidenced by the successful development of a dynamic framework incorporating digital models that robustly support the retention of significance in heritage assets. Through the integration of precise digital models, this framework facilitates informed decision-making, promoting sustainable management practices for heritage conservation. By consolidating historical and geometrically accurate data into a unified digital repository, the framework enhances clarity regarding the cultural, academic, and historical significance of heritage assets. This comprehensive approach not only aids in the effective maintenance, repair,

and refurbishment of these assets but also empowers stakeholders to make well-informed decisions, balancing preservation and utilisation.

The implementation of this framework marks a transformative shift in conservation practices, fostering a modern approach that ensures heritage assets remain relevant, appreciated, and protected for future generations. By providing comprehensive, accessible records, it promotes a multidisciplinary approach to heritage asset management, emphasising the importance of preserving the significance of historical structures while adapting them to contemporary contexts. The framework's integration of sustainability principles, stakeholder engagement, and digital technologies aligns with broader goals of inclusive governance and collaborative efforts to safeguard shared cultural heritage.

The management of heritage assets, as demonstrated by the case studies of the Arkwright Building, Hawara Pyramid, and Nottingham Castle's Ducal Palace, requires a proactive, holistic approach that balances traditional conservation methods with modern technologies. These case studies underscore the importance of high-quality data acquisition, meticulous planning, and skilled operatives in producing accurate and useful digital models. As technological advancements continue, the potential for more sophisticated digital heritage applications expands, offering innovative methods to document, preserve, and interpret cultural heritage. However, it remains crucial to recognise the limitations of current tools and to approach digital heritage projects with a clear understanding of each site's specific needs and challenges.

Effective heritage management is contingent on accurate, comprehensive data, the integration of digital models, and active stakeholder engagement. As illustrated by the case studies, the incorporation of digital technologies significantly enhances documentation, conservation, and interpretation efforts. Yet, it is vital to address the challenges associated with data quality and model accuracy to ensure sustainable preservation and interpretation of cultural assets for future generations. The proposed framework provides a versatile and multifaceted approach to heritage management, designed to address contemporary challenges and opportunities. By aligning with international standards and guidelines, the framework emphasises

sustainability, ethics, and stakeholder engagement as core principles in heritage management.

The integration of advanced digital technologies within this framework addresses key challenges in heritage management, including climate change, development pressures, and the necessity for adaptive reuse. Serving as a comprehensive platform for storing and managing accurate data, the framework identifies the critical information needed to achieve desired outcomes and outlines methodologies for data collection and collation. This approach not only supports the sustainable preservation of cultural heritage but also contributes to the broader discourse on heritage management by offering nuanced insights and comprehensive perspectives.

While the integration of digital models presents significant opportunities for revolutionising how heritage assets are understood, preserved, and managed, it also poses challenges. Realising the full potential of these models requires careful planning, robust data management, and a flexible theoretical framework that can adapt to the unique and evolving nature of each heritage asset. By focusing on data quality and relevance, and fostering collaborative engagement among stakeholders, digital models can become invaluable tools for heritage conservation, ensuring the preservation of cultural heritage for future generations.

The proposed theoretical framework delineates essential components, such as policy and ethics, significance, stakeholders, and management systems, all of which are crucial to the decision-making processes facilitated by the digital model. It effectively maps out the flow of influence and information, ensuring comprehensive coverage of all aspects of heritage management. The continuous streaming of data in and out of the digital model fosters a dynamic and contemporary resource capable of supporting asset management while maintaining both the significance and sustainability of the asset.

By embedding a digital model enriched with historical and geometric data, the framework enhances heritage management, offering protection for the asset's significance through accessible formats such as virtual reality experiences and 3D films. This innovative framework bridges the gap between theoretical concepts and practical applications, promoting an ethical, proactive, and data-driven approach to heritage conservation. Ultimately, it represents a

significant contribution to heritage management, ensuring the preservation and socio-economic benefits of cultural assets for future generations.

While limited stakeholder engagement has been observed to hinder effective decision-making processes, the three case studies demonstrated that the presentation of accurate and accessible models effectively mitigated this issue. The digital representations served as intermediaries, facilitating a deeper understanding of heritage assets. However, it is crucial to ensure that these digitally driven resources are not only accurate but also comprehensive and reflective of the most current information available.

The case studies also demonstrated the importance of engaging stakeholders through both formal and informal approaches, primarily via the creation and dissemination of precise digital models. These models garnered significant interest from both primary and peripheral stakeholders, underscoring their recognition of the asset's value and their support for its sustainable management. The research confirms that a comprehensive approach, grounded in a relevant literature review and supported by empirical evidence from action research, can build a depth of knowledge and understanding that benefits heritage management.

The research establishes that the proposed framework, with its dynamic digital model, effectively supports heritage management by elucidating the links and flow of information in a dynamic process. By testing digital outputs with both involved and peripheral stakeholders, the research highlights the value of engagement and knowledge dissemination in enhancing the management and appreciation of heritage assets.

The principal findings of this research position the proposed framework as a constructive catalyst for change, effectively integrating a diverse array of components into a cohesive structure that facilitates the sustainable stewardship of heritage assets. However, this apparent simplicity conceals a nuanced and multifaceted complexity. The constituent dimensions of the conceptual framework - namely Stakeholder engagement, Asset, Policy and Ethical considerations, and Management strategies - are underpinned by a dynamic digital model. This model exhibits flexibility, attributable to the defining variables of each asset, which, in their unique combinations, resist standardised classification. These variables exert a direct influence on the

digital model, the architecture of which is informed by the parameters outlined in Figure 58: Considerations for a LiDAR Campaign. The interplay of these elements engenders a targeted and holistic solution, one that prioritises the significance of the asset while advancing its sustainable management.

Action research facilitates transformative development within the researcher, shaped by the iterative nature of the investigative journey. The advancement of knowledge is intrinsic to all scholarly inquiry, particularly when engaging with complex foundational data through a heuristic lens. The interplay between theoretical constructs and empirical investigation fosters a synergistic dynamic, wherein insights gained from each domain reciprocally enhance understanding and are cyclically reintegrated into the evolving solution. The inherent complexity of the research presents a multi-centric challenge, whereby the adjustment of a single variable within the system can recalibrate the outcome, yielding novel perspectives. The cultivation of research expertise necessitated a refined objectivity, enabling the identification of strategic levers to optimise output quality. The resolution of the framework through a pragmatic, hands-on methodology not only extended the inquiry beyond theoretical abstraction but also contributed meaningfully to the researcher's methodological proficiency, aligning with and reinforcing their inherent strengths. This integrative process not only deepened the researcher's theoretical acumen and practical dexterity but also demonstrated the transformative potential of action research as a vehicle for both scholarly advancement and personal growth.

6.9 Limitations

While this research has yielded significant insights and demonstrated the potential of digital models in heritage asset management, several limitations have been identified, largely driven by time constraints. As time progresses, newly published literature may offer additional perspectives or frameworks that could further inform or support the research findings. Although the selected literature provides a comprehensive overview of relevant content at an appropriate depth, certain areas, such as the integration of solid modelling techniques or the use of heat maps to detect deviations in the models, warrant deeper exploration to enhance understanding and application.

The case studies employed in this research were well-chosen and pertinent to

the development of the framework. However, applying the framework in a real-world project would have allowed for the identification of any constraints that may need to be addressed. For instance, the creation of a detailed brief for a model tailored to a client's specific requirements could serve as a practical test of the planning stage, highlighting key elements that should be included to guide the project effectively. In heritage conservation projects, an extensive initiation phase is essential, during which data is collected and incorporated into documents like Conservation Plans or Design and Access Statements. Ideally, these reports should be readily available at the project's outset to avoid delays in decision-making. The availability of a digital model at this early stage would significantly reduce the time spent gathering necessary materials and facilitate robust decision-making from the start, thereby strengthening the project's foundation, this is not investigated.

Stakeholder feedback was generally constructive and objective. However, employing a more extensive range of questions presented in a formal style could have generated a broader spectrum of quantitative data for analysis. This data could have provided a more binary foundation upon which to build the framework, enhancing its development through an iterative process. Such an approach would not only ensure the framework's suitability for integration but also bolster stakeholder confidence in its application within the industry.

Although stakeholder participation in workshops and seminars was highly beneficial, the research did not differentiate between involved and peripheral stakeholders or consider their integration into the study. This distinction is crucial for interpreting feedback accurately, as the impact of different types of stakeholders can vary significantly. Understanding whether the influence of involved stakeholders is uniform or distinct from that of peripheral stakeholders is vital for integrating their perspectives into the framework. This consideration could inform whether greater emphasis should be placed on the feedback from involved stakeholders compared to peripheral ones, potentially leading to more nuanced applications of the framework.

In the second case study, it was observed that the mudbrick material affected the resolution of the point cloud and the resulting data quality. While the underlying issue was recognised and clarified, the proposed solution has yet to be tested. Conducting further tests would provide valuable insights into

conducting geometric data collection campaigns, particularly when dealing with coarse or dark materials. Within the discourse, it was suggested that increasing the number of campaign stations might improve resolution and, consequently, data quality. Employing smaller, faster instruments could also enhance data capture, thereby mitigating any disadvantages currently perceived. However, these hypotheses need to be rigorously tested against prevailing practices to validate their effectiveness.

A proposal was made to retain geometric data as a point cloud rather than converting it into an object-based model. This approach would involve identifying areas of interest and comparing them against contemporary data collection campaigns to detect changes that could be exploited in future projects. However, this proposed workflow remains untested in practical field settings, highlighting a potential area for future research.

The recent introduction of SLAM instruments presents an opportunity to improve data capture quality, particularly for high-level or difficult-to-reach surfaces. Testing this technology against traditional photogrammetry methods, which utilise cameras mounted on poles or UAS platforms, could provide valuable insights into its efficacy. Additionally, further investigation is required into scaling techniques and the data used for colourisation. For example, HDR images, which attempt to compensate for reduced light levels, may contribute to a blue aura effect in the data. Understanding the causes and potential solutions for these phenomena could significantly enhance data quality.

The final case study at the Ducal Palace in Nottingham Castle involved a dynamic approach to data capture. However, there was an opportunity to engage more extensively during the project's progression beyond the archaeological phase. Developing the digital model further during this critical stage could have enriched understanding and allowed the contractor to distribute updated information via mobile devices, recording new discoveries for inclusion in the digital repository. Such an approach would have enabled the model's dynamic evolution, providing a more comprehensive and current representation of the heritage asset.

In summary, while the research effectively achieved its primary objectives, there are several areas where further exploration could add depth to specific

elements. These include testing the framework in live projects, refining data collection methods, and incorporating a broader range of stakeholder feedback. Addressing these areas would enhance the robustness and applicability of the digital models in heritage management, ensuring that they continue to evolve in line with industry needs and technological advancements. These considerations will be further elaborated in Section 6.12 - Future Research, which outlines potential directions for advancing this field of study

6.9 Opportunities to Refine the Framework

Reflecting on the previous section, several areas within the framework require further refinement and consideration to enhance its effectiveness in heritage asset management. One of the primary opportunities for refinement involves re-evaluating stakeholder engagement strategies. As previously identified, there are two main categories of stakeholders: involved and peripheral. It is essential to engage both groups in the dissemination of knowledge to foster a comprehensive understanding of the heritage asset's significance. For instance, by educating visitors about the historical and cultural value of an artefact or setting, incidences of vandalism may be reduced as users develop a deeper appreciation for the site. However, critical decisions that directly impact the asset, such as determining the location of car parking based on archaeological considerations, may need to remain within the purview of involved stakeholders.

To further refine the framework, it is crucial to reassess the understanding generated by the relationships between stakeholders and the digital model. This reassessment should be conducted through a case study at the initiation stage of a project. By selecting a suitable project or portion thereof, prework can be undertaken to develop a comprehensive digital model that integrates both geometric and historical data. Once the model is released, use and interactions facilitated should be closely observed to gain insights into the decision-making processes that reference the model's data. Monitoring through automated data capture would help assess the model's effectiveness and identify areas where the framework could be refined or expanded. This iterative process will ensure the model remains relevant and adaptable to the evolving needs of heritage management.

Additionally, the digital model itself presents opportunities for further refinement. The current model incorporates three types of data, but only two have been thoroughly clarified. Specifically, the data concerning artefacts, such as materials and technologies, requires further development. Collecting and testing this information is essential to fully integrate it into the digital model. This process of refining and federating the model with comprehensive artefact data will yield practical benefits and enhance the framework's utility. The time invested in these refinements will contribute to a more robust and nuanced understanding of the heritage asset, ultimately supporting more effective management and conservation efforts.

The output of the digital model should also undergo additional testing to optimise its utility for various stakeholders. Previous iterations have demonstrated the potential of interactive solutions in museum settings, where stakeholders could engage with both the building and its collections. However, there is further scope to refine these outputs to better cater to the needs of professionals and skilled operatives directly involved in the project. By tailoring the information to improve accessibility and usability for these stakeholders, the framework can provide a more targeted and effective tool for heritage management. Furthermore, it is imperative to ensure that any interventions proposed by stakeholders are evaluated for their potential impact on the asset's significance. Promoting ethical practices in this regard may necessitate adjustments to the framework to ensure its robust application across diverse scenarios.

Incorporating relevant software into the framework should not be overlooked. However, given the rapid pace of technological advancement and the growing array of available software packages, the framework must remain adaptable and not be restricted by any specific technological solution. To support this flexibility, it is crucial to empower stakeholders to choose the software that best meets their needs, in collaboration with their technology providers. This approach aligns with the framework's emphasis on inclusivity and user-centred design, ensuring that the digital tools employed are tailored to the unique requirements of each heritage management project.

Overall, these proposed refinements underscore the importance of a dynamic and iterative approach to developing and applying the digital model within

heritage management. By continually reassessing and updating the framework based on empirical evidence and stakeholder feedback, the model can evolve to meet the complex and changing needs of heritage conservation. Engaging both involved and peripheral stakeholders, refining the digital model's data inputs, optimising outputs for various user groups, and maintaining flexibility in software integration are all critical components of a robust and effective heritage management strategy.

In conclusion, while the current framework provides a solid foundation for heritage asset management, there remains considerable potential for enhancement through targeted refinements. By embracing a holistic and inclusive approach that incorporates diverse stakeholder perspectives, adapts to technological advancements, and prioritises ethical considerations, the framework can be strengthened to better safeguard our shared cultural heritage. Future research should continue to explore these areas, with a focus on testing and validating the proposed refinements in real-world contexts to ensure their practical applicability and efficacy.

6.10 Contribution to Knowledge

This research has made a significant contribution to knowledge by defining a theoretical framework for the complex process of sustainable heritage asset management, focusing on significance. The refined framework places a dynamic digital model at its centre, supported by key pillars: stakeholders, significance, and management strategies, all governed by ethics and policy.

Transitioning from static to dynamic digital models represents a major advancement in heritage preservation and management. Traditional methods often rely on sporadic maintenance efforts, lacking strategic foresight and comprehensive understanding of the cultural and historical significance of assets. In contrast, dynamic models introduce a proactive approach, enabling more informed decision-making and fostering a holistic understanding essential for sustainable heritage management.

A central feature of this paradigm shift is the integration of diverse historical datasets into a unified digital repository to provide a holistic understanding. Currently, these datasets, which include maps, images, reports, texts, and records, are dispersed across libraries, museums, and private collections

worldwide, often inaccessible. Centralising them in a digital repository ensures that stakeholders have access to high-quality data, supporting sustainable management efforts and preserving the intrinsic significance of heritage assets. For stakeholders to engage meaningfully with the asset, it is imperative that they have confidence in the integrity and quality of the content provided. A dynamic digital model holds significant potential to serve as the cornerstone of a comprehensive conservation plan and is an initial step toward facilitating informed and robust decision-making processes.

The conceptual framework developed in this research is structured around four fundamental pillars: management, asset significance, stakeholders, and ethics/policy. Represented as a rotating tetrahedron, this model illustrated the dynamic interrelationship of its principles, emphasising a holistic approach to heritage management underpinned by ethical and policy considerations. Empirical research and case studies have advanced this framework, highlighting the need for accurate, accessible digital models to support decision-making processes and address the diverse challenges faced in heritage conservation. In doing so, the framework offers a dynamic, adaptable, and sustainable approach to the management of heritage assets.

The theoretical framework, iteratively refined from its conceptual foundation, elucidates the interconnections between its core pillars and the digital model, thereby reinforcing an active, bidirectional flow of data. Within this framework, policy and ethical considerations serve as overarching principles that guide the three primary pillars: management, significance, and stakeholders. These pillars maintain a dynamic tension with the central digital model, ensuring continuous dialogue and interaction. However, the management pillar is further shaped by additional directives that define and steer the digital model's functionality.

The digital model itself is designed to integrate and process project data across multiple dimensions, including geometric, historical, and artefactual information, captured at various stages of the intervention process—pre-intervention, during intervention, and post-intervention (see Figure 67). While the model comprehensively incorporates geometric and historical data, artefact data - particularly concerning materials and technologies - was excluded from the current research due to the complexities involved in its

collection. It is important to recognise, however, that some of this artefact data may be derived from historical records, though it is generally anticipated that such data will predominantly surface during the intervention phases.

This nuanced approach highlights the framework's adaptability and responsiveness to evolving data inputs, thereby promoting a robust and sustainable methodology for heritage management that remains aligned with ethical standards and policy directives. Similarly, the principles underpinning the dynamic digital model, which integrates contemporary and newly discovered data, position it as a pivotal force within the field. By providing a synthesised, flexible, and dynamic core, this model represents an innovative contribution to knowledge in the heritage sector.

This research has made a substantial contribution to the field of sustainable heritage asset management by defining a comprehensive theoretical framework that focuses on significance. By incorporating a dynamic digital model supported by the key pillars of stakeholders, significance, and management strategies - governed by ethics and policy - this framework advances beyond traditional methods that lack strategic foresight. Instead, it introduces a proactive, holistic approach, integrating diverse historical datasets into a unified digital repository. This model not only enhances informed decision-making but also fosters adaptability, ensuring robust and sustainable heritage management aligned with ethical and policy directives.

6.11 Future Research

Following the literature review, the empirical investigation advanced the research framework, expanding its scope and depth. It is worth noting that while some elements for future research have been outlined in Section 6.10, titled "Opportunities to Refine the Framework", these suggestions hold the potential to evolve into significant prospects within the broader research landscape. Although the relationship between benefit and significance has not been explored as an isolated topic, it is anticipated that this aspect will naturally become a focal point in subsequent research endeavours.

It is crucial to recognise that the final iteration of the framework remains, to some extent, untested. To address this, an interactive event could be organised to evaluate the framework's potential benefits to the sector. This

event should engage a diverse group of stakeholders, including both involved and peripheral to the asset. These individuals, with their rich knowledge and understanding, would be invaluable in providing feedback on the framework's appropriateness and potential for future application.

An additional area identified for future research is the democratisation of data, particularly in relation to accurate digital models. These models can serve as a foundation for generating 2D, 3D, and even 4D media, facilitating the distribution of knowledge, especially in museum and educational settings. Internet-based applications offer a platform for sharing this knowledge, which can foster a deeper understanding and, potentially, increase public interest in visiting historic sites. Fostering engagement with the asset and providing pre-visit knowledge could support a deeper connection with the site, ultimately contributing to safeguarding its significance.

Extending the model to function as a collaborative tool, such as BIM or AIM, could be particularly beneficial for interventions. This approach would also encourage stakeholder investment in the decision-making process, thereby extending the benefits to the asset. The research identified DSS and the ToC as approaches that warrant further exploration in conjunction with the digital model and the framework. Integrating these methodologies could provide a more comprehensive approach to asset management, enhancing the decision-making process and ultimately contributing to the sustainability of the asset. For stakeholders to effectively engage with the asset, they must have confidence in the quality of the content they are working with. A dynamic digital model has the potential to become the foundation for the conservation plan, and this should be investigated as a first step toward robust decision-making.

Refining the framework further could serve as a primer for a second investigation aimed at testing the framework in a real-world project. This investigation could take two forms: one focusing on isolating a single asset, and the other focusing on a specific project. Given the complexity of asset management, particularly in multifaceted environments, testing the framework on a single asset - such as the Ducal Palace at Nottingham Castle - would provide valuable insights. By breaking down the management process into strategic, intermediate, and functional levels, as well as addressing

emergent issues, the framework could be applied in conjunction with a comprehensive digital model. This approach would allow for the framework to be introduced, enhanced, and monitored, with data from the experience used to further refine and advance its application and content.

Applying the framework to a single event or project that develops over time would engage the feedback loop, similar to the action research method commonly used in the construction industry. By testing the framework in collaboration with stakeholders, researchers could assess their access to and confidence in the model, thereby enhancing their contribution to the decision-making process. This approach would also generate future directives for stakeholder involvement in the management of historic assets, leading to sustainable solutions that enhance the significance of the asset.

Building on this point, the research identified that while artifact data was included in the digital model, it was excluded from collection due to difficulties in isolation. The assumption was that data would be amassed by the project team and saved back to the model during the project and upon completion. This process would involve quality checks against existing information, with anomalies identified for further investigation. However, this is a complex workflow requiring skilled researchers, which may not be feasible for all projects. Investigation would provide precise understanding of the problem.

The application of the digital model in a project context would necessitate a centralised repository and an accessible interface. Existing project management software, particularly those based on 2D media for mobile devices, could be adapted to accommodate asset historical data, making it accessible throughout the project to all construction actors. Collecting data to evaluate the project's benefits, including cost, time, and significance, would generate a unique understanding for the sector, contributing to improved decision-making processes.

The second case study highlighted difficulties in accurately recording material surfaces using LiDAR due to their specific attributes. While some research has been conducted to determine optimal angles of incidence and moisture detection, materials like mudbrick show poor returns of laser light, warranting further investigation. The solutions proposed in the case study need to be examined, particularly as this issue is not unique to mudbrick and could inform

ground surveying practices more broadly.

Finally, the area of standards, particularly in data capture, requires further exploration, clarification, and articulation. Standards serve as the minimum benchmark for quality, often becoming the target to aim for. However, this approach may leave vulnerable assets, and those with exceptional OUV, without sufficient information to support robust decision-making. This is where ethical principles should come into play, as minimum standards may be insufficient in certain contexts. Careful investigation is needed to ensure that there is alignment between standards and the importance of the asset.

In conclusion, there is significant scope for further research using the framework as a foundation to explore the extensive subject of robust decision-making in sustainable heritage asset management, particularly through the lens of significance. This research has the potential to contribute to a deeper understanding of how digital models and stakeholder engagement can be harnessed to preserve and enhance the value of historic assets.

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Appendix 1

Nottingham Castle Historic Narrative

The site was the location of the Nottingham Castle originally belonging to the Royalty. At the outbreak of the Civil War after Charles II left Nottingham, the site passed to the Parliamentarians and by June 1643 Colonel Hutchinson was in charge, Allen (1888). There were many offers from supporters of the King to purchase the site, for example the sum of £10,000 plus incentives from The Earl of Newcastle, Charles Cavendish, Hicklin (1834). The Council of State ordered the slighting of the Castle in 1651, undertaken by Major Poulton in a period of two weeks, Godfrey (1896). The intention was to reduce the threat to the town of Nottingham, according to Hamilton (1999) making the local population very happy.

It was during the restoration of Charles II to the throne that George Villiers, second Duke of Buckingham as the legitimate heir of the Earl of Rutland reclaimed the Castle of Nottingham in its ruinous state, Hicklin (1834), Throsby (1795). Villiers leased the castle from 1641 to 1663 and shortly after sold the ruined Castle to William Cavendish for £4,400. Woodhouse (2000), William's interest in the castle stemmed from his father who had, in addition to making the earlier offer to buy the site, commissioned a plan of the Castle drawn by Smythson. To purchase the site William had to sell the majority of his property portfolio in Derbyshire, Hicklin (1834). There were a number of factors influencing this undertaking, he was older and whilst some saw it as a move towards retirement there was additional pressure as he was not welcome in court. The construction of the palace started after the death of William's wife Margaret, some said it was a distraction from the loss. Finally, there was a statement in the name of Cavendish spending the wealth, Worsley (2001).

William was both the patron and the designer, this building was to suggest his wisdom in architecture so called "arketectur". The mason Samuel Marsh undertook work in Cavendish's Bolsover Castle, Architectural History (1961) was named as the architect yet he was taking his lead from William. The mansions Cavendish visited when in voluntary exile on the Continent inspired the classical Italianate design however there were flaws for example in the

window spacing and broken string courses, Worsley (2001), (see App. Figure 1). The number of decisions and changes made on site reflected the internal politics of the household, Worsley (2001).

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App. Figure 1: A view of the front of the Castle of Nottingham belonging to his Grace the Duke of Newcastle, (Deering 1751)

The Ducal Palace was to be located in a prominent position overlooking the valley with the caves below and on the original foundations of the castle. However, the available footprint was small so Cavendish instructed that the rock should be hewn away to broaden the site destroying any remaining archaeology, Sheffield and Mills (1984). Day to day activities on site were overseen by Marsh, he directed the contractors and workers. Cavendish only saw the building rise one yard out of the ground before he passed away in December 1676, but he left instructions that his son Henry was to complete the Palace. Cavendish set up a trust for the completion overseen by Marsh, Richard Neale (a steward on the duke's staff), Richard Mason (the Duke's solicitor) and Thomas Farr (a member of Henry's staff), Deering (1751), Worsley (2001). Furthermore, William's will instructed that the trust had to complete the building in accord with the model he had left Throsby (1795) which clearly defines in plan form the 'C' of Cavendish, Woodhouse (2000) (See App. Figure 2).

Whilst it is not clear who determined where the stone used in the build originated, Donington stone is used extensively however the rusticated front was Derbyshire Grit and the staircases are Mansfield stone, Hine (1876). Furthermore, whilst the exterior wall face is Wrought Ashlar the interior leaf used rough dressed stone, whereas the internal walls were constructed of rubble stone and clay. It is said "the castle was built on arches" Hickin (1834), the thickening of certain walls suggests inverted arches to resist pressure in the foundations hence the quote. There is little of the stone from the original castle in the building as the Earl of Rutland in receiving the Castle as an

unwanted gift in 1623 had demolished buildings and sold the materials, Allen (1888). Statues representing the Cavendish family members were included in the detailing including the equestrian centrepiece in the East elevation cut from Donington stone by Wilson, Orange (1840). (see App. Figure 1).

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App. Figure 2: Plan of the state apartments at Ducal Palace as originally built (Woodhouse, 2000)

The only inventory identified for the construction materials identifies cedar wood and stone for the chimneys (possibly fireplaces) purchased between 1680 and 1683, this would suggest fit-out materials, especially as it was completed at this time. The interior was furnished luxuriously panelled rooms, guilt impressed leather for the ballroom, velvet curtains and tapestries and family portraits to complement the grand rooms with large windows to soak up the view. The Duke of Newcastle, Henry Cavendish did not want to take permanent occupation, the palace was used for entertaining borne out in part by the magnitude of the kitchens and in 1719 John Vanbrugh altered the building to rent as apartments, English Heritage (2008) (see App. Figure 3). When the duke was not in-residence Hine suggests the Castle Green was used "… as the resort of the aristocracy of the town", Woodhouse (2000).

The first were taken by a Mrs. Plumbe and a Miss Kirkby, a wealthy rather eccentric lady who stayed until passing away. This long lease was a common occurrence at the palace, Orange (1840). The last tenants were W. B. Rawson

Esq., Miss Greaves and the Reverend Joseph Gilbert who it was assumed use the facilities as a boarding school. Eventually, in 1829 the palace was left untenanted, Allen (1888).

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App. Figure 3: Plan of the Ducal Palace ground floor (University of Nottingham, 1769)

The Reform Bill during 1831 was in the parliamentary process proposing revision to social order. The workers were attempting to wrestle power from the aristocracy and Nottingham with large industrial areas was particularly restless, Bramley (1878). The City Mayor called a meeting in the marketplace requesting calm, Hicklin (1834). Dismissal of the Bill caused the large crowd to riot attacking property connected to the anti-reformers, People's Histreh (2010). After attacking several properties including Colwick Hall, a distance from the centre, the rioters cried "to the castle", Hicklin (1834). The Castle in a prominent position over Nottingham was seen to represent the Dukedom, the controlling aristocracy hence the attack, (see App. Figure 4).

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App. Figure 4: A view of Nottingham Castle overlooking Nottingham from Northwest (Mercian AS)

The attack started around 6pm when six men entered the Palace through a window in the north end, tearing tapestry and breaking the railing of the staircases, more as an act of robbery than protest. The family portraits had been removed some years earlier so were not to be destroyed at this time. Forty men joined in smashing windows and breaking tables to set the fire, (see App. Figure 5). The ringleaders were consulted to determine how to burn down the building, openings were made through the floors, bannisters lit and placed in the holes, the extensive wood flooring and furniture helped the fire take hold around 7pm, Hicklin (1834). The flame was intense, a dun-coloured smoke rose, and the chemical reaction of the molten lead roof produced sparks falling in all directions, Hicklin (1834).

A small detachment of soldiers could have successfully defended the Palace against the mob therefore the lack of reaction by the authorities is a contested issue, Hicklin (1834). The magistrates did sent troops to the buildings representing public order such as the prison and the town hall, People's Histrih (2010). It could be argued as the site was not within the town's boundary it would not have to pay compensation for the destruction. However, there is a possibility the magistrates wanted revenge against the Duke, People's Histreh (2010). Eventually, a detachment from the Hussars was sent but when riding

around the Palace they realised it was too late and returned to the town, Hicklin (1834). Thackwell admitted later the rain did more than the authorities to quench the fire, Wylly (1908).

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App. Figure 5: South view of Nottingham Castle (Parker & Dawe, 1831)

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Figure 39: The ruins of the Ducal Palace after the fire (Picture Nottingham)

The damage to the Palace was extensive (see Figure 39), the roofless shell, the lead that once covered the roof poured down the walls and along the floors. The busts and the statue of Cavendish on the horse had been attacked

with a crowbar, Hicklin (1834). All the fine woodwork, floors and staircases were incinerated, Brand (2003). The Duke would not restore the building nor sell to those who would, he saw the fire as a direct affront by the magistrates demanding an economic compensation for the damage. The authorities failed to bring to justice the perpetrators however they did charge some prisoners with arson of other property, Hicklin (1834). Fletcher (2001) goes further to state that the Duke was discouraged from investigating the Nottingham Reform Bill Riots. The Duke's diary stated he hoped to receive £25-30,000 after his initial suggestion that £60,000 was needed to reinstate the Palace, Fletcher (2001). However, he argued the riot had caused him losses of around £200,000, Brand (1984), and in August 1832 the case was heard by the Special Assizes in Leicester, who awarded £21,500 in compensation to be paid by the City Council. The jury considered this just as the building prior to the fire had been of little use to the Duke either for pleasure or profit, Matineau (1908). The compensation was accepted but spent elsewhere; the blackened ruin was left, Brand (2003).

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App. Figure 6: Nottingham Castle green and Robin Hood Rifle volunteers (Brewhouse Yard, 1866)

Dereliction followed over the next four and a half years as the exposed position subjected the remnants of the walls to the worst of the weather, such that the walls appeared to have no structural capability, Hine (1879). The unattended site became overgrown, Bramley (1878) yet continued use as a

place for recreation especially during popular festivals for example Easter and Whitsuntide, Bramley (1878) (see App. Figure 6). After the death of the 5th Duke of Newcastle, Henry Pelham-Clinton proposals for refurbishment were presented such as a prison, Court of Justice and military barracks, all were dismissed, Hamilton (1999).

Adjacent to the Ducal Palace, the park owned by the Duke, was used by the town's inhabitants as a public space despite insistence it was private property. As early as 1824 the Duke considered development of the estate, Fletcher (2001) but, as there were insufficient funds available, he attempted to sell it. Rumours abound suggesting development of the parkland started protest in the town, Brand (1984), the Duke, upset with the town folk, especially after losing the palace, tried to push ahead. Eventually, when the land was in the hands of the trustees, W. E. Gladstone and F. Ouvry, University of Nottingham (2009), Brand (2003) along with the architect Philip Hardwick development began. The architect Thomas Chambers Hine was responsible for virtually 200 out of almost 650 houses constructed in The Park.", Brand (2003), furthermore Hine opined the negative influence the burnt-out Ducal Palace provided as the backdrop to the Park Estate development, Brand (2003)

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Figure 40: Nottingham Castle as a ruin (Hine, 1876)

The Duke allowed a group of volunteers, the Robin Hoods upholding order in the city to use the site of the derelict palace under Sergeant Major White. By 1859, the members of the Robin Hood Rifles accounted 400 male residents of the town, Sutherland (2017) (see App. Figure 6). T C Hine, the architect, was associated with this corps, he was asked by the Rifles to parade in the Castle grounds, however, this involved removal of the flight of steps, a change which Hine won permission for but later regretted, Hine (1879) & Brand (2003), (see Figure 40).

Upon the death of the Duke, a team of appointed trustees including William Ewart Gladstone, and George Warren, Lorde de Tabley, Fletcher (2005) took control of the estate. In 1872, Sir Henry Cole, K.C.B of the South Kensington Museum (V&A), send a letter to Alderman Ward Mayor of Nottingham, with the purpose of establishing a museum with a connection to the South Kensington Museum. Hine (1879) & Allen (1888) (see Figure 44). The idea behind the proposition was to build the national importance of the Nottingham School of Art; the South Kensington museum would supply suitable objects for exhibition in Nottingham with the City Council providing the relevant arrangements for its safe custody, Brand (2003). In this situation, Mr Alderman delivered a solution that satisfied the Trustees, hence the Duke, the City Council and the local people. Bramley (1878) The Bill was passed and by 1875, the Corporation took a lease of 500 years at an annual rent of £200 for the purposes of a public Museum and Exhibition. The trustees of the Duke (the Right Hon. W.E. Gladstone and Lord de Tabley), and other persons legally interested in the estate, gave their assent to the scheme, Allen (1888). The project gained the approval of the inhabitants of Nottingham, who felt it removed the stain of their riotous predecessors, Hine (1876). Hence, the Museum appeared as a clear solution providing reconciliation between the parties.

The cost of the work for building restoration were estimated at £20,000, Allen (1888), however, the final figure stood at £26,200 (£10,580 was met by private subscription with the remainder being provided by the Corporation). Allen (1888) & Brand (2003) Thomas Chambers Hine was selected as the architect of the Museum; he recalled during a meeting that he was originally approached by the trustees of the Park Estate for suggestions as a use for the ruined Palace, Brand, (2003). For two years Hine had been creating designs

for the Castle, which never came to fruition as funding was not available. Privately, Hine and Son were the only architectural practice invited to prepare a proposal and their plans approved in 1876 took two years to complete, Brand (2003) with the changes mostly internal.

As a means of increasing the daylight, the original three floors were reduced to two, Hamilton (1999). "The new staircase was of stone with a cast iron balustrade and for the formation of galleries two storeys, the lower of 18 feet (approx.14.5mts) and the upper of 23 feet (approx. 7.0mts), replaced the three storeys of the Ducal Palace. This meant that the new floors cut across the windows of the old staterooms.", Brand (2003). Externally, Hine added a balustrading above the facade at parapet level to hide the new roof of the galleries, and replaced detailing in the windows, inserting mullions and transoms. The external staircase in the courtyard on the West did not correspond to the change of internal floor levels so Hine proposed removal to attach a colonnade, Woodhouse (2000). The service wing to the North remained as a shell until 1889 when Herbert Walker, a local architect, led a two-year restoration rebuilding the main elevation to contain workshops and additional gallery space.

The museum and gallery opened to the public in 1878 by the then Prince of Wales, soon to be King Edward VII, and his wife, under the directorship of George H. Wallis, Wood & Reese (2016). The Palace remained until 2018 virtually as Hine left it on the completion of the project, areas of internal refurbishment were undertaken, a lift inserted and externally a small extension on the Northwest corner helped the development of a gallery.

Note;- References located within main list

Appendix 2

Geometric					Historic		
Artifact	Equipment	Environment	People	Locale	Location	Sources	Types
Asset	Instrument	Climate	Expertise	Geographic	Local	Repositories	Maps
Materials	Peripherals	Weather	Skills	Density	National	Archives	Photographs
Use	PPE	Season	Number	Classification	International	Libraries	Records
Architecture	Transport	Air-quality	Respect	Culture		Museums	Books
Occupancy	Availability	Vegetation	Adaptability	Architectural		Newspapers	Plans
Permissions		Moisture	Meticulous	Access		Registers	Pamphlets
Access		Contamination				Owners	Diaries
Safety		Microclimate					

App. Figure 7: Considerations for a LiDAR campaign (By author)