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Review

Beyond Heritage Science: A Review

Craig J. Kennedy [1,*], Michael Penman [2], David Watkinson [3], Nicola Emmerson [3], David Thickett [4], Frédéric Bosché [5], Alan M. Forster [1], Josep Grau-Bové [6] and May Cassar [6]

[1] School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh EH14 4AS, Scotland, UK; a.m.forster@hw.ac.uk
[2] Division of History, Heritage and Politics, University of Stirling, Stirling FK9 4LA, Scotland, UK; m.a.penman@stir.ac.uk
[3] School of History, Archaeology and Religion, Archaeology and Conservation Section, Cardiff University, John Percival Building, Colum Drive, Cardiff CF10 3EU, Wales, UK; watkinson@cardiff.ac.uk (D.W.); emmersonnj@cardiff.ac.uk (N.E.)
[4] English Heritage, Rangers House, Chesterfield Walk, London SE10 8QX, England, UK; david.thickett@english-heritage.org.uk
[5] Institute for Infrastructure and Environment, School of Engineering, University of Edinburgh, William Rankin Building, Robert Stevenson Road, The King's Buildings, Edinburgh EH9 3FB, Scotland, UK; f.bosche@ed.ac.uk
[6] Institute for Sustainable Heritage, University College London, 14 Upper Woburn Place, London WC1H 0NN, England, UK; josep.grau.bove@ucl.ac.uk (J.G.-B.); m.cassar@ucl.ac.uk (M.C.)
* Correspondence: craig.kennedy@hw.ac.uk; Tel.: +44-131-451-4629

Abstract: Heritage science is an established and thriving field of enquiry. Initially considered as inherently cross-disciplinary, encompassing both the needs of conservators and practitioners and the high-quality evidence produced by scientists, heritage science has, through its expansion in recent years, formed a discipline in its own right. Here, we examine how heritage science can, and to an extent has, moved beyond the straightforward scientific analysis of historical materials and artefacts through an exploration of heritage science's interactions with four key themes: (i) historical and archival research, (ii) conservation practice, (iii) policy at governmental, organisational and institutional levels, and (iv) a view to how new technologies, such as machine learning and artificial intelligence, can shape the future of heritage science. Much of the review narrative is framed via the analysis of UK-based case studies; however, they deal with issues that are international in nature (universal) and therefore transcend the UK context. Taken together, we demonstrate that heritage science as a discipline is capable of directly instigating or (re-)framing new areas or avenues of research, as well as enhancing and feeding into existing research questions, and has adapted and evolved along with emerging technologies and funding opportunities.

Keywords: heritage science; history; conservation; policy; practice; digital technologies; machine learning; artificial intelligence; robotics

Citation: Kennedy, C.J.; Penman, M.; Watkinson, D.; Emmerson, N.; Thickett, D.; Bosché, F.; Forster, A.M.; Grau-Bové, J.; Cassar, M. Beyond Heritage Science: A Review. *Heritage* **2024**, *7*, 1510–1538. https://doi.org/10.3390/heritage7030073

Academic Editor: Francesco Soldovieri

Received: 29 January 2024
Revised: 4 March 2024
Accepted: 10 March 2024
Published: 12 March 2024

1. Introduction

Heritage science has existed in one form or another for decades, though the term itself was coined in the UK House of Lords Science and Technology Committee report *Science and Heritage* in 2006. The reason for the creation of this term was that the most used phrase up until that point, "conservation science", was deemed inadequate to describe the whole range of activities that the sector was undertaking [1].

Conservation science was, by that stage, undertaking works beyond the conventional scientific analysis to aid in the conservation of cultural objects and artefacts with a clearly defined need. Archaeological science, archaeometry and remote sensing activities were all taking place in addition to traditional conservation science.

Since the coalescence of activities around and international adoption of this term, the heritage science discipline has grown rapidly. This can be explained in part by two factors.

Firstly, the expansion of the range and capabilities of scientific equipment that can meet the needs of heritage scientists. Portable technologies and non-destructive equipment are ideally suited for a sector where the subject of study is of such value that it cannot, or should not, be damaged or, in some cases, moved [2]. In recent years, the sensitivity of such equipment has significantly improved such that high-quality scientific data gathered in this way are being usefully applied across the sector, whereas in the past, the quality of the data produced on-site was often inferior to what was available in a laboratory setting [3].

Secondly, funding for the heritage science sector has improved in recent years, with more funding organisations recognizing the value that this sector can bring. Organisations such as the European Union have for many years encouraged and funded transnational projects in the field of heritage science that have brought together researchers to produce a flourishing international community of scientists and practitioners. Such communities are visibly seen today through entities such as E-RIHS (European Research Infrastructure for Heritage Science) and the UK National Heritage Science Forum [4]. More recently, in the UK, a new focus from the Arts and Humanities Research Council has emerged, evinced by the creation of UK heritage clusters with a headquarters at Sci-Tech Daresbury, a laboratory that has a long association with research into heritage artefacts.

The range of activities undertaken by the heritage science field has continued to evolve and expand. These activities have developed at a rapid pace since a 2009 series of reports gathered evidence of the activities undertaken at that time under the four general "heritage" themes: archaeology, built heritage, collections, and libraries and archives. These reports gave a snapshot of the state of heritage science in the UK at that point in time and led to the development of the UK National Heritage Science Strategy [5].

Here, we review and expand upon how heritage science has continued to grow in recent years and has developed research links to a number of other research areas. Importantly, these research linkages can be bi-directional, with research activities in heritage science informing partner disciplines. Much attention has been paid over recent years to how other research areas and foci can influence heritage science; here, we explore the opposite: how heritage science has influenced other sectors.

The review begins with a look at the past and how heritage science has influenced historical research and either confirmed or challenged accepted historical narratives. This is followed by an examination of how heritage science has impacted conservation practice. Then, we look at how heritage science has shaped policy. The review finishes with a look to the future, particularly how heritage science meets the needs of new and emerging technologies such as artificial intelligence, remote sensing and machine learning.

2. Heritage Science and Historical Studies

Historical and archival research has a natural linkage with heritage science in that both relate to understanding the past. However, many scientific analyses of historic objects do not directly consider the history of the artefact involved; for example, fundamental studies to establish the decay mechanisms of historic materials. Often, such studies utilize materials that are historic in age but not in terms of significance. Studies into parchment and wood, for example, have aimed to understand the decay pathways of complex biological polymers that are exposed to variable environmental conditions with a view to offering guidance on storage conditions [6,7].

Such studies are incredibly useful in providing scientific information that can be applied to valuable cultural assets that cannot be subjected to analysis, either due to the fragile condition of the object or its importance, or through the reluctance of heritage managers to allow valuable cultural artefacts to undergo any kind of examination [8]. This is explored in more detail in Section 3.

The relationship between heritage science and the conservation of historical sites and material remains is now well established, with language and protocols increasingly enshrined in academic practice and professional frameworks [5,8,9]. In the wake of that inter-disciplinary emergence, allied collaboration between heritage science and historians, as well as heritage practitioners and curators concerned with interpretation and education, has also evolved and grown, if not always easily [10].

As Gilchrist [11] has argued, archaeology and the scientific analysis of material remains and deposits remain powerful tools—though still open to challenge—in confirming or revising established historical chronologies and their interpretations, often seemingly firmly entrenched over generations and based upon well-disseminated written records and cultural memory. This may especially be the case in the context of interpreting a 'sacred' historic building, landscape, object or even human remains, where the meaning and value attached to those traces are often contested over time by both custodians, locals, visitors and academics.

Such potentially definitive or disruptive reach through science is perhaps most readily illustrated where emerging techniques and technology can be applied to the (often retrospective) interpretation of excavated or recovered material remains previously overlooked or hitherto limited to cautious typological observation and categorisation, or which have often left little or no allied evidence in the written record.

2.1. Utilising Heritage Science to Understand Ecclesiastical Sites

Ecclesiastical sites contain a significant number of objects and artefacts that can, interpreted in depth, tell the story of the history of the place and the evolving nature of religion over the centuries. One such material strongly associated with church buildings is stained glass, which figuratively displays liturgical messages, such as biblical stories; in recent years, heritage science has greatly expanded our knowledge and understanding of such glass and, in turn, enhanced our understanding of the history of religious sites.

X-ray fluorescence (XRF), scanning electron microscopy with energy dispersive X-ray analysis (SEM-EDX) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) can be variously applied to medieval stained and painted glass shards found in ecclesiastical archaeological contexts to analyse their compositional materials, techniques, geographic origins and dating [12]. Analysis of such glass recovered in excavations of the Benedictine abbey of Glastonbury (Somerset), legendary home to Arthur's remains within a medieval shrine, highlighted the careful and conscious reincorporation of 12th-century 'durable' blue glass—most often associated with Virgin imagery—into later 14th-century extensions of the monastic choir with new fenestration. This identifies key phases of the new building and religious patronage at Glastonbury, which crucially sought to retain both the antiquity of its origins and particular cult/liturgical iconography. This saw medieval worship increasingly focussed on a Lady Chapel erected in the 14th century atop an earlier sacred site located, unconventionally/unexpectedly, to the west of the choir high altar area where Arthur's tomb was raised [13].

Similarly, recent 'windowlyser' reassessment of the west end entrance 'Ancestors of Christ' narrative windows of Canterbury's Benedictine Cathedral Priory (Kent) has confirmed earlier researchers' suspicions that these should be re-dated earlier to c. 1130–60, challenging accepted notions of the iconographic and liturgical development of this great church into the 13th century (following a fire) and the impact there of the cult shrine of Thomas Becket (d. 1170); this in turn informed a recent digital recreation of the shrine integrating the new scientific findings with the extant written and material record [14,15].

Scientific analysis of recovered glass from the ruins of the Benedictine abbey of Dunfermline (Fife, Scotland, UK) might also suggest a late 13th-century–early 14th-century focus for a major redevelopment of this great royal mausoleum and cult church where the historical record is highly fragmentary, even silent. But several recent projects at Dunfermline underline the welcome fact that new investigations to learn the history of an object or place or their traces can be initiated precisely because of advances in heritage science and are thus truly inter-disciplinary, led by those approaches from the outset rather than as a later tool to confirm or problematise established narrative assumptions.

This is especially the case at Dunfermline, where a Protestant parish kirk was erected in the Georgian era (1818–1821) atop the wrecked abbey choir. The presence of the kirk prevents any ground-proofing via excavation of the post-Reformation remains of that half of the medieval church and its many royal, noble and clerical tombs, its chapels and altars, and the east-end pilgrimage shrine (1250) of St/Queen Margaret (d. 1093). However, refined non-invasive ground-penetrating radar (GPR) survey techniques—deploying low-level frequencies (250 and 400 MHz) at half the scan intervals (25 vs.50 cm) usually recommended by heritage agencies—has recovered key aspects of a major historical site previously thought completely lost and which suffers from a sorely limited historical record [16] (Figure 1).

Figure 1. August 2022 GPR scan areas marked in brown on a composite of 2016–19 GPR scans below the floor of Dunfermline Abbey Church, Fife (Scotland, built c. 1817–21), in search of the walls, fittings and burials of the overbuilt medieval Benedictine choir. This overview illustrates the radar's identification of an unrecorded cruciform southern chapel, a mirror of the relatively well-documented Lady Chapel to the north. © EMC Radar and Atlas Geophys.

The GPR results have revealed a focus of burials of elite couples on a large scale in the northern Lady aisle and adjacent transept chapel of Dunfermline's choir, tangible proof that has in turn permitted a reinterpretation of the intangible heritage of the site: veneration and patronage focussed around the model and shrine/tombs of 'founding' royal couple, Margaret and her husband Malcolm III, a liturgical pattern not easily discernible in the extant cartulary record. GPR has also recovered a symmetrical southern transept chapel of St John the Baptist, previously unnoticed in the archival record, and exposed 17–18th-century Protestant burials by locals which sought ritual and physical association with the prestigious site of St Margaret's Catholic shrine.

However, this Dunfermline project's most striking historical reinterpretation to date arises from the ability of heritage science to also prompt reassessment of and fresh dialogue with the record evidence, including, in this instance, rehabilitation of medieval and antiquarian records hitherto disbelieved or ignored by historians. GPR has recovered potential remains of the medieval high altar settings of the choir, physical evidence confirmed by overlooked antiquarian observations, and which has in turn challenged the traditional identification and commemoration of a grave disturbed in 1818 as being that of the original site and form of interment of King Robert I/Bruce (1329), perhaps the most iconic king in Scotland's history, since then very much the focus of the site's heritage. Together with an allied project by Historic Environment Scotland deploying petrology, tool-mark and polychrome analysis, and digital reconstruction, GPR suggests Bruce's box-tomb monument could have lain instead within the northern choir/aisle space (Figure 2), embracing the Margaret–Malcolm and elite couples' liturgy but also with a focus around the importance of royal childbirth and family within the adjacent Lady Chapel [17]. This, in turn, has prompted further scrutiny of the medieval records, including the suggestion that the surviving financial rolls for the purchase of Bruce's tomb in Paris may be sufficient to allow for its having been a double, royal couple monument. Current analysis at the National Museum of Scotland, assessing the datable composition and style of cloth of gold fragments originally found within the disturbed Bruce grave in 1818, may add further nuance to the emerging argument that that interment may have been a post-Reformation rescue burial, and thus an anomaly in recovering the medieval layout and liturgy of Dunfermline Abbey.

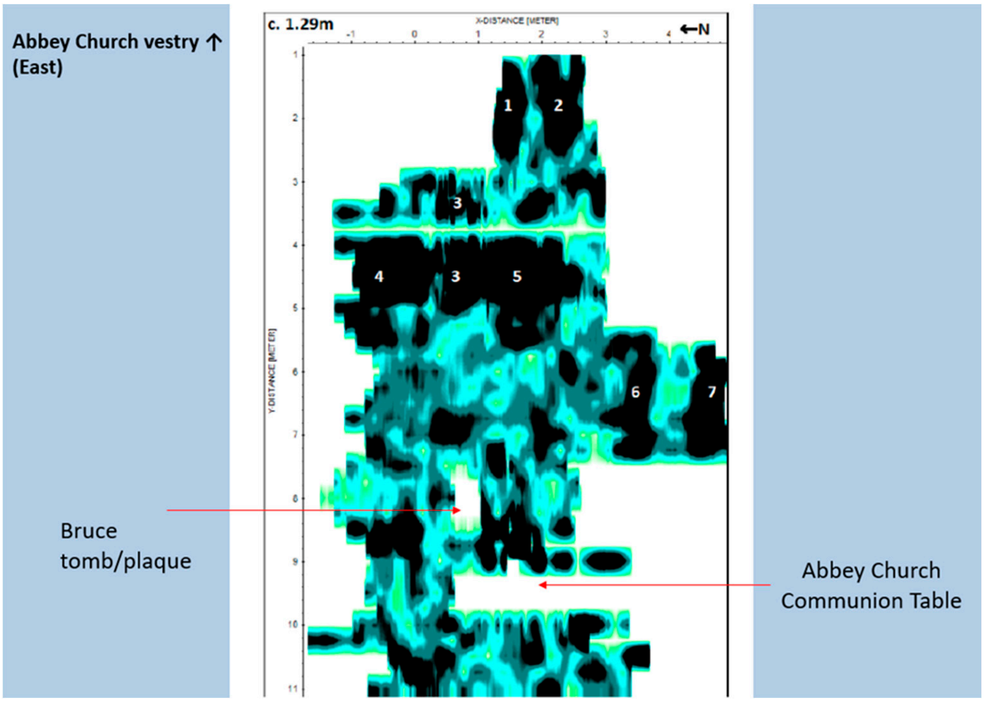

Figure 2. GPR Time slice extracted at c. 1.29 m [250 MHz] probing the alter screen settings around the central medieval choir 'Bruce grave' and high altar of Dunfermline Abbey. No firm documentary evidence survives as to the location and form of these chancel features, and debate had surrounded the question of how far east the altar might or might not have been moved east when the church was extended c. 1250. © EMC Radar.

2.2. The Vinland Map Controversy

There are cases where scientific analysis, which is open to interpretation, can give conflicting understandings of the history of an item of cultural value or a site. At Dunfermline, this might be said to be illustrated by two rival forensic medicine projects—at the Universities of Glasgow/Liverpool and West Michigan—which found evidence both for and against the assertion of English and Flemish medieval chroniclers that Robert Bruce had died of leprosy [18,19]. However, one far more controversial, complex and evolving example where heritage science was used to both confirm and challenge the historical narrative is that of the scientific analysis of the Vinland Map.

Discovered in 1957, the map, bound in a volume with the Tartar Relation, was purchased by Yale University. In 1965, a book was published the day before Columbus Day titled *The Vinland Map and the Tartar Relation* [20]. The significance of the Vinland Map was that it purported to show that Norse explorers had reached North America around 50 years before Columbus; if accurate, then this would have a major impact on our understanding not only of Norse history but also the history of European exploration and settlement in North America. This Map therefore challenged the most widely accepted European narrative on the discovery of America.

In 1966, the Vinland Map Conference was held at the Smithsonian Institute, and researchers from around the world had the opportunity to question the authors of the book. Here, some doubts were raised as to the authenticity of the map. For example, even within the book, mention was made of the high degree of similarity between the Vinland Map and the World Map of 1436 by Bianco. One outcome of the Vinland Map Conference was that several of the speakers asked for scientific examination of the ink and parchment, an early example perhaps of heritage science being utilised in this manner. The idea here was that if heritage science could demonstrate that the ink and parchment were contemporaneous with the 15th century, the argument for the map's authenticity would be strengthened. Conversely, if the scientific examinations were able to demonstrate that either the ink or parchment was modern (e.g., from the 20th century), then this would be conclusive evidence of the Vinland Map being a forgery.

However, rather than immediately settling the issue, heritage science was used in the following decades to both confirm and challenge the authenticity of the Vinland Map.

In terms of the parchment, radiocarbon dating clearly demonstrated that it dated to AD 1434 $\pm$ 11 years [21]. As such, there has been little controversy around the age of the substrate of the map.

Microscopic analysis of the ink [22] suggested that the ink was not similar to Icelandic inks of the 15th century. McCrone and McCrone [23] in 1974 employed microprobe analysis, optical microscopy, electron microscopy and X-ray diffraction to analyse samples of the ink and found that the ink on the map contained titanium dioxide in the form of the mineral anatase. The conclusion of that study was that anatase was not commercially available until around 1920, and thus, scientifically, it could be stated that the Vinland Map was a forgery.

However, the findings of this paper did not immediately settle the issue. In 1987, Cahill et al. [24] used particle-induced X-ray emissions (PIXE)—a technique not readily available in the early 1970s—to further analyse ink samples from the Vinland Map. This study was better able to quantify the titanium in the samples and found that it was present only in trace amounts. As such, the prospect that the ink—and therefore the Map—was a genuine 15th-century production could not be ruled out, according to the authors. Further, Olin [25] speculated that titanium might occur in nature with iron, and as iron gall inks were used on the Vinland Map, the presence of titanium should not discount the possibility that the map was genuine. Olin [26] went on to speculate that the presence of carbon in the ink could be evidence that the map was in fact medieval.

Interestingly, the debate regarding the Vinland Map then became one of interpretation of the data between heritage scientists rather than utilising new techniques. Towe [27] refuted the claims of Cahill et al. through a re-examination of their evidence and that of other studies to state that, in his view, the map was a forgery. Further, Towe [28] and Clark [29] both refuted Olin's article regarding the presence of carbon.

In the 2000s, a new view was put forward—that the Vinland map was badly damaged when discovered in 1957 and may have been subjected to an undocumented attempt at conservation-restoration [30]. As such, the presence of 20th-century ink need not mean that the map is a forgery; a theory rebutted by Towe et al. [31] but accepted by Larsen and Sommer [32].

Such was the notoriety of the map by this stage, due to the fact that it served as an example of heritage scientists in a very public disagreement spanning decades, that when René Larsen stated in 2009 that "We have so far found no reason to believe that the Vinland Map is the result of a modern forgery", this became worldwide news.

As new techniques and methods became available, they were often trialled on the map. More recently, Raman spectroscopy has been utilised [33]. In 2021, Yale University released a press statement stating that a combination of X-ray fluorescence, field-emission scanning electron microscopy (FE-SEM) and Raman spectroscopy [34] used on the document was able to conclusively state that the titanium is of modern origin, and that the titanium pervaded the entire document.

Interestingly, the Vinland Map serves in some ways as an exploration of the development of heritage science. Initially thought of as the answer to the question of whether or not the map was a forgery, and as such had significant implications for the established historical narrative, the decades of debate and conjecture have given this document a historical narrative and, indeed, a notoriety of its own.

3. Heritage Science and Conservation

Heritage science is a recent descriptor for the role of science in the investigation and preservation of tangible culture. As such, it incorporates conservation science, which has its origins in the birth of conservation as a discipline that aims to preserve the longevity of heritage objects and structures. As a collective term, conservation science encompasses the activity of scientists working within conservation, conservation practitioners engaging in scientific research and scientists from outside the heritage sector involved in solving its problems. Collectively, these groups create a collaborative synergy to deliver outputs that inform standards and guidance documents within the conservation sector and provide the data that support evidence-based decision making within conservation practice. Science has always underpinned the development, understanding and evidencing of preservation techniques and strategies. Exploring how and why it occupies this pivotal role within the preservation process identifies it as the essential platform for developing predictive evidence-based preservation procedures. This demonstrates how, although conservation science is a recent term, it has historically always been the driving force behind the development of the conservation discipline and its practices.

3.1. Historical Context

While it is difficult to identify when the preservation and repair of venerated or valued cultural objects and structures began, evidence indicates that this has long been practised in many cultures [35]. Roman Samian ware excavated from civil and military sites in the UK displays evidence of ancient repairs using metal rivets [36]. The exact reasons for this are unknown, but suggestions vary from the cost to the unavailability of replacements, and it is unlikely that the repair was a process practised by a specific group of individuals who might be termed conservators. In the 11th century, when describing craft and art techniques, Theophilus established that understanding the working properties of materials was essential within artisan and craft skill sets [37], and evidence suggests that these practitioners would have carried out maintenance and repair which, judged by the standards of the time, might today be classified as 'conservation'. The Sistine Chapel ceiling paintings were 'restored' in 1625 by the resident gilder and in 1710 were cleaned by a painter [38]. These examples indicate that, although a working knowledge of material properties to support practical applications does not constitute the use of science, materials science is a natural fit for conservation practice.

The evolution of science and the understanding it could provide gave it a central role in solving problems related to preserving cultural heritage, particularly in national collections. Faraday's 1843 identification of sulphur emitted by gaslights causing 'red rot' in leather book bindings shows how scientific investigation provided evidence to guide the control of decay long before the term 'preventive conservation' was coined in the 1970s [39]. In the 19th and early 20th centuries, the influence of science grew as the advent of large national museums created public sector responsibility for preserving their collections. Museums began to establish scientific laboratories and appoint science-based individuals to focus on preserving their collections. Using their scientific knowledge and practices to study decay variables and mechanisms of change, they began to develop evidence-based processes and laid the foundations from which the conservation profession grew.

In 1888, the chemist Friedrich Rathgen was one of the first such scientific appointments. He managed the chemistry laboratory of the Königliche Museen zu Berlin in 1888 and published a guide to treatments for archaeological objects [40]. In the National Museum of Denmark, the chemist Gustav Rosenberg published his experimental work on metals and their conservation [41]. This work focused on archaeological material as, unlike the slow change that many historical and fine art objects underwent, it presented immediate and complex problems. The role of chemists and science in conservation grew as Alexander Scott became the first director of the British Museum Scientific Laboratory in 1920, and Harold Plenderleith joined him in 1924. The laboratory became a stand-alone department in 1931 [42]. Their work [42,43] linked material properties and technology to decay processes, thereby rationalising conservation procedures. This linkage between understanding materials and developing conservation strategies is echoed by the analytical chemist Alfred Lucas in his volume 'Antiques: Their Restoration and Preservation' [44], where he employed first-hand experience of preserving material from Tutankhamun's tomb to report his methods. Assessing the condition of materials from the decay variables they were subjected to and then using this to identify potential conservation procedures and their limitations is a generic theme in archaeological publications from the earliest times [45]. The influence of science on conservation began to be more clearly defined as time progressed. Edward Forbes became the first director of the Fogg Art Museum Department for Technical Studies in 1928, which defined its research as including 'the fields of chemistry, microscopy, physics' supporting 'inquiry into the scientific care and restoration of works of art' [46], and employed the chemist Rutherford Gettens. More scientific research laboratories were created in large museums as time progressed, including the Boston Museum of Fine Arts in 1929 and the Metropolitan Museum in New York in 1930 [39]. Elsewhere in Europe, similar initiatives were taking place. Long-established public institutions, such as Opicificio delle pietre dure in Italy, began to establish restoration laboratories that used modern scientific techniques to examine works of art prior to their treatment.

As conservation developed towards a recognised profession, supported by chemists like Gettens and Plenderleith, the role of scientists and science in guiding and developing conservation practice grew with the advent of research posts focused on the needs of conservation practice. These continued the pattern of employing chemists. The organic chemist Anthony Werner moved from academia to the National Gallery in 1946 and later became Keeper of the Research Laboratory at the British Museum (1959–1975). Their contributions to the conservation profession often reflected initial training, such as Werner's work on synthetic varnishes and coatings in heritage preservation [47]. Larger institutions dedicated multiple posts to conservation science as research appointments. In the British Museum, trained scientists applied their knowledge and research skills across the conservation spectrum, often focusing on solving in-house conservation or authentication problems that provided outcomes that could be extrapolated across the sector.

Publications acting as basic texts for conservation practitioners continued to originate from pure scientists. Gary Thomson, a research chemist based in the National Gallery (1955–1985), produced the first overview of the environment and its control within museums in 1978. His dual-purpose textbook, aimed at both practising conservators and conservation researchers, established the blueprint adopted by chemists working in conservation for their own publications [48,49]. Since its first issue in 1955, the international conservation journal *Studies in Conservation* has contained a wide range of scientific articles written by pure scientists, who are normally employed as conservation scientists within the conservation profession, as well as conservation practitioners. This pattern is reflected today in other mainstream conservation journals and across major conference publications.

3.2. Science in Conservation Training

Historically, while science was embedded in the practice of preserving heritage material via the almost universal appointment of scientists to roles influencing conservation practice, there was no specific training for conservation practitioners. Their backgrounds were diverse, with various strengths that may or may not have included science literacy, despite their engagement with objects, leaving them well placed to recognise how science could benefit their activities. As the number of conservation training courses increased rapidly from the 1950s onwards, this need to embed science in training curricula was recognised by the generic definition of conservator/restorer [50] that was adopted by The International Council of Museums (ICOM): 'Training should involve the development of sensitivity and manual skills, the acquisition of theoretical knowledge about materials and techniques, and rigorous training in scientific methodology to foster the capacity to solve conservation problems by following a systematic approach, using precise research and critically interpreting the results' [50].

This continues to be reflected in the structure of many training courses today, as the Royal Danish Academy's current curriculum notes: '. . .conservation science, which aims to prevent and treat the deterioration of objects of cultural and natural heritage in the broadest sense of the word. The profession is characterised by its mix of theoretical knowledge and practical skills. It includes the ability to assess ethical, aesthetic, humanistic, technical and scientific issues in a systematic way" [51].

While conservation science is integral to training conservators, the scope of scientific understanding they will possess is limited by the breadth of the conservation discipline and the wide range of knowledge and skill sets required to address this [52], which means collaborative research is the way forward.

3.3. Science in Conservation Practice

Although early conservation approaches focused more on interventive treatments that retained or restored the physical and visual integrity of objects, the scientists advocating and reporting them recognised the importance of the environment as a tool for influencing the chemistry and physics of change. Rathgen [40] noted the result of post-excavation exposure of archaeological iron objects to the atmosphere, '. . . even in the driest of rooms, is the same: all sooner or later undergo change, and portions of rust become detached, until in the course of time every trace of the metallic core is oxidised'. Later, Rosenberg [41] published his studies on the mechanisms of change this involved, the variables that drove them, the chemistry of the corrosion products and their physical impact on an object. Even at this early date, there was an awareness that understanding materials and the mechanisms of change they undergo are prerequisites for developing successful evidence-based conservation procedures.

Instituting actions to treat deteriorating materials without knowledge of the chemistry and physics of their change is a speculative process that relies on empirical theory, and this can be challenging to reconcile with the ethical concepts underpinning the profession. Science can be used to reduce this speculation and may eventually eliminate it. Understanding materials, their mechanisms of change and the variables that influence them is essential for preventing or controlling their change, which is the core goal of preventive conservation. By advocating strategies for the long-term preservation of heritage materials before and after World War 2 [39], Rutherford Gettens effectively identified that fully integrating the science of materials into conservation could change it from a discipline that reacted to damage to one that sought to prevent it. To do this, it is necessary to collaborate with pure and applied science disciplines that can offer the knowledge, skill and equipment necessary for producing the depth of understanding required to devise and evidence conservation policy and practice. Since preventive conservation comprises 'all measures and actions aimed at avoiding and minimizing future deterioration or loss' [52], it could not develop or move forward without all science disciplines generating the information necessary to support this goal, which requires understanding mechanisms of change and their outcomes for all materials in every environment.

Where intervention is essential to prevent physical or chemical change, science provides an understanding of the materials to be treated, the material(s) that will be used in the treatment and the interaction of the two. Integrating this with the short- and long-term goals of the treatment being studied provides the blueprint for assessing its impact and effectiveness. Such studies often involve collaborations between heritage and discipline-specific scientists and practising conservators. High-profile examples of such collaborations include the development of treatments to prevent the collapse of degraded waterlogged wood as it dries, controlling the corrosion of metals and the use of transparent polymer coatings in conservation practice. Science that identifies flaws in treatments and materials is equally as important as the studies that identify their benefits. It is essential for supporting science to be unbiased and of good quality, with a robust methodology and a contextualised sample set in order that its outcomes can be extrapolated usefully to heritage contexts.

Science can be viewed as a jigsaw of data that has to be pieced together to explore its fit to the conservation goal. Often, pieces of the jigsaw are missing or incomplete, and it is the science literacy, training, experience and skill of the conservator that determine if enough of the jigsaw can be completed to provide evidence for their intended action. This requirement emphasises the need for a high level of science literacy within conservation training programmes. Dangers arise where the gaps in the scientific evidence are too great, but the perceived benefits and attractions of a material or action to conservation practice lead to its being adopted by the profession, and a number of cautionary tales exist. The use of soluble nylon in conservation practice, without sufficient understanding of its properties, caused damage to objects as it aged [53], and synthetic picture varnish solubility was called into question [54].

3.4. Collaborative Research in Conservation Science

Collaborations, here defined as the input of scientists from non-conservation disciplines, can arise in many ways. Interdisciplinary collaboration between conservation and either the pure or applied sciences is longstanding. This may occur via specific funding programmes such as the 2014–2023 EPSRC Science and Engineering in Arts, Heritage and Archaeology (SEAHA) doctoral training programme, which trains students in cross-disciplinary heritage science with the goal of establishing links between academia, heritage and industry. There are also more general ongoing or short-term national funding programmes, such as the Arts and Humanities Research Council (AHRC) in the UK or, internationally, the European Horizon programme that has the broad aim of supporting research and innovation in specific areas. Access to instrumental and analytical facilities, like the Neutron Centre in Budapest, is facilitated by funding programmes such as IPERION. Attracting research funding of all types to conservation science is often driven by the profile of an object or structure. There will always be high-profile cases that act as catalysts for multi-disciplinary research. The series of ship excavations that included the 17th-century Swedish wooden warship Wasa (1961) and the Bremmen Kogge in Germany (1962) galvanised research and attracted outside expert input to advance the whole process of waterlogged wood preservation.

Establishing science-based research links with disciplines outside of conservation is made easier where there is a heritage-focused interest within the external body, such as the European Federation of Corrosion (EFC) Working Party 21 Corrosion of Archaeological and Historical Artefacts, whose members are a mix of corrosion and conservation science professionals. This is an excellent opportunity for the conservation sector to establish sector-specific collaborations, but conservation sector professionals face the challenge of high fees for the annual EUROCORR conference that is pitched to the corrosion industry. A more general challenge for the conservation science sector and conservation practitioners engaging in aspects of scientific research is access to publications. Many employers and private practitioners will not subscribe to the specialised publications associated with a sector like corrosion or climate change. Consequently, it is not just the science literacy of conservators that governs the dissemination of science into mainstream conservation but also logistics and finance.

The ideal collaborative relationship is where industry and conservation goals are the same. An example of this can be found with the French Alternative Energies and Atomic Energy Commission (Commissariat à l'Énergie Atomique et aux Énergies Alternatives—CEA). They explored the performance of ferrous metals for the storage of nuclear waste based on reverse engineering the corrosion processes occurring on archaeological iron during burial to assess the longevity of storage containers [55,56]. This produced a detailed understanding of corrosion mechanisms [57–60] and was extended by collaboration with French conservators investigating the mechanisms of aqueous desalination [61–63] and subcritical desalination methods for controlling the corrosion rate of iron [64]. In tandem, complementary studies by conservation scientists in the UK investigated how relative humidity initiated the post-excavation corrosion of iron to identify corrosion thresholds [65,66] and rates as an evidenced numerical risk scale [67]. Collectively, these studies advanced management and treatment practices in the sector at a level of understanding and rate beyond that which could be achieved if research had remained in-house within the conservation sector. Not only was the skill set of corrosion scientists important, but also their access to state-of-the-art analytical tools, which produced an ongoing collaborative legacy with conservation practitioners.

A factor that is often overlooked when identifying the success of collaborations is the importance of a dynamic individual who galvanises research. At the CEA, Professor Philippe Dillman's deep interest in iron produced the large iron corrosion research group that created collaborations with the conservation sector. Similar patterns can be seen elsewhere, such as Per Hoffmann within wood conservation [68–71]. Elsewhere, collaboration between industrial companies is created where conservation goals and the goals of a manufacturer for its products merge.

Sector-organised conferences have provided a platform for inputting science and reporting collaborations. Recent Advances in Conservation [72] reports the 1961 International Institute for Conservation (IIC) conference, whose multiple contributors originated from university science departments, commercial corporations and sector-based institutions. Other conferences, such as 'Corrosion and Metal Artifacts—A Dialogue Between Conservators, Archaeologists and Corrosion Scientists', attract world-leading figures like the corrosion scientist Marcel Pourbaix [73], producing conference publications that are highly visible for and readily available to conservators. Sector-domiciled collaborative groups such as ICOM-Committee for Conservation (ICOM-CC) Metals and Wet Organic Archaeological Materials working groups run triennial conferences that report research spread across an international profile, and this is predominantly science-focused.

Successful collaborations are built on the science literacy of conservators, signalling the importance of science in the training curriculum. This should be robustly maintained or, preferably, strengthened to improve understanding of conservation actions. The scientific training a conservator receives should fully equip them to identify problems and articulate the questions that will lead to a drive to find solutions. It should focus on understanding methodology, interpretation and thought processes within science to provide a blueprint for communicating with scientists and self-development post-training. This generates a research-led investigative approach that can free conservators from the limitations of knowledge-based training.

3.5. Dynamic Growth in Evidence-Based Conservation Practice

Conservation science progresses conservation practice. Without the dynamic that science offers to conservation decision making, it will stagnate and stand still. No matter to what extent stakeholders employ ethical, political and social contexts to rationalise a conservation decision, applying it will require knowledge supplied by scientific understanding, irrespective of whether the decision involves preventive or interventive action. Simply doing nothing requires scientific understanding to predict its consequences. Understanding materials and their decay mechanisms, quantifying rates of change and their outcomes, and determining the impact of reaction variables on longevity are essential ingredients of all decision making in conservation (Figure 3). This role effectively identifies the science of materials as the root from which conservation practice grows.

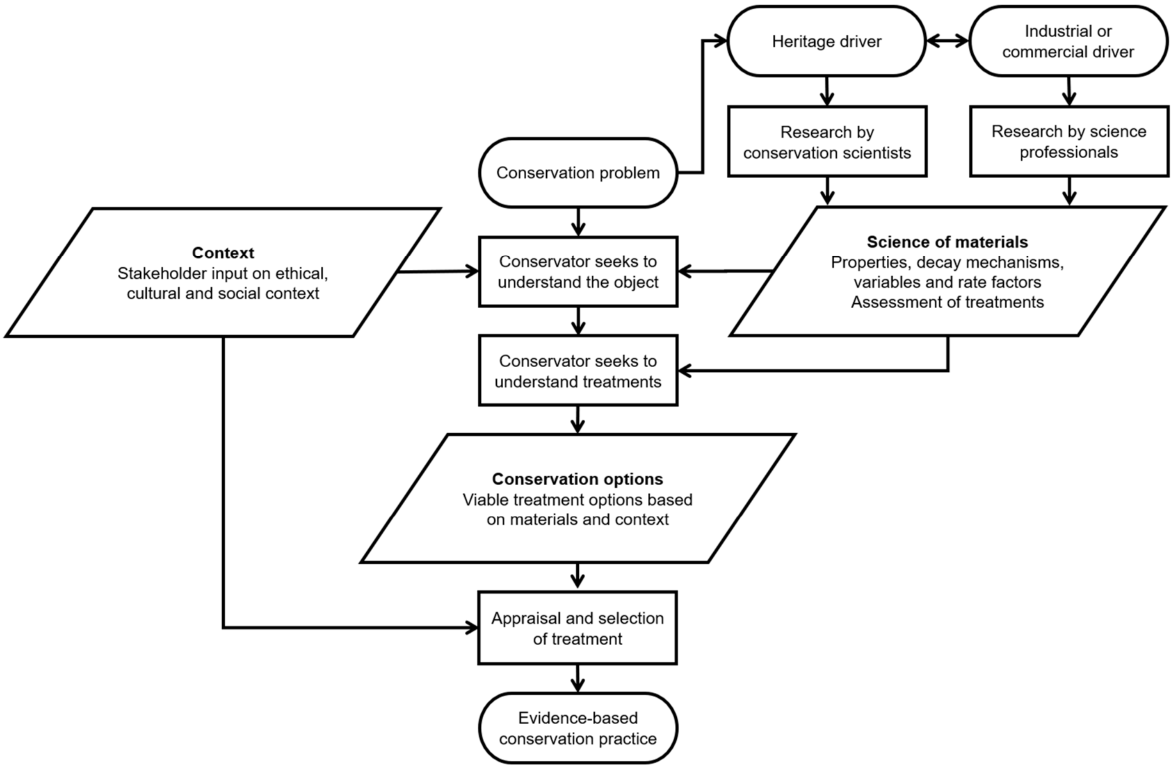

Figure 3. Flowchart showing scientific input for decision making in conservation practice.

The input of science to conservation must continually grow to evolve and improve evidence-based decisions in conservation practice. This is increasingly evident as the sector races to identify more sustainable practices in the face of a climate emergency. There is a growing urgency to provide alternatives to treatments that have been developed and evidenced over decades and only with the redeployment of science can conservation hope to meet this challenge.

There is a wealth of talent, knowledge and expertise available across sectors that could be directed toward conservation science, but the question of how to generate a strong and lasting pathway for connecting conservators, conservation scientists and science professionals remains. The ongoing development of science in conservation may be placed at risk by the reduction in the number of conservation science posts and staffing in established centres for research in conservation during the past couple of decades. A failure to grow science within the sector and create links to science outside of it places the ongoing development of evidence-based decision making within conservation practice at risk.

4. Heritage Science and Policy

The connections between heritage science and policy are many, and they have multiplied in number and deepened over the last decade. Heritage science is an applied discipline that generates new knowledge about heritage in order to make a real-world difference. In heritage science, evidence is always collected with the purpose of being used, which naturally leads the discipline towards decision making, interpretation, management and policy. The impact-led nature of heritage science is evidenced by the link to four "Societal Challenges" defined by the National Heritage Science Forum in the UK [74]. The relationship between heritage science and heritage policy is akin to medicine and health policy, or ecology and environmental policy. In other words, heritage can be seen as a national asset supported by government policies, which can be informed by evidence. This natural fit does not mean that connecting heritage science and policy is easy. Less than a decade ago, ICCROM identified the need to influence policy as a key area of development for heritage science [75]. Much has changed since. While there are areas for further development, there are clear indicators that heritage science is demonstrating its value to governments. To focus this analysis, here we adopt a practical definition of policy as 'statements of the government's position, intent or action' [76], as cited by [77]. This section summarises the main ways in which such statements depend on the research of heritage scientists, provides a few prominent illustrative examples from the UK, and concludes with future research challenges.

The government's interest in heritage has steadily increased over the past two decades. This is seen in Figure 4, which shows the number of publicly available documents on the UK government website that include the keyword "heritage". The search results encompass documents on services (n = 22), guidance and regulation (706), news and communications (3722), research and statistics (320), policy papers and consultations (395), and transparency and freedom of information releases (344). Visibly, the total number of documents that mention heritage published every year has been continuously increasing since the online availability of documents began (dark purple line). To account for potential biases due to varying rates of digitization during these decades, the figure also includes the same data but as a percentage of the total published documents each year (green line). Two main observations can be derived from this visualisation. Firstly, the frequency of documents mentioning heritage has never been higher and continues to increase. Secondly, the relative importance of the term shows two clearly differentiated waves, one that occurred in the period from 2010 to 2015, and one that began in 2021 and is still growing in 2024. While it is not the purpose of this research to examine the historical causes of these differentiated waves of interest, we can advance some preliminary hypotheses: the 2010–2015 wave coincided with some important changes in the heritage policy landscape, namely, the reconfiguration of English Heritage and the associated consultations, as well as the activity in the wake of the House of Lords report on heritage science [1]. However, there may be other external and internal factors influencing policy in this period, so this remains a matter for further analysis. A source of error that should be filtered in future analysis is the usage of the word "heritage" in irrelevant documents. For example, "heritage" can be part of the names of commercial enterprises, or mentioned in passing in policy documents that have a much broader focus. However, this makes up a relatively low part of the sample (in 2010, chosen randomly to test for this bias, less than 10% of the documents are irrelevant). We can take this dataset as a significant sample of the many ways in which the government states its position, intent or action on heritage. Our question, therefore, is how heritage science is used in these statements.

In the analysis of science uses in policy, three main forms of utilizing research are common, first listed by Beyer [78]. His research outlines that the utilization of science can be instrumental, conceptual or symbolic. Instrumental use involves the direct use of research findings in policy formulation. Conceptual use refers to using research in a more general way, for example, to frame issues rather than to inform specific policies. Symbolic refers to the use of research findings as a political or persuasive tool to legitimize or sustain predetermined positions. It can be argued that heritage science has been useful in these three ways, even though some further research would be needed to find exactly to which degree.

Instrumental uses are the most evident. For example, preventive conservation is a branch of heritage science that has the main objective of informing collection and environmental management. This type of instrumental use has a long history because as soon as evidence has existed to improve collection care, it has found its use in policy. A very early example is the testimony given to a Select Committee by the scientist Michael Faraday, who opined in 1850 on whether the National Gallery should be moved to the outskirts of London to protect its collection from 'inorganic fumes from chimneys and the organic miasma from the crowds' [79].

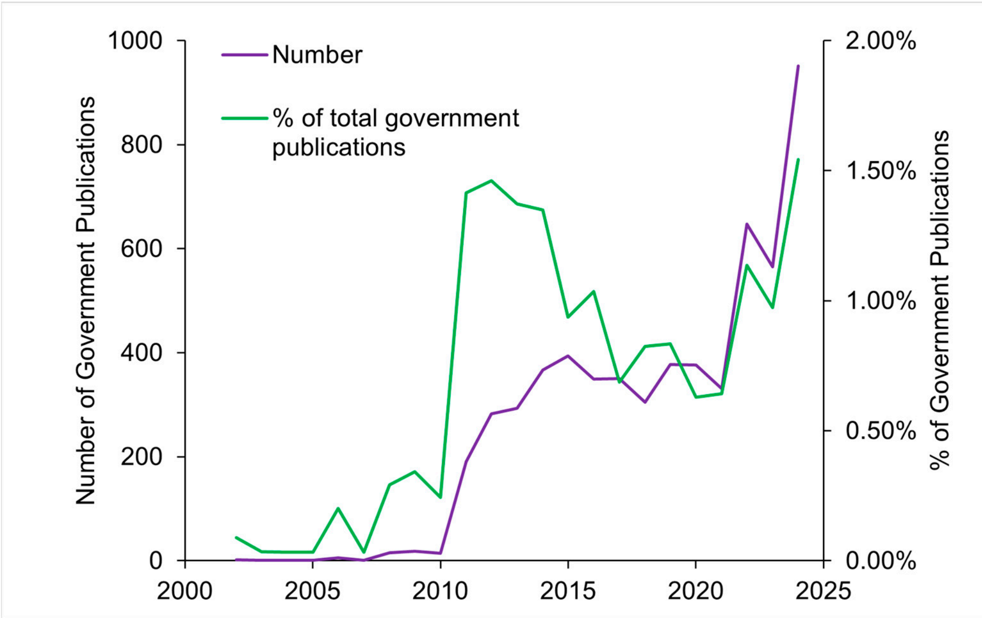

Figure 4. Number of publications containing the keyword "heritage" available on www.gov.uk accessed on 5 February 2024, in number of publications per year and as a fraction of the total available digital publications for that year.

To analyse the uses of heritage science in policy, it is useful to begin by unpicking the diverse forms of heritage science. Heritage science is a highly heterogeneous field that draws on methodologies and theories from a wide variety of disciplines and collects diverse data that are received by policymakers in different ways. For practical purposes, let us propose a simple division of the body of work of heritage science. While this division is reductive, it offers a practical structure to our discussion. The division we propose is in four levels of analysis:

- Molecular level: In other words, "objects under the microscope". This is the practice of heritage science that produces the largest number of peer-reviewed publications. Closely associated with technical art studies, conservation science and archaeological science, it involves the use of analytical chemistry equipment to obtain information about materials and artefacts. On the surface, it may be difficult (even to practitioners of this type of science) to imagine a connection between molecules and policy. But as we shall see, it is of considerable instrumental and conceptual importance.
- Degradation level: In other words, "heritage in its real management context". If we add a time dimension to molecular analysis, we enter the realm of the study of the dynamic change in materials. This branch of heritage science is concerned with degradation and ageing and, therefore, is particularly useful in informing collection management strategies.
- Environmental level: If we add a spatial and site-based dimension to the study of material degradation, we enter the domain of environmental risk. This area of heritage science focuses on the study of interactions between heritage and the atmosphere at different scales, from the local to the global. It involves a substantial component of modelling, mapping, risk assessment and comparisons of alternative scenarios.
- Social level: If we finally consider social interactions with heritage in addition to the previous considerations of material, time and space, we enter the domain of complex social systems. Heritage science at this level studies issues such as the perception of degradation by the public, the relationship between communities and the dynamics of their local heritage, and, more broadly, how heritage values relate to decision making.

Each level of this simple classification of heritage science interacts with policy in its own ways. Heritage science at the molecular level provides hard evidence or, more accurately, ensures the means to provide hard evidence about heritage. Such evidence is often a precondition to policymaking. For example, the 2018 Strategy on Conserving and Protecting Underwater Cultural Heritage in the British Antarctic Territory [80] is predicated on the existence of means to locate, document and assess the condition of heritage assets, in some instances at the limits of sensing technology. This specific document exemplifies a typology of policy that, while it may not directly refer to publications on material analysis, relies on the existence of active research in analytical technologies. Another case in point is any policy related to the repatriation of heritage [81], enabled by a clear understanding of origin and provenance that requires the support of scientific information. In both examples, the usage can be instrumental (by using science to establish the facts that enable the implementation of the policy), but it is more often conceptual. That is, policymakers rely on the fact that the relevant fact-finding methodologies exist and can be adapted to different needs.

Heritage science at the degradation level studies how heritage assets change, and therefore it has many instrumental applications, both in "capital P" policies (i.e., governmental) and "lowercase p" policies (e.g., institutional and organisational policies on the management of certain collections). A prominent example are the environmental guidelines for museums within the Government Indemnity Scheme [82]. This scheme provides affordable indemnity cover to cultural objects provided that exhibition conditions meet certain standards, which are based on the latest preventive conservation research. Another example of how this type of research informs legislation is the Heritage Protection Bill and associated documents such as the white paper "Heritage protection for the 21st century." [83]. These policy documents refer extensively to "evidence of damage" as a trigger for the development of new policy. Heritage science develops the tools to identify and monitor damage and, more importantly, the theories and vocabulary to interpret it. The definitions of key terms such as deterioration and damage used in heritage science research [84] are echoed in policy documents, such as the recent "Scoping Culture and Heritage Capital Report" [85]. This report is part of recent developments that centre on the ability of heritage science to predict future damage. The Department for Culture, Media and Sport (DCMS) has been utilizing heritage science within its Culture and Heritage Capital Programme. This programme aims to assess the value of culture and heritage assets through robust appraisal and evaluation. Heritage science is being integrated into this initiative to estimate the condition of physical assets, understand their sustainable usage, and articulate their economic impact more effectively.

Heritage science research at the environmental level has many policy uses, for example, in risk mapping and, most prominently, in relation to global warming. One of the most viewed documents in gov.uk in this area is The Climate Change Adaptation Report, prepared by Historic England and the English Heritage Trust [86] as a response to the third-round Adaptation Reporting Power call from the Government, as per the Climate Change Act 2008. It focuses on adaptation and includes hazard mapping results, initial findings of risks to the National Heritage List for England and actions that were adopted in the later Climate Change Strategy [87]. This strategy is predated by the Climate Action Plans of Cadw in Wales in 2020 [88] and the equivalent from Historic Environment Scotland [89]. These reports indicate the strong policy interest, in full force for a decade, in addressing the impacts of climate change on the environment and cultural heritage. This has naturally become an extremely active area of policy engagement, with multi-faceted connections between science and policy. In the UK, these links are created through specialist networks (such as the Climate Heritage Network), professional organizations (such as the Historic Environment Forum, which published the report "Heritage Responds" focusing on climate change) and the National Heritage Science Forum (which organised the Climate Emergency Deep Dive event in January 2024, updating the sector on the most recent research).

Finally, heritage science at the social level of study, displays a clear relationship with policy. Here, the government often participates in the collection of primary social data, with researchers providing conceptual frameworks for interpretation. A good proportion of the

320 documents categorised as "research and statistics" in gov.uk fall within the remit of this area of heritage science. For example, there are evidence-gathering reports on experiencing heritage (i.e., Experience of heritage by adults in Northern Ireland, 2016/2017), cultural engagement (Engagement in culture, arts, heritage and sport by adults in Northern Ireland 2022/2023, the multiple "Taking Part" surveys), and sociological research (The role of culture, sport and heritage in place shaping, 2017).

This preliminary analysis indicates that there are substantial instrumental and conceptual policy uses for heritage science. Further research is needed in the following areas: (1) exploring symbolic uses, their typology and importance; (2) understanding the historical evolution of policy interest in heritage, in particular the reasons behind the separate waves of interest in the UK, as well as studying similar global patterns; and (3) mapping the barriers to policy engagement that still exist in some domains of heritage science, such the physical sciences domain, which despite being proportionally the most productive, is perceived to have more indirect policy relevance.

5. Heritage Science: From Analogue to Artificial Intelligence

Digital technologies pervade almost all aspects of contemporary society, and the likely projected transformation is so significant that it has been termed the fourth industrial revolution (Industry 4.0). One area that is being transformed by Industry 4.0 is heritage science, with digital technologies gaining importance over the last few decades. Indeed, these are noted across an increasing array of applications [90,91], encompassing conservation maintenance, fabric repair, building operation and management, through to wider practice for documentation, architectural analysis and intervention [92,93]. In this section, we largely focus on these innovations within an architectural capacity. It must, however, be emphasised that these technologies and digitally oriented techniques are not limited to buildings and are indeed fundamental in many cases to artefact conservation, archaeology, library-based collections, etc. [94].

5.1. Classical Measured Survey, Analogue Photogrammetry, Early Adoption of CAD and Monitoring Technologies

Traditional measured surveys for historic building recording are time-honoured, with rudimentary onsite sketches being used to log hand-measured dimensions and information relating to structure and fabric [95]. These survey drawings would then be often utilised to create formal dimensionally functional drawings for recording purposes or for multiple other project management and design needs (e.g., adaptation and refurbishment, 'take-off' for bills of quantities, etc.). These manual surveys were logically a laborious undertaking with a high degree of error, had limited interoperability and were, in many cases, subjective [96]. Notwithstanding, some digital technologies have been utilised in the heritage sector for decades, with many applications evolving from classical approaches to building conservation management and practice [97,98]. A primary example is the adoption of computer-aided design (CAD) over the last 40 years (1982—creation of Autodesk) to produce architectural drawings. Over that period, CAD largely replaced hand drawing for the production of graphical documents relating to historic buildings.

In addition to manual hand-measured survey drawing, photographic techniques were used, including analogue photogrammetry and rectified photography [95,99,100]. These techniques facilitated the creation of scalable elevation drawings that were especially useful for large-scale complex masonry surveys, etc. While of great value, they were highly specialised, and the resulting processes still presented limited interoperability.

Beyond this, an array of monitoring sensors and supporting techniques have developed and are taking many forms. An important traditional technique was the use of 'tell-tales' for structural health monitoring. These were used to monitor structural movement in buildings specifically and enabled a basic assessment of progressive, dynamic 2D movement in structural elements to be ascertained. These 'tell-tales' were rudimentary glass slides or, in more sophisticated cases, calibrated plastic slides attached to the masonry surfaces with epoxy resins. Glass slides yielded limited information in so much as they would simply break upon movement and not relay information of the magnitude of the forces or 3D directional movement. Calibrated tell-tales would only give a measurable reading of the degree of movement in a 2D plane. Advances in calibrated 'tell-tales' were noted, and the introduction of vernier markers and linear variable differential transformers (LVDTs) that have been increasingly combined with data loggers were commonplace by the 1980s.

5.2. Development of Digital Survey and Monitoring Technologies

Laser scanning and digital photogrammetry (in particular structure-from-motion photogrammetry) have emerged in the last couple of decades and are now commonly employed in contemporary building conservation [101–105]. Laser scanning and structure-from-motion photogrammetry largely obviate the aforementioned hand-logged onsite dimensional survey. Indeed, they enable the rapid acquisition of dense 3D coloured point cloud data (which can then be converted into textured meshes) that capture the geometry (and appearance) of the surveyed scene with unprecedented accuracy and detail; indeed, high-profile examples of aerial LiDAR are associated with the large scale archaeological discovery of lost settlements in the Amazon and evidence of hitherto undiscovered temple complexes in Cambodia. Additional macro-scale use of digital technologies has been noted in the field of structural health monitoring (SHM) in assessing ageing infrastructure and buildings adopting satellite-based synthetic aperture radar interferometry (InSAR) combined with geographic information system infrastructure (GIS) [106]. Laflamme et al. [107] indicate that modern measurement technologies for SHM are developing apace, and these can be characterized under four primary areas: 'distributed embedded sensing systems, distributed surface sensing systems, multifunctional materials and remote sensing'. These facilitate data collection, analysis and ultimately actionable information for building performance relating to deterioration, deformation and wider condition assessment in structure, fabric and surrounding built environment contexts. Whilst satellite and GIS-based systems are becoming increasingly prevalent in large projects, embedded SHM sensors such as vernier markers and LVDTs for small-scale works are still frequently noted for cost efficiency and familiarity. These have themselves become more advanced and have moved from analogue to digital forms, adopting radio/Bluetooth connectivity to data loggers to ease installation and data retrieval.

Digital reality capture technologies are becoming increasingly more accessible, with some versions of these solutions even available on 'smart' phones. Yet, significant residual challenges remain related to the effective extraction of value (i.e., actionable information) from point cloud data. This issue has only recently attracted interest in the sector [108,109].

Additional prominent technologies that are increasingly utilised and are contributing to the increase in the acquisition of useful digital data of structures include ground penetrating radar (GPR), acoustic sensors, handheld XRF and borescopes. Of particular importance, data collected that relate to thermal, hygrothermal and moisture-related monitoring and performance, etc., are commonly sought. The logging of such data can be useful for diagnostics and to better understand the performance of the structure, linking the fabric with wider environmental conditions (rainfall, ambient air temperature, relative humidity, etc.). The capture of such data and subsequent logging required is often attained remotely.

For all of the inherent benefits of all of the cases outlined above, data interpretation has long remained essentially manual and smarter, and multi-modal and integrated analysis is the subject of research and development. Data processing in building heritage science is discussed further in Section 5.4.

5.3. Heritage Building Information Modelling (HBIM) and Digital Twinning

Digital surveying (also known as reality capture), and in particular dense 3D point cloud acquisition, has been critical to the start of a more holistic digitalisation journey, which is often referred to under the umbrella terms of building information modelling (BIM) and now increasingly digital twinning (DT).

Building information modelling (BIM) is "the [collaborative] process of generating and managing information about a building during its entire life cycle". At the heart of BIM is the building information model (BIM Model). A BIM Model is a digital semantically rich representation (generally with a 3D model) of the building or infrastructure asset. The systematic structuring of BIM Model data (in particular when conforming with international OpenBIM standards) facilitates interoperability. Historic BIM (HBIM) is commonly used to refer to the application of BIM methodology in the context of historic buildings. While fundamentally identical to BIM, the term is used to highlight inherent challenges to model information in such contexts, where physical elements may not have regular shapes or 'standard' information representation are not suitable to capture the variability and complexities often experienced in that context.

The reality capture data (3D and colour) acquired by laser scanning and structure-from-motion photogrammetry (see Section 5.2) have proved to be ideal for the production of HBIM models of existing buildings [97,110–113], with users adopting the point cloud data as underlay from which they can manually model the different elements composing the asset. This process, commonly referred to as scan-to-(H)BIM, has certainly transformed modelling capability in the historical and heritage built environment, but it remains a tedious manual process with significant challenges, and potentially delivers models lacking the level of granularity necessary for certain applications [114]. For example, conservation and maintenance may need to be able to identify individual stones in some building façades, something that standard BIM authoring tools do not enable [93,115].

Digital twinning (DT) can be seen as an extension and generalisation of the BIM concept. Similarly to BIM, it relates to digitalised processes based on structured digital data representing the 'twinned' object or asset. However, DT extends this by embedding the concept of bi-directional data flows between the physical object and its digital twin with the vision that they ensure that any change in the physical object, captured with sensors, is reflected in the digital twin for effective decision making, with the resulting actions digitally communicated to possibly alter the state of the physical object through the use of automatic actuators [116–118]. It should be highlighted that the concept of DT is not specific to the built environment and in fact emerged from the manufacturing sector. DT can thus be applied to buildings, statues, paintings, etc., alike. Prominent applications of digital twins in the context of historic buildings include comfort (lighting, humidity, temperature) [119–121] and energy optimisation in buildings [122–124] or bridge operation management-based load/structural monitoring [125,126].

5.4. Data Processing Technologies: The Rise of Artificial Intelligence

Traditionally, survey and monitoring sensor technologies for evaluating conditions and performance were disparate in nature. They had limited integration capability with other techniques, and the data outputs were often analogue. Conversely, as discussed in Section 5.2, today data collected regarding the performance of historic buildings are increasingly digital in nature. While the analysis of these data was initially and long remained manual, computer algorithms are progressively being developed to accelerate, scale up and objectify the extraction of useful, actionable information.

At first, traditional signal analysis methods were considered, such as Fourier analysis for frequency analysis, simple thresholding, or change detection between data from two epochs. For example, change detection in successive epochs of digital 3D reality capture data can help structural health monitoring by visualising holistic three-dimensional displacement [107] in conjunction with advanced LVDTs. However, data interpretation in this case has remained essentially manual.

However, the last 20 years have seen the emergence of artificial intelligence (AI), with machine learning being the precursor of deep learning, which is now prominent, with algorithms capable of complex pattern recognition and inference. For example, ML and now DL algorithms have been proposed for detecting defects in visual and 3D data of building fabric [127–129] (see Figure 5). Supporting ML/DL algorithms have also been explored for automating the supporting task of segmenting reality capture data (images or point clouds) of a structure semantically into its different elements or materials in order to enhance scan-to-HBIM modelling and ease the task of defect detection [114,130–133] (Figures 5 and 6).

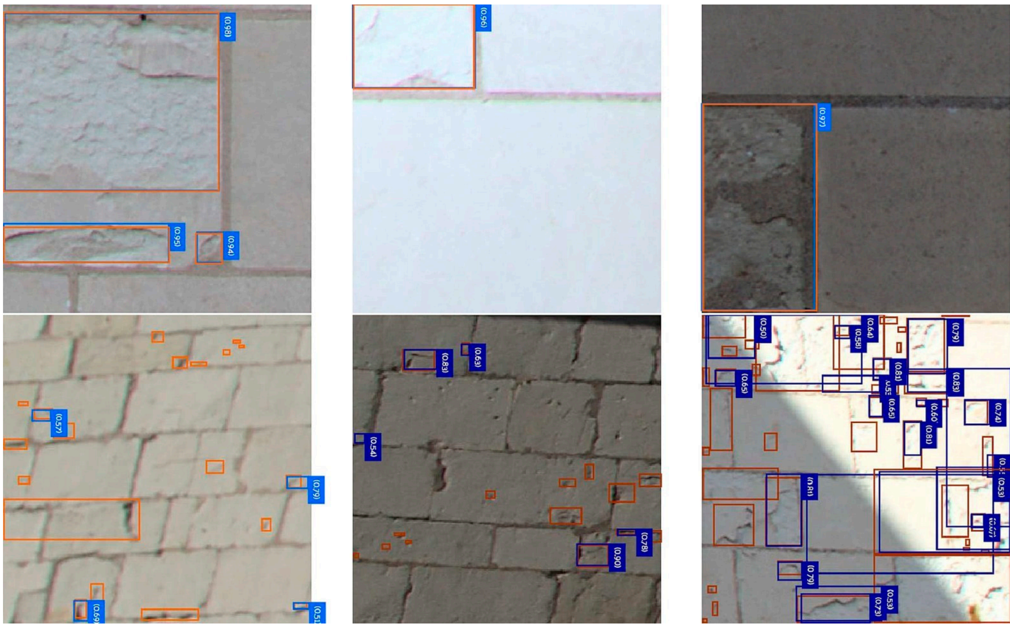

Figure 5. Detection results of the proposed network on some test set images. Ground truth bounding box in red and predict bounding box with confidence in blue. First row: examples of best precision; second row: examples of bad precision. Reproduced with permission from [128].

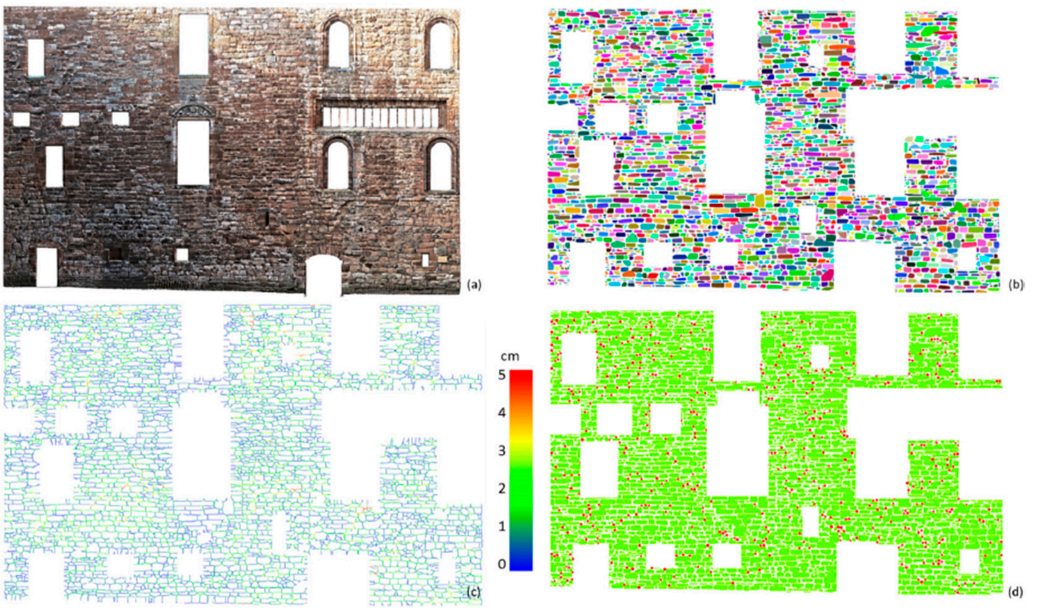

Figure 6. Linlithgow Palace courtyard west wall. (**a**) Three-dimensional coloured point cloud. (**b**) Algorithmically derived automatic segmentation of rubble masonry units from the Linlithgow Palace point cloud. (**c**) Automatic mortar regions and mortar recess depth analysis. (**d**) Mortar regions with large joint sizes denoting pinning/gallet requirements. Taken from Valero et al. [93], Reproduced with permission.

Similar advances are being made in the domain of GPR data processing [134], fibre Bragg grating (FBG) network data processing [135] and acoustic emissions (AEs) analysis [136].

5.5. Robotic Applications for Heritage

The drive for robotic applications in heritage is largely associated with monitoring with the deployment of sensor technologies, and technologies for materials reproduction (see computer numerically controlled (CNC) robotic applications).

For small-scale, moveable heritage objects, the deployment of robotic solutions for conservation has seen significant progress over time, with solutions like CultLab3D able to automatically capture and integrate multi-modal data (geometry, texture and physical–optical material attributes) to create truthful reproductions with micrometre precision.

In the context of heritage buildings, the inherent complexity, size and bespoke nature of the vast majority of historic structures have rendered most of the robotic platforms currently available of limited use and difficult to deploy. Indeed, most robotic platforms are noted in the context of contemporary construction and architectural forms that are more likely to be characterised as being relatively homogenous and uniform in external form relative to historic buildings (e.g., climbing robots with vacuum/suction mechanisms [137,138]. That said, unmanned automated vehicles (UAVs) have been successfully used for attaining digital reality capture data from heights [139] and in confined spaces [140,141] (Figure 7). However, although drones have been used for decades, the range of sensors that can be deployed has remained limited due to the combination of limited payloads and the lack of drone solutions that make contact with surfaces in a controlled manner (which would be required for the deployment of a range of other sensors).

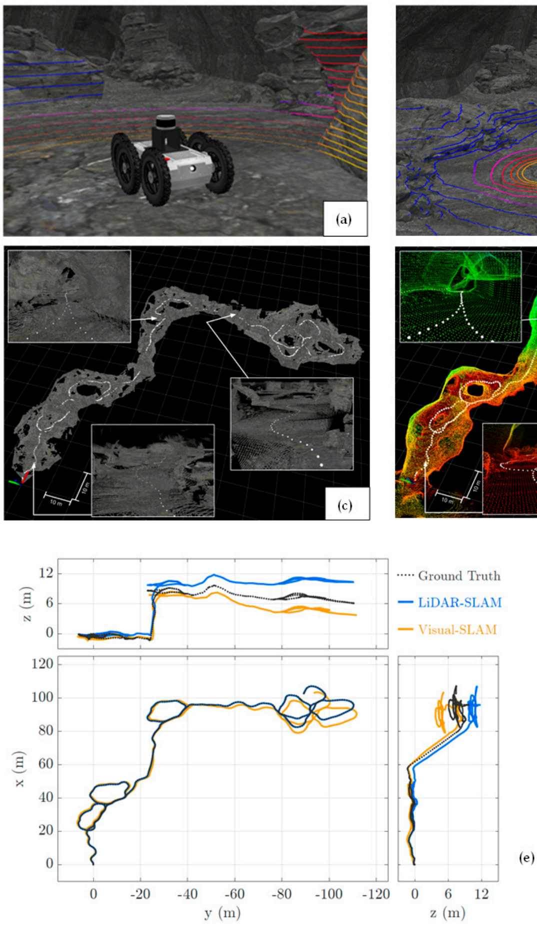

Figure 7. Experimental setup with CoppeliaSim simulator. (**a**) Simulated EspeleoRobô with LiDAR. (**b**) Inside view of the cave environment. (**c**) Visual-SLAM point cloud mapping results and visualization in a simulated DAPRA cave scenario. (**d**). LiDAR-SLAM point cloud of the same. (**e**) Odometry estimation of both methods. Taken from Azpúrua et al. [140], reproduced with permission.

Aside from robotics for sensing, increasingly sophisticated cutting technologies have been noted in stone reduction processes in quarries. The production of 'dimensional' stone (sawn on six sides) has enhanced productivity in conservation masonry applications [142]. More recently, advances in digital reality capture twinned with computerised numerical control (CNC) robotic routers have led to accurate reproductions of architectural carved enrichment elements, sculpture and artefacts [143] (Figure 8). These can be produced in an array of material types and will be potentially transformational in terms of productivity and cost efficiency these techniques.

Figure 8. A reproduction of Canova's Cupid and Psyche starting from a 10-ton block of white Carrara marble by the Robotor system. Reproduced with permission from [143].

Innovation is also noted in construction automation for new-build applications such as full-scale mortar printed structures and an array of automated construction processes, including, amongst others, masonry bricklaying and blockwork laying. However, these technologies have not meaningfully permeated into the historic built environment to date.

5.6. Shaping Other Disciplines

While the growth in digital solutions and robotics in the heritage sector is certain, some challenges will remain that we explore in this section. Some of these are general to the use of those technologies, while others are more specific to the heritage sector.

Within the context of facilitating connection within an often fragmented heritage science sector, the European Research Infrastructure for Heritage Science (E-RIHS) was established in 1999. This digitally oriented EU-funded project has a mission statement that is predicated upon safeguarding heritage by connecting people, creating open access to information, and sharing common strategies and practices that aid effective conservation (https://www.e-rihs.eu/; accessed on 5 February 2024). The touchstones of 'Developing, Connecting Creating and Safeguarding' are supported by the Programme and fundamental major platforms under the umbrella of IPERION HS (integrated platforms for EU research on HS) have been developed that include 'ARCHLAB (access to organized scientific information/datasets), DIGILAB (Digital Laboratory), FIXLAB (access to fixed state of the art laboratory equipment and staff) and MOLAB (Mobile Laboratory)'. E-RIHS supports digitally progressive applications for conservation, with interoperability being seen as critical to the organisations' success. Structures such as E-RHIS, which are multi-disciplinary and multi-national in nature are logically much welcomed and reflect the complex needs of an increasingly technological heritage sector.

Innovation in sensors, logging and analysis has the potential to link the data to the model—the twinning can have many benefits, such as triggering the right time maintenance intervention, understanding energy performance, etc. It must be recognised that data collection, analysis and storage are not cost-free, and data collection for the sake of it can be a drain on resources. A realistic assessment of how much data is required and its ultimate use is important. Indeed, considerations of storage, security and ensuring digital permanence are all important factors when developing digital solutions.

Artificial intelligence, particularly current developments in deep neural networks, is revolutionizing data analysis, decision making and communication. The incredible speed at which AI is developing is both exciting and concerning in general, as well as in the specific context of heritage science. Alongside new sensor capabilities, AI will enable professionals to gain an understanding of the condition of heritage artefacts and make better-informed decisions. AI and wider applications of digital technologies also raise concerns related to copyright protection and wider issues of authenticity when historic architectural components become increasingly easy to reproduce and indistinguishable from the original fabric [144].

As discussed earlier, while robotics is rapidly emerging in the construction industry, it remains focused on the new build sector. In the context of heritage, significant barriers are impacting its uptake, associated with the inherent complexity of historic structures. For change to occur, robotic solutions will have to be developed that are capable of navigating in various environments, composed of different types of materials (e.g., brickwork, stones) and with complex and varying geometries. Development in AI alongside novel robotic platforms (e.g., soft robots) will undoubtedly contribute to support such developments. Notwithstanding, like in the new-build sector, solutions will likely first emerge to support inspection and monitoring, while solutions dedicated to conducting actual maintenance or repair works are likely to develop upon technology maturation.

Finally, whilst being potentially transformational in terms of productivity and cost efficiency, robotic technologies such as CNC and 3D printing machines create concerns relating to specific aspects of building conservation philosophy, given the ability to reproduce almost identical copies that may be indistinguishable from the original fabric. Such issues are central to building conservation and were indeed at the heart of the development of what we see today as modern building conservation. These form the bedrock of philosophical debate on fabric intervention and design, and considerations on legibility, indistinguishability, respect for patina, honesty and integrity have become enshrined in subsequent successive publications of international conservation charters and philosophical frameworks [145–147]. Of particular note in this philosophical journey was the battle between the 19th-century 'restorers' and 'conservative repairers' that was borne out of issues of conjecture in architectural element and scheme reinstatement, and indistinguishability in fabric repair [148]. Bell [147] discusses the 'Restorers' with specific attention given to Viollet-le-Duc (French architect and arguably the most famous proponent of restoration). Bell [147] highlights that (restorers) 'held the principle of l' unite de style when working on ancient buildings. It followed Viollet-le-Duc's definition of restoration—to restore a building is to bring it back to a state of completeness which may never have existed at any given time. The "Restorers" valued aesthetic and structural consistency, a complete, even if deceptive, image above all, and therefore maintained that every building and every one of its components should be reconstructed, re-created or completed in its predominant style as a creative act. To them, the value of the new appearance of their design was well worth the distortion of historical evidence, the loss of aesthetic integrity and the eradication of all the visual and emotional qualities that genuine (or authentic) age brings with it'.

Conversely, there were proponents of 'conservative repair' such as John Ruskin (19th-century philosopher and writer) and, later, William Morris (19th-century artist, writer and political activist). Such was the concern regarding 'conjectural restoration' and the potential for falsification in the historical record that Ruskin stated, 'Let us not talk of restoration; the thing is a lie from beginning to end' [149]. The logical argument was that the need for 'incontestable documentary or physical evidence' must be present before 'restoration' can be substantiated, and pre-digital-reality-capture, this was rarely present (with the potential exception of classical pattern book applied architectural schemes). Indeed, digital reality capture creates a robust foundation for 'incontestable evidence' for the recorded building or artefact and therefore supports the notion of 'recreating elements and components with no conjecture. This may be defensible, but the creation of an identical reproduction of a component does not help reconcile the issue of indistinguishability between new and old fabric. This situation is well-documented in the 'Ship of Theseus' thought experiment, which asserts that if every individual piece of a ship is replaced, and looks identical to the original, is it the 'same' ship or simply a new reproduction? Indeed, this paradox could be argued to be exacerbated by digital applications, given that reproduction will increasingly become indistinguishable given the advances in digital techniques. When seen through a 'Ruskinian' lens, it could be argued that we are potentially entering into a 'golden period of deceit?', one in which we cannot differentiate fabric and therefore increase the likelihood of falsifying history [144].

In addition, wider concerns have also been raised with respect to the implications for the reduction in traditional craft skills (such as stone carving) and the loss of intangible cultural heritage [144,150,151]. This is of fundamental importance, and again, these are enshrined in the international charters and philosophical frameworks that direct considerations of defensible conservation. The ability to recreate artefacts without human hands deviates from the almost universal assertion of the aspiration to 'respect traditional materials and craft skills'. Whilst the materials element may be satisfied, the obviation of craft skills is of grave cultural concern. Examples of such tensions include the support for traditional Japanese techniques and craft skills in which individual master craft workers (holders) are given statutory protection and are government-funded to reduce the likelihood of loss of the passing on of intergenerational craft knowledge. It is clear that dialogue is required in this space to ensure that effective protections are given to craft workers so that centuries of iteratively developed knowledge are not lost.

6. Conclusions

Here, we have considered the impact of heritage science on a range of other specialisms. We have considered the past, not only in terms of the development of heritage science as a discipline but also in terms of how heritage science has helped us better understand the history of places, structures and objects. It is somewhat unique in that this discipline ranges from molecular science at the nanoscale [152] to cityscapes [153]. It is an increasingly useful and powerful tool to confirm or challenge historical narratives.

We have examined the impact that heritage science has on conservation, evolving and developing over decades to become the thriving, innovative discipline it is today, capitalizing on the myriad of advances in technology and understanding that heritage science offers.

Likewise, in terms of the present, we have explored how heritage in general, and heritage science in particular, is playing a rapidly increasing role in the formation of policy at governmental, institutional and organisational levels.

Finally, with a view to the future, we have examined how heritage science is moving into the digital age with the rapid advances in remote sensing, machine learning, artificial intelligence and robotics. Indeed, heritage science is firmly within the 4th digital industrial revolution.

What we can conclude from these collective studies is that heritage science is not a fledgling or niche discipline but is in fact a thriving, expanding and rapidly evolving field of research that has linkages far beyond what has traditionally been considered heritage.

Author Contributions: Conceptualization, C.J.K. and A.M.F.; writing—original draft preparation, C.J.K., M.P., D.W., N.E., D.T., F.B., A.M.F., J.G.-B. and M.C.; writing—review and editing, C.J.K.; visualization, C.J.K. and M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analysed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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