Taylor & Francis
Taylor & Francis Group

International Journal of Architectural Heritage
Conservation, Analysis, and Restoration

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/uarc20

Data-Driven Multi-Scale Study of Historic Urban Environments by Accessing Earth Observation and Non-Destructive Testing Information via an HBIM-Supported Platform

Georgios Artopoulos, Paris Fokaides, Vasiliki Lysandrou, Marissia Deligiorgi, Panos Sabatakos & Athos Agapiou

INTERNATIONAL JOURNAL OF ARCHITECTURAL HERITAGE
https://doi.org/10.1080/15583058.2023.2199408

Taylor & Francis
Taylor & Francis Group

RESEARCH ARTICLE

OPEN ACCESS Check for updates

Data-Driven Multi-Scale Study of Historic Urban Environments by Accessing Earth Observation and Non-Destructive Testing Information via an HBIM-Supported Platform

Georgios Artopoulos [a], Paris Fokaides [b], Vasiliki Lysandrou [c], Marissia Deligiorgi [a], Panos Sabatakos [d], and Athos Agapiou [c]

[a]STARC, The Cyprus Institute, Nicosia, Cyprus; [b]School of Engineering, Frederick University, Nicosia, Cyprus; [c]Department of Civil Engineering & Geomatics, Cyprus University of Technology, Limassol, Cyprus; [d]HIT Hypertech Innovations, Athens, Greece

ABSTRACT

Digital analytical tools combined with 3D documentation are used incrementally in building rehabilitation in the conservation state analysis process. In the last decade, due to the current advancements in the Architecture Engineering Construction (AEC) industry, the application of BIM methods in heritage building conservation started becoming more attractive for specialists and practitioners. In light of the latest concepts in data management at city level, as a result of the discussion about smart city representations, the use of a shared digital environment that caters to technical studies related to conservation analysis, building provenance, structural changes, and urban context transformations can lead to reduced time, improved quality, and lowered cost of city management for all domain experts and city stakeholders. This paper explores the benefits of multi-scale and discipline digitization for the restoration of heritage buildings, highlighting the potential impact of innovative data integration, methods, and workflows on architectural renovation and energy upgrades. Specifically, it focuses on the integration of conservation information for heritage buildings and large-scale environmental analysis data for historic clusters in modern cities.

ARTICLE HISTORY
Received 16 December 2022
Accepted 23 March 2023

KEYWORDS
4D spatial data management; digital twin of historic clusters; heritage building information modelling (H-BIM); LCA; NDT; online BIM; remote sensing

1. Introduction

The renovation industry accounts for 57% of Europe's total workload of architecture operations (Mirza & Nacey Research Ltd, The Architects' Council of Europe 2021). Arfa et al. define the adaptive reuse of heritage buildings as "a complex process, which aims to preserve the values of heritage buildings while adapting them for use in the present and transferring them to the future" (Arfa et al. 2022). The European Commission has set the adaptive re-use of heritage buildings as one of the main pillars of its framework for action on cultural heritage, announced in 2018 (European Commission 2018). The significance of the unprecedented opportunities provided by digital technologies in the preservation and restoration of physical heritage assets is also acknowledged (European Commission 2011). According to a report of the Building Performance Institute Europe (Dol and Haffner 2010), 37% of the buildings in southern Europe were built before 1960. This justifies the significant opportunities associated with preserving and re-using the heritage building stock. Heritage buildings, considered hereafter as any structure built before the period between 1945 and 1981 (depending on a country's specific legislation), represent arguably the most challenging part of a city's building stock in a process that intends to update the building sector, due to the many architectural and aesthetic constraints involved in protecting their character during conservation and renovation operations (EP 2010).

The use of Industry 4.0 practices, like Building Information Modelling (BIM), in the service of heritage buildings restoration and renovation, may constitute one of the responses of the construction industry to the challenge of the sustainable management of heritage buildings. Recent developments in BIM suites respond to the need for streamlined data curation and the exchange of data between the various disciplines involved in construction, that now can be achieved using a Common Data Environment (CDE) (Preidel et al. 2018). The introduction of a CDE in the architectural workflow is considered a major step towards digitalising the collaborative operations with

CONTACT Athos Agapiou athos.agapiou@cut.ac.cy Department of Civil Engineering & Geomatics, Cyprus University of Technology, Limassol, Cyprus
This article has been corrected with minor changes. These changes do not impact the academic content of the article.

engineers. Through the centralized management of data, as well as the integration of information and data streams, the enormous amount of information stored in models and objects can be consistently synchronized and simultaneously accessed. Currently, there are many efforts of employing BIM and smart digitization practices, in the form of Heritage BIM (HBIM) workflows, in the heritage field (Yang et al. 2020). HBIM method is about linking metadata of historical, conservation data acquired through 3D documentation and onsite observation to parametric models and representations of the building (Antonopoulou and Bryan 2017). BIM allows for the integration and accessing of all building data necessary for the conservation, management, design and maintenance activities (Martinelli, Calcerano, and Gigliarelli 2022). Multidisciplinary applications include structural analysis (Dore et al. 2015), historical and architectural analysis, as well as environmental and energy analysis (Brumana et al. 2017). More specifically, the integration of detailed geometric information linked with simulation results (e.g., building energy performance simulation and design scenarios simulation) can assist collaboration, decision-making and management during interventions help with the design of the building and its systems (Gan et al. 2019). BIM representations of heritage buildings linked with all relevant analysis datasets and cost information can support efficiently any conservation or retrofit construction operation (Lee and Kim 2017). Today, HBIM is accepted in managing multi-discipline datasets to enable in-depth studies of a building's historical and material conditions (Cursi et al. 2022). Specifically, HBIM is employed to enhance collaboration between different disciplines, providing shared access to several analytical methods used in the study and rehabilitation of architecture, including its use for building diagnostics (Bruno et al. 2019) and historical and architectural analysis (Masciotta et al. 2021). That is, through the use of 3D visualization of design scenarios about building retrofit operations all the stakeholders of the process that are engaged can better communicate and agree on the options to be implemented, a highly significant task for heritage buildings which are subject to limited opportunities for reuse and renovation due to conservation laws, safeguarding the integrity of cultural heritage.

Major challenges in modeling a heritage building in BIM software tools involve the complexity of representing its geometry and construction irregularities, and lies in semantically structuring information of its material condition, historical phases, etc. (Radanovic, Khoshelham, and Fraser 2020). More specifically, the following main challenges are identified by the authors for the broader use of HBIM in the field:

(1) Data management: The variety of data types and complexity of heritage buildings (geo-metric complexity, structural irregularity, material condition) require effective modelling and data management strategies, for interoperability, to facilitate the integration of different data sources in the HBIM dataset.
(2) Integration of non-geometric data: HBIM methods focus on the integration of multiple discipline, oftentimes non-geometric data, including historical, cultural, and environmental data, which poses significant operational challenges due to the heterogeneity of said data sources.
(3) Scalability and sustainability: any BIM dataset repository need to be flexible and user-driven to allow for future sustainability through data enrichment. This requirement poses significant challenges in terms of data structuring, processing, visualization, and user authentication.
(4) User acceptance: The adoption of HBIM by heritage practitioners and stakeholders is critical to its penetration to the community as a good practice for building conservation and rehabilitation. User acceptance can be challenging due to a lack of awareness, training, and technical expertise, as well as concerns over data ownership, privacy, and security.

Historic England (2018) highlights the benefits of a holistic approach in understanding the building asset within, among other aspects, its surrounding environment, for devising an energy efficiency strategy in a more balanced way. In this context, state-of-the-art methods of material provenance and characterization and degradation should be employed to support conservation and refurbishment interventions (Bruno et al. 2019). Nowadays, various efforts are emerging in the literature occupied with studying a building within its environment though digital platforms that provide access to integrated building datasets (Logothetis et al. 2018). Operating at building scale, there are platforms that rely on parametric HBIM representations to facilitate heritage studies and conservation (Diara and Rinaudo 2021; Malovrh Rebec, Deanovic, and Oostwegel 2022). At the same time, various digital platforms focus on 3D modelling and real-time simulation of urban environments and architecture, integrating geolocated information with procedurally modelled representations of the city neighbourhoods or remote sensed 3D reconstructions. For example, notable efforts have focused in integrating GIS and BIM datasets to link 2D data, 3D parametric representations of building elements and geoinformation utilising an HBIM approach (Vacca et al. 2018). More recently, the ENCORE platform, a result of EU H2020 research (ENCORE CONSORTIUM 2021), provides a sophisticated online interface to BIM models of procedurally generated building types, enabling access to building information, monitoring of building structure through reality capture techniques and semantically enriched metadata of building information.

Despite the numerous efforts to innovate in the field of 'scan to HBIM' tools (Pepe et al. 2021), as well as in semantic structuring of information and Geographic Information System (GIS) connectivity (Barazzetti 2021), a systematic review of the literature highlights more challenges that need to be addressed when trying to integrate HBIM and other information techniques practiced in engineering disciplines. Specifically:

- A significant gap lies in the integration of information about quantitative non-destructive techniques (NDT) for the diagnosis of heritage buildings into HBIM workflows (Tejedor et al. 2022);
- There is hardly any evidence in the literature on the integration of environmental analysis data retrieved by Earth observation satellite imaging into online platforms that host HBIM building datasets;
- Despite the fact that BIM-to-Life Cycle Assessment (LCA) techniques have reached maturity, represented by numerous studies and even commercial software (Panteli, Kylili, and Fokaides 2020), there is currently no discussion in the literature related to the integration of whole building LCA into HBIM workflows that provide access to datasets through online platforms.

Recognizing these important gaps of existing online platforms, this study introduces the PERIsCOPE's project vision, to develop a portal for heritage buildings. This is achieved by integrating into the contemporary built environment, a novel HBIM-supported platform with advanced operations (PERISCOPE 2020).

Implementing good practices (Historic England 2018), the research addresses the gaps identified above by bringing information about the material condition of heritage buildings together with environmental data (by mans of earth observation analysis), which is one of the categories of information used in conservation state analysis practices, to enable the holistic study of a parametric, semantically enriched, representation of cultural heritage (by means of HBIM) within its environment. Observing at a neighbourhood scale, current techniques used for capturing structural and geometric information about historic clusters (Haala and Rothermel 2015) include airborne, terrestrial laser scanning and photogrammetric documentation methods that produce diverse quality of 3D data. Data fusion of the datasets produced by these reality capture methods provides a reliable set of geometric descriptions for generating the appropriate database that enables contextualising building-scale information within the urban environment. This 3D representation of the urban environment is necessary for hosting useful information regarding the rehabilitation of buildings, including information about environmental conditions produced through earth observation methods, as introduced below. This article presets how for example, the integration of said datasets can offer insights to the study of weather-related material damage of built structures. Naturally, enabling access to all these datasets with the support of a GIS-enabled platform that can assist in user queries (including land use and change detection in monitoring of the historic urban fabric) is an added value for the sustainability, interoperability and re-use of the online platform presented.

PERIsCOPE platform integrates enhanced layers of information including satellite imaging, NDT measurements and LCA indicators, with the aim to extend the field of applications of HBIM-supported platforms. In this study, a brief overview on the state of the art concerning the exploitation of the proposed techniques for the assessment of heritage buildings, as well as on the current state of development of online platforms, is presented. The procedures followed for the retrieval of the enriched set of information and indicators, as well as on the practices for their data integration and presentation, are discussed. This article aspires to expand the scope of online HBIM-supported platforms, by enhancing their applications with additional scales of data and analytical tools, initiating a scientific discussion on further options that may be provided through better data interoperability.

2. Materials and methods

Earth observation for monitoring cultural heritage sites and landscape has been widely adopted in the last years. The distribution of open access satellite datasets, the capability of capturing multispectral submeter resolution images as well as big-data image processing advancements have driven scientific research towards to more detail and advanced applications for heritage studies (Agapiou and Lysandrou 2019; Luo et al. 2019). Indeed, multitemporal satellite datasets have been used in the past to map land-use changes around heritage sites and clusters, mapping therefore significant threats (hazards) (Cuca 2017), while the use of thermal sensors has been already suggested in the past for capturing thermal anomalies over large areas, including areas with heritage interest, linked also with micro-climatic conditions such as the urban heat island phenomenon (Meng et al. 2019). Despite the plethora of applications, the use of HBIM as a method of correlating the information from space to ground has been already acknowledged (Rodríguez-Gonzálvez et al. 2017) but rarely applied. This should be linked to the rather different scales of observations that are usually employed for heritage buildings from ground or low altitude sensors (i.e., few centimetres resolution) compared to the macro-scale of observation that a satellite can offer.

Non-destructive techniques (NDT) constitute any of a wide group of analysis techniques used in the building industry to evaluate the properties of building materials and elements, without causing any damage (Hellier 2003). It is self-evident that in the case of heritage buildings, where no rigid information concerning the building materials and structural details may be available, the choice of NDT for assessing the structural and thermal features of the building, is the only alternative. According to the literature, the most widely used NDTs in the building sector are Infrared Thermography (IRT), Ground Penetrating Radar (GPR), Light Detection and Ranging (LiDAR)/Laser Scanning, Ultrasound, Close-Range Photogrammetry and Through Wall Imaging Radar (TWIR) (Artopoulos 2020). Especially the Infrared thermography (IRT) has met an extensive popularity in the recent years among the NDTs for building diagnostics, mainly due to the raising concerns related to the improvement of the energy efficiency of the building sector (Kylili et al. 2014). The information required for the implementation of a quantitative IR thermograph includes the emissivity factor of the building materials, the reflective temperature of the environment, as well as the atmospheric conditions, namely the ambient temperature and relative humidity (Fokaides and Kalogirou 2011). To the best of the authors' knowledge, as of today, there is no remote sensing technique that can define the required surface properties of building materials in such an accuracy that allows the extraction of reliable results. In order to accomplish consistent building diagnostics using aerial IRT scanning, extended post processing of IR images is required, which though does not deliver the same quality of results as red-green-blue (RGB) images (Rekha, Sreenivas, and Kulkarni 2018). The flightpaths of unmanned aerial vehicles (UAV) technologies also affect buildings' facade reconstruction accuracy as well as the detection of heat losses (Lin et al. 2018). To this end, despite the progress in the field of UAV IRT scanning (Dabetwar et al. 2022), as of today, onsite in situ buildings IRT constitutes the most reliable approach for buildings NDT. There is still no evidence for the integration of NDT measurements into HBIM-supported platforms, despite the progress in both fields, and the widespread application of NDT for assessing the structural and thermal conditions of heritage buildings (Tejedor et al. 2022).

Life Cycle Assessment (LCA) (International Standardisation Organisation (ISO) 2006) is established as the main technique for assessing the sustainability of whole buildings. Whole-building LCA combines the mass-specific environmental indicators of the individual buildings' materials and the bill of quantities of a building (Kylili, Ilic, and Fokaides 2017). Inevitably, both information may be extracted by a BIM document. The whole building LCA may be extracted by analysing a BIM document and linking the individual materials to Environmental Product Declarations (EPDs) (Panteli, Kylili, and Fokaides 2020). Recent evidences reveal that LCA may be a useful tool for the quantitative assessment of environmental, economic and social impact of restoration process, as well as for the identification, prioritization and engagement of stakeholders at the restoration, conservation and valorization process of heritage buildings (Blundo et al. 2018). Integrating LCA indicators into an online platform would certainly facilitate access and enhance design scenarios for the restoration of heritage buildings.

2.1. Research workflow

The presented online platform is supported by using satellite remote sensing processing and digitization methods to enable better decision-making (Xiao et al. 2018) through a user-friendly HBIM-supported digital environment. The presented workflow (Figure 1) is developed driven by the study of two pilot study areas (historic clusters that are challenged by urbanization), located on the island of Cyprus (35.1264° N, 33.4299° E, WGS). The selected areas allowed the implementation of a comparative understanding of the impact of climatic conditions on construction materials. A number of heritage buildings in these areas were selected by an expert committee, comprised of academics in conservation science, architects, historians of architecture, representatives of professional bodies, such as ICOMOS Cyprus, also engaging the competent officers of the local authorities. The pilot heritage buildings were identified based on the following criteria: architectural value; historical value; location; typology; ownership;

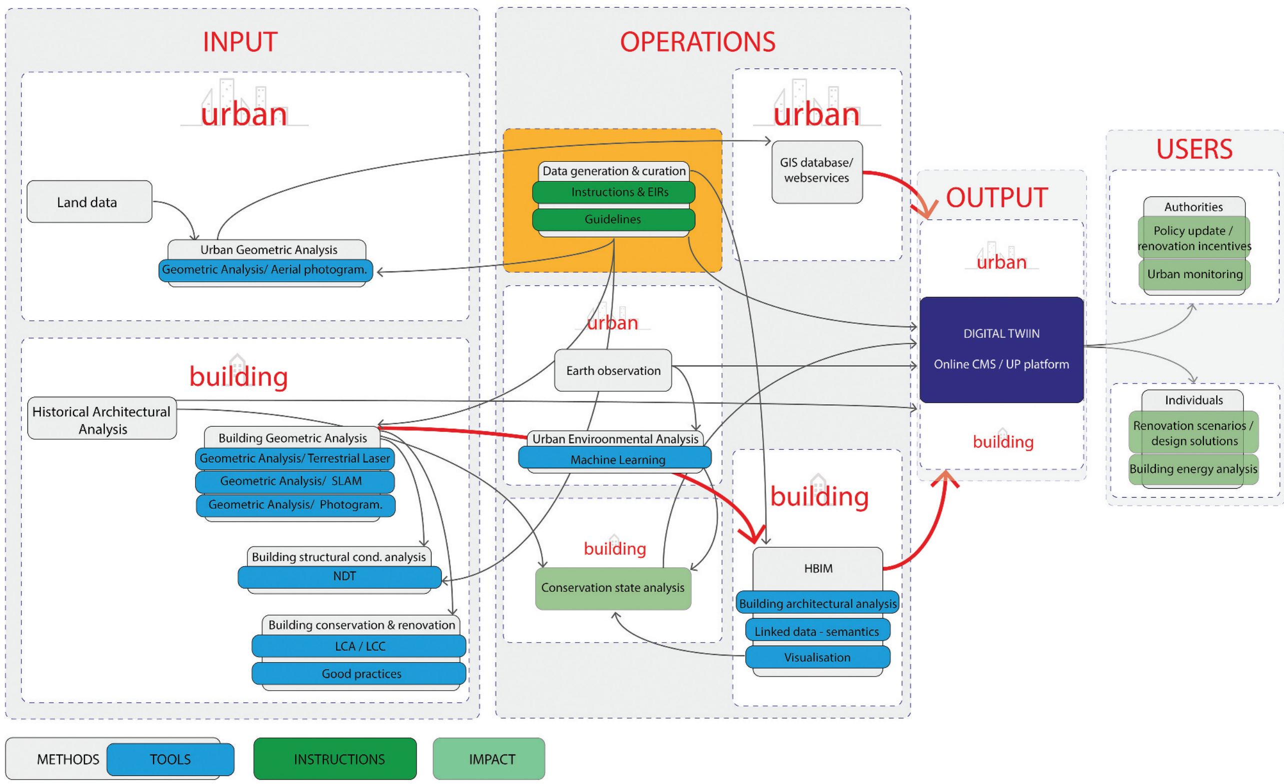


Figure 1. Diagram that illustrates the steps of the proposed workflow organized in terms of input data, operations (methods), output and user category and the dataflow between the steps, by scale (urban and building scales). Colour coding marks the instructions and guidelines produced by the authors to help data producers perform the appropriate operations, according to international standards and good practices, in order to generate datasets that will be Findable, Accessible, Interoperable and Reusable, as well as compatible with the project platform. The use of said platform is expected to impact positively the operations of the identified user groups.

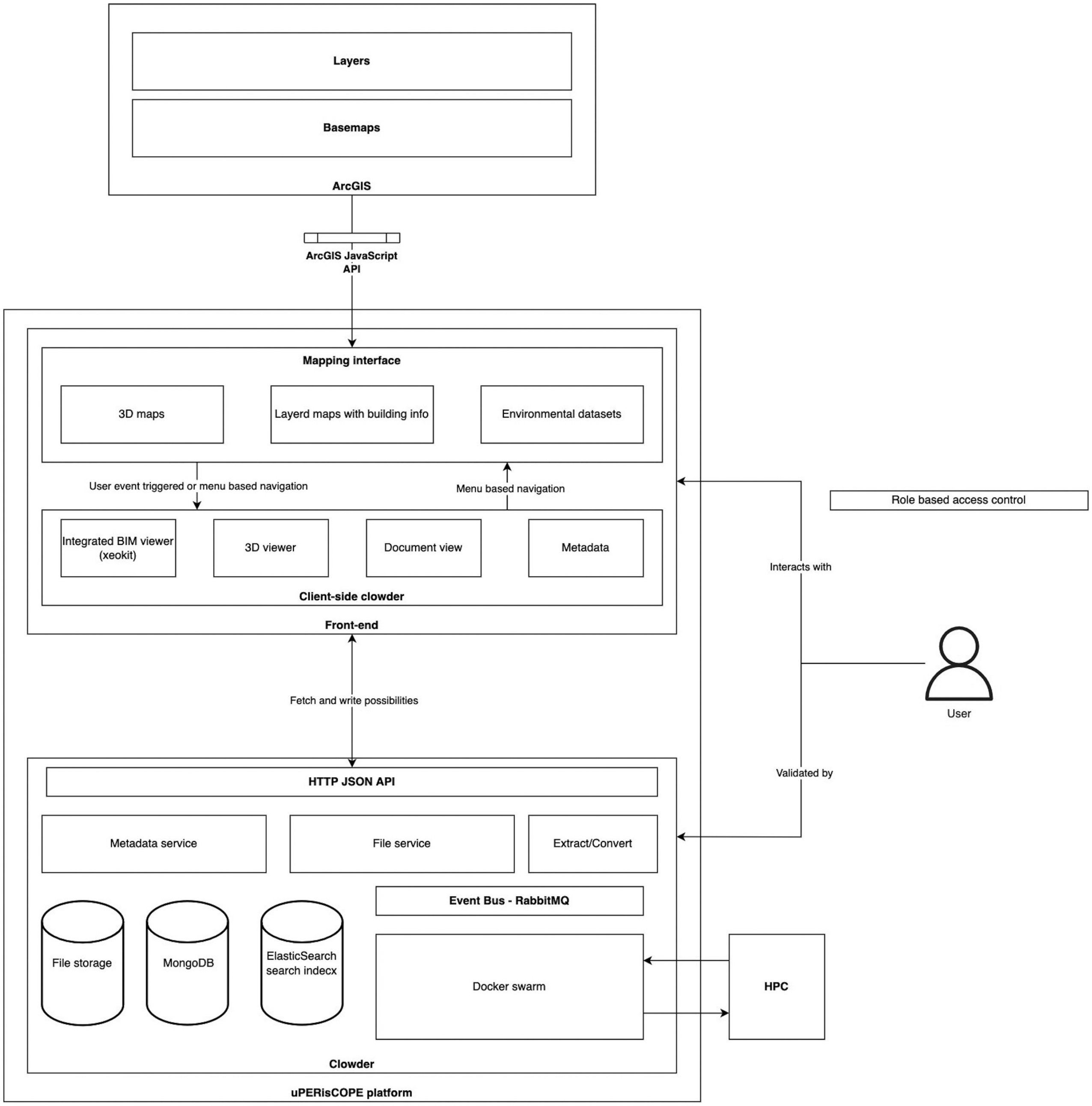
construction date, method and material; structural condition (stability) as a result of climate, decay and human activity. Sample datasets of satellite analysis and of one pilot building that support the findings of this study are openly available in Zenodo at 10.5281/zenodo.7426346 (accessed on 25 February 2023); 10.5281/zenodo.7404274 (accessed on 10 March 2023), respectively. Further datasets that support the findings of this study are openly available in UrbanPERIsCOPE platform at https://uperiscope.hpcf.cyi.ac.cy/ (accessed on 30 March 2023). Below are the main methods that comprise the presented workflow (Figure 1).

2.1.1. Scan-to-BIM

3D documentation techniques are used for reality capturing the structural and geometric complexity of historic clusters and the pilot buildings (Figure 3; Figure 4) that become accessible through the online environment of the platform to support conservation state analysis with accurate visualizations (Figure 5). These documentations are carried out in parallel with historical studies (bibliographical, archival, archaeological, etc.), which involve the study of historical layers (present and previous uses) and the assessment of the heritage significance and vulnerability to change, e.g., Figure 6 shows building phasing. The HBIM-supported online platform allows users to control semantic hierarchies of historic buildings' architectural elements (Figure 7). In order for the platform to be sustainably expanded in the future, important provisions were taken by the authors to ensure that datasets will continue being integrated and ingested. To achieve this, all the required Employer's Information Requirements (EIRs), including 'scan-to-HBIM', 'HBIM implementation', 'exchange information requirements for NDT' and 'content management and data integration' manuals, as well as the relevant metadata schema (Artopoulos 2020), were produced according to the respective international standards per operation, such as the ISO 19650 (ISO 2018).

2.1.2. Earth Observation

Multi-temporal satellite observations are used in the presented workflow; specifically, the EarthExplorer platform was used to download the Landsat 7 M+ and 8 LDCM archives. The Landsat collections were rescaled to reflectance values and brightness temperature using



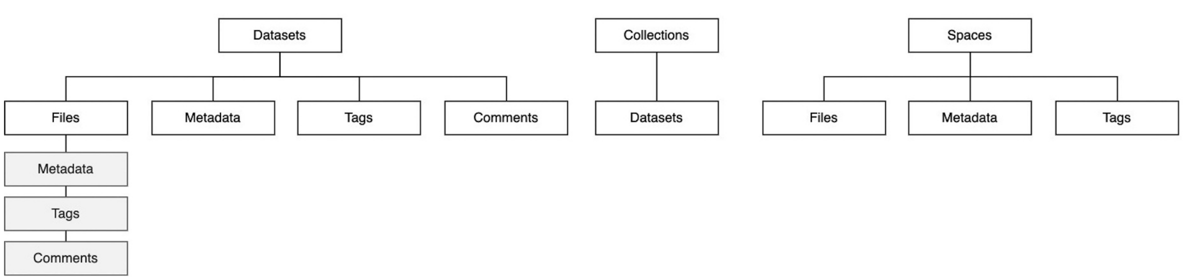


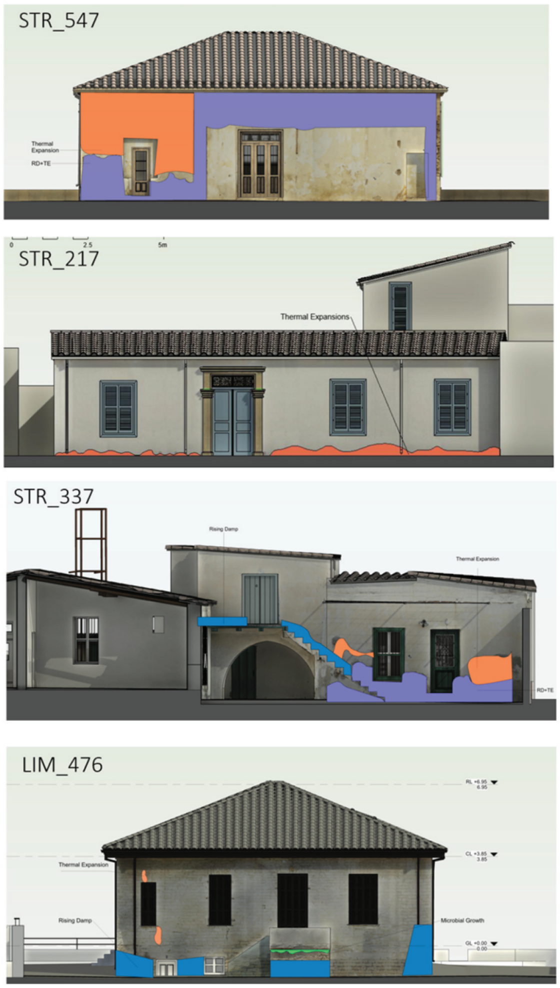
Figure 2. [Top] Architecture of the PERIsCOPE platform; [Bottom] Multiple ways of user-driven dataset access mode, as dataset, collection and spaces.

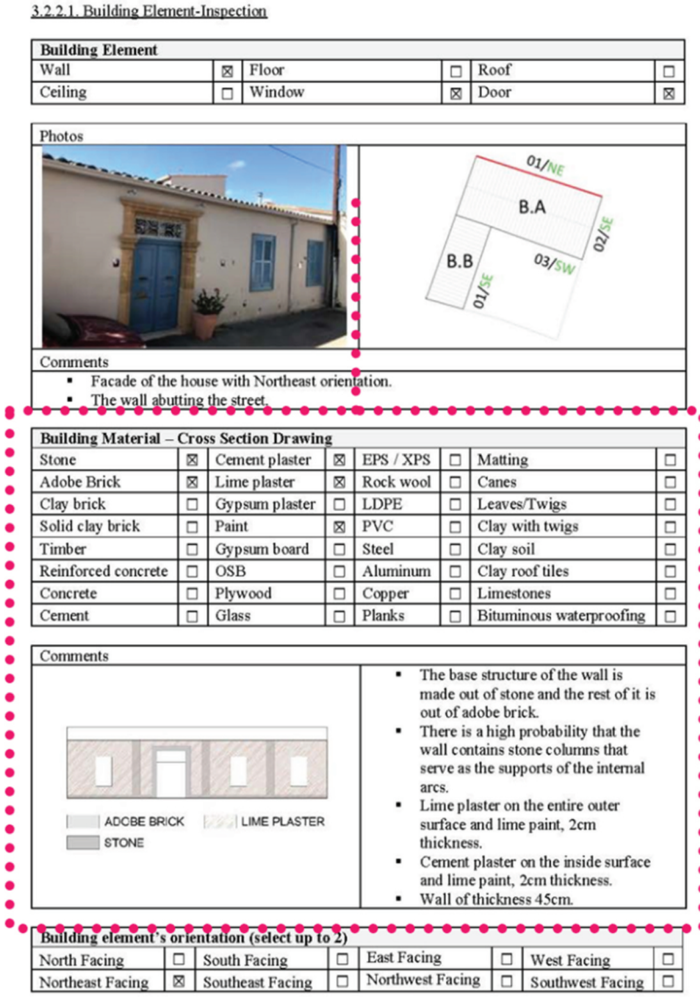
Figure 3. BIM modelling of a pilot building (of rural vernacular architecture typology) in the historical core of Strovolos aligned with the reality capture 3D point cloud.

Figure 4. Textured representation of the exterior facades of pilot building incorporating 'as is' building material conditions from the 3D point clouds.

radiometric rescaling coefficients and thermal constants, respectively. Over 140 satellite images covering 2013 to 2020 were analysed, of which 16 images of winter period, 30 of spring, 57 of summer, and 38 of autumn were used. Due to cloud coverage, these fluctuations between the different number of datasets per season were expected. Google Earth Engine cloud platform was used to process the optical data. Optical products, such as the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Built Index (NDBI), characterising vegetated and built-up areas, respectively, were extracted through this platform. The two indices' equations can be found below.

$NDVI = (\rho_{NIR} - \rho_{red})/(\rho_{NIR} + \rho_{red})$ (eq. 1)




3.2.2.1. Building Element-Inspection

Building Element					
Wall	☒	Floor	☐	Roof	☐
Ceiling	☐	Window	☒	Door	☒

Photos

Comments
- Facade of the house with Northeast orientation.
- The wall abutting the street.

Building Material – Cross Section Drawing							
Stone	☒	Cement plaster	☒	EPS / XPS	☐	Matting	☐
Adobe Brick	☒	Lime plaster	☒	Rock wool	☐	Canes	☐
Clay brick	☐	Gypsum plaster	☐	LDPE	☐	Leaves/Twigs	☐
Solid clay brick	☐	Paint	☒	PVC	☐	Clay with twigs	☐
Timber	☐	Gypsum board	☐	Steel	☐	Clay soil	☐
Reinforced concrete	☐	OSB	☐	Aluminum	☐	Clay roof tiles	☐
Concrete	☐	Plywood	☐	Copper	☐	Limestones	☐
Cement	☐	Glass	☐	Planks	☐	Bituminous waterproofing	☐

Comments

- The base structure of the wall is made out of stone and the rest of it is out of adobe brick.
- There is a high probability that the wall contains stone columns that serve as the supports of the internal arcs.
- Lime plaster on the entire outer surface and lime paint, 2cm thickness.
- Cement plaster on the inside surface and lime paint, 2cm thickness.
- Wall of thickness 45cm.

Building element's orientation (select up to 2)							
North Facing	☐	South Facing	☐	East Facing	☐	West Facing	☐
Northeast Facing	☒	Southeast Facing	☐	Northwest Facing	☐	Southwest Facing	☐

Figure 5. (a) Examples of visual integration of conservation state analysis such as hygrothermal properties, decay phenomena and crack pattern analysis on the elevations of the BIM models of the case study buildings. (b) Example of conservation state analysis report that provides all the necessary information about the materials and the general condition of the building under study.

$NDBI = (\rho_{SWIR} - \rho_{NIR})/(\rho_{SWIR} + \rho_{NIR})$ (eq. 2)

where ρ_{NIR} refers to the reflectance value at the near-infrared part of the spectrum, ρ_{red} refers to the reflectance value at the red part of the spectrum, and ρ_{SWIR} refers to the short-wave infrared reflectance value at the near-infrared part of the spectrum. Time-series annual maps from 2013 to 2020 were constructed based on the obtained NDVI and NDBI indices for the investigated locations. These maps were utilized to do a diachronic interpretation and evaluation of the landscape changes in the two testbed areas in Cyprus.

2.1.3. Non-destructive testing (NDT)

The infrared (IR) thermography technique was used to measure the thermal transmission properties of plane building components, as well as to reveal mechanisms impacting the structure of the heritage buildings. For the needs of this study, a FLIR E40bx thermal camera was employed (FLIR 2022). The specifications of the thermal camera are given in Table 1. The post-processing of the results was performed by means of the Thermography Software FLIR Tools (ibid 2022b).

The weathering mechanisms examined using IR thermography included rising dampness, thermal expansion, microbial growth and chemical weathering (Xystouris et al. 2021).

2.1.4. Life Cycle Assessment of Heritage Buildings (LCA)

For the whole Life Cycle Assessment (LCA) of the heritage assets, the bill of quantities, delivered by the produced BIM documents and the Environmental Product Declarations (EPDs) of individual building materials are employed. The EPDs are delivered in accordance with the

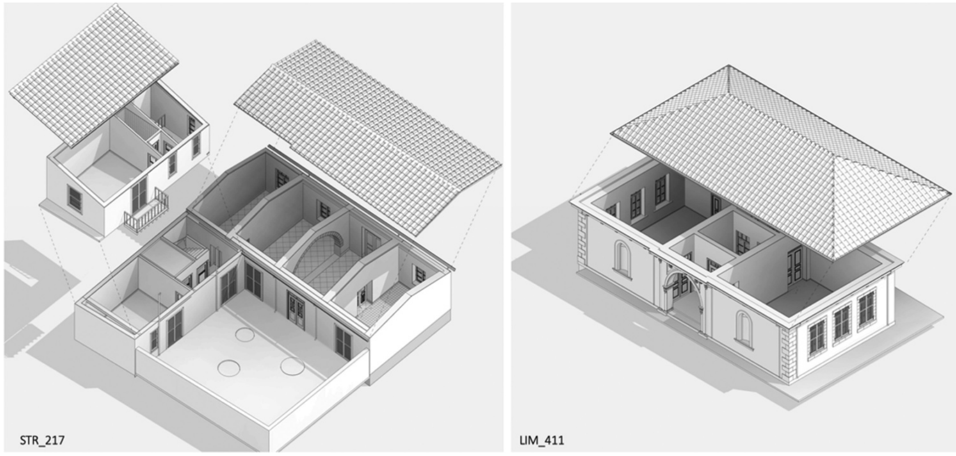


Figure 6. Use of HBIM for the analysis and visualisation of pilot building historical phases, to support the study of building changes and interventions in the structure.

Table 1. Technical Specifications of Thermal Camera.

Property	Value
Field of view	25° × 19°/0.4 m
Thermal sensitivity	45 [mK]
Spectral range	7.5–13 µm
IR resolution	160 × 120 pixels
Object temperature range	−20 to 120°C
Accuracy	± 2°C

EN 15804 standard (Agapiou and Lysandrou 2019). The extracted indicators, which were integrated into the PERIsCOPE platform were in accordance with the Level (s) scheme (ENCORE CONSORTIUM 2021). The list of the environmental indicators included in the platform is given in Table 2.

The indicators are delivered for different stages of the building constructions, including the pre-construction, the product, the construction, the use and the end-of-life stage, in compliance to the EN 15643 standard (CEN 2021).

2.2. *Online Content Management Platform*

The presented platform addresses the need of key stakeholders, like authorities, policymakers and professionals, for storing, accessing, analysing, and updating heterogeneous data of heritage buildings, which currently are found in unstructured data repositories or scattered, inaccessible databases. The research responds to these needs by providing the appropriate operation protocols (Artopoulos and Deligiorgi 2021) and an online platform that enables dataflow between the various key disciplines involved in

Table 2. Life Cycle Assessment (LCA) Indicators in accordance with Level(s).

Abbreviations	Description	Units
ADPE	Abiotic depletion potential for non-fossil resources	kg Sbe
ADPF	Abiotic depletion potential for fossil resources	MJ
AP	Acidification	kg SO_2e
Bio-CO2	Biogenic carbon storage	kg CO_2e bio
DT	Distance travelled	km
EP	Eutrophication	kg PO_4e
ERG	Energy	kWh
FC	Fuel consumption	litres
FW	Use of net fresh water	m^3
GWP	Global Warming Potential	kg CO_2e
ODP	Ozone depletion potential	kg CFC11e
PEEXR	Total use of primary energy ex. raw materials	MJ
PENRT	Total use of non-renewable primary energy	MJ
PERM	Use of renewable primary energy resources as raw materials	MJ
PERT	Total use of renewable primary energy	MJ
POCP	Formation of ozone of lower atmosphere	kg Ethene
WC	Water consumption	m^3

heritage building restoration by integrating (i) the modelling and parametric management of architectural information of heritage assets through an HBIM method; (ii) the multimodal and reliable (Figure 3) geometric documentation of architectural typology and features (Figure 7); (iii) the conservation state (Figure 5), chronological phasing, construction method, the definition of structural condition and identification of material decay (Figure 4); and (iv) the diachronic analysis of environmental conditions at a neighbourhood scale. All information of the heritage assets is integrated into the PERIsCOPE platform which allows different access levels to the various stakeholders of the process. The online platform gives access to the available environmental, territorial and architectural analysis datasets, while providing easy, user-friendly tools for online handling of the 2D, 3D representations, media and data analysis reports of each building via 3D GIS, 3D reality capture, immersive visualization, BIM (IFC) as well as image-based and PDF previewers. The integration of all above data offers opportunities of accessing information through 3D representations of the built environment, which are considered hereafter as a kind of a Digital Twin of the urban areas under study. Significantly, all these datasets are complemented with textual inventories of guidelines, Exchange Information Requirement (EIR) documents in support of the data generators' operations.

As the development process of this platform is currently ongoing, by means of software versioning and user feedback collection through key stakeholder workshops and training sessions engaging public authority officers, policy-makers, professionals, researchers and students, this paper focuses mainly on how the presented workflow and online platform enable users to access environmental data at a neighbourhood scale through remote-sensing satellite sensors and ground investigation results from non-destructive testing studies of the material condition of the respective heritage buildings' structures.

2.2.1. Analysis: platform components, features and tools

The diagram in Figure 2 illustrates the high-level system architecture of the PERIsCOPE platform (i.e., the core components, tools and methods of communication between them), aiming to highlight the underlying logic of the system's operation, including, but not limited to, the data provision process,

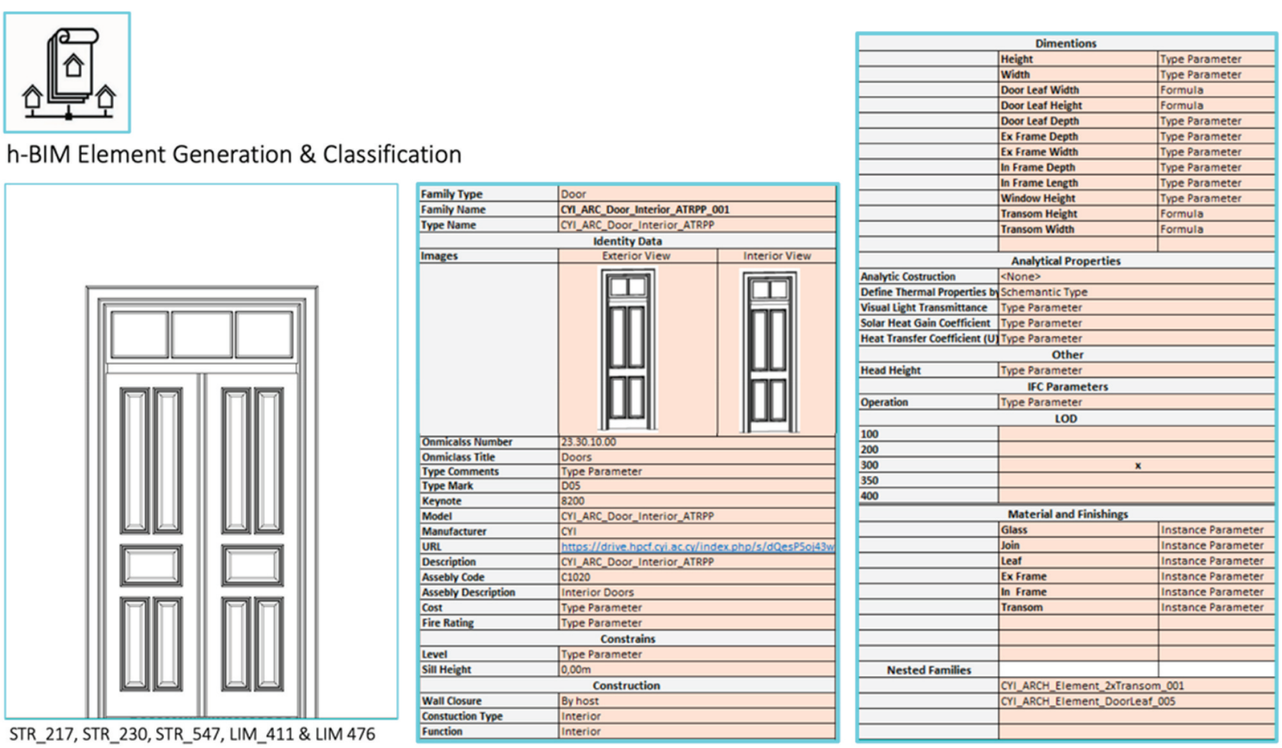


Figure 7. Example of the generation of a new family of historical openings, using the parametric modelling capacity of BIM. The creation of a library (online database) that contains parametric architectural elements classified by architectural typology of heritage buildings requires the detailed study of traditional construction techniques of every asset. Furthermore, the geometric characteristics and technical rules applied to the construction of these elements, including ornamentation or window typology are represented in this database, thus rendering it a valuable resource for the stakeholders of the building renovation process.

core features and functionalities. For the foreseen results to be feasible, the system works as follows:

(1) ArcGIS is the main mapping server and provider, communicating with the system's front-end via the ArcGIS JS API.
(2) Clowder Framework[1] acts as the main content management system; that is, all files and data is stored in Clowder, which is connected with the system's front-end with an API. Clowder is hosted in CyI's High Performance Computing facility, to allow for the needed resources and computing power to be allocated to the platform. Clowder is based on:

- MongoDB (https://www.mongodb.com) (accessed on 10 December 2022) as the main object-oriented database.
- Elasticsearch (https://www.elastic.co/) (accessed on 12 November 2022) for browsing and searching.
- Traefik (https://traefik.io/) (accessed on 22 April 2022) as a network proxy.
- RabbitMQ (https://www.rabbitmq.com/) (accessed on 14 August 2022).
- Portainer (https://www.portainer.io/) (accessed on 26 June 2022) for managing the docker containers.

One of the major advantages and features of the Clowder Framework is the use of data extractors, which provide the ability to handle multiple events during file uploads and manipulate them according to the needs of each use case. Based on this feature, and with the aim to expand the native capabilities of the presented platform, custom data extractors were developed to handle file conversions and parse metadata, to allow for consistent data entry process.

Regarding the integrated datasets, Clowder Framework's default system of spaces, datasets, and collections is used (Figure 2), allowing for the visualization of public and user-defined elements, depending on the individual user's access rights. All the above-mentioned information is visible in the client-side as well as in the backend interface, albeit uploads and edit actions are only available in the latter.

The aim of the platform is to allow users to have different levels of access, making use of Role Based Access Control (RBAC), which is also implemented and handled via Clowder. Users are authenticated from Clowder; however, only authorized ones are able to log, view and edit files in Clowder's backend, depending on the access level. A core distinction is made between the following groups:

- Viewer: Unauthorized users are able to see data through the front-end of the platform.
- Editor: Privileged users are able to view Clowder's backend, upload files, make use of extractors, edit and delete data, etc.
- Admin users with the ability to manage other user roles and permissions.

(1) In the front-end of the system, which is based on React JS, the two components mentioned above (e.g., ESRI ArcGIS and Clowder), and the data delivered from them is mapped and presented to users. To do so, field values from ArcGIS feature layers are matched with a key value of each item in a dataset, space or collection in Clowder, to combine the geospatial and logical presentation of each building asset.

Through these tools, data extractors and previewers, the pilot building information that is integrated in the platform is visualized and becomes accessible by means of the representation interfaces presented hereafter, including an online BIM viewer. All architectural and engineering representation methods respect and implement state-of-the-art professional standards and good practices. Specific tools are embedded in the front-end of the system, including Enscape exports rendered in the browser using WebGL (Figure 8) and the Xeokit Toolkit browser-based BIM viewer (Figure 9). Understanding the importance of viewing IFC models in the platform, and properly display their properties for users, attention was given to the BIM viewer to make full use of the tool's capabilities and limit loading times, to the extent possible. A Clowder data extractor was developed, which automates the conversion of uploaded files from the industry standard IFC format to the viewer-optimized XKT, without data loss. This allows the viewer to present users with

- A Tree View to navigate the IFC elements in models.
- A Plans View that provides methods for visualizing IfcBuildingStoreys.
- Section Planes which can be used to slice portions off models and reveal internal structures.
- Context Menus that pop up whenever we right-click on an Entity within our Scene.

[1]Clowder Framework 2022 http://clowderframework.org/ (accessed on 16 July 2022).

Figure 8. The presented online platform provides to users access to non-intrusive methods results both via the HBIM of the building and through real-time photorealistic visualisation of the data, with the support of the Enscape™ Rest API.

Figure 9. Alpha version of the online HBIM-supported platform: [left] building page provides access to historical information, in the metadata tab, and to linked data, including results of non-intrusive methods implementation and the building life cycle assessment. [right] Alternatively, the user can interact with the HBIM model of the building asset.

- A Nav Cube at the bottom right that lets us look at the entire Scene from along a chosen axis or diagonal.
- Perspective or orthographic projection.
- Fly over or first-person navigation.
- Element selections.
- Element hide.
- Full screen view.

3. Results of case study

In this section, selected use cases of the proposed platform's value-added services are presented. Particularly, a brief description and the background of each use case is described, as well as the actors involved, assumptions, pre- and post-conditions. Information related to the trigger of each use case as well as the successful end conditions are also provided.

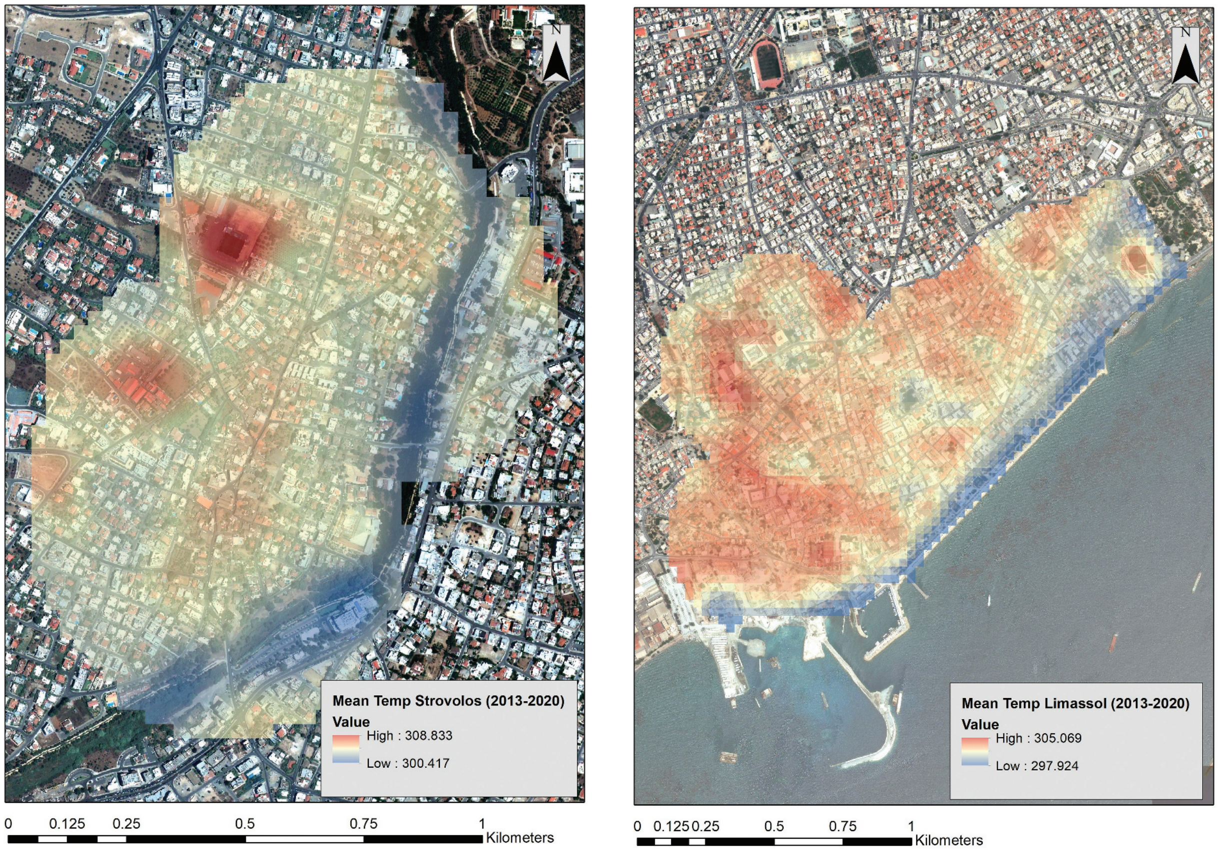


Figure 10. Mean temperatures of Nicosia [left]; and Limassol [right] for 2013–2020 (Agapiou and Lysandrou 2021).

3.1. Earth observation use case

Satellite datasets are studied in the GIS environment supported by the online platform. Figure 10 (left) displays the mean temperature findings for the Nicosia case study from 2013 to 2020. The red colour denotes higher mean temperatures, whereas the blue indicates areas with lower mean temperatures. Lower temperatures have been noted around the *Pediaios* river, which crosses the case study from southwest to northeast. In addition, two hot spot locations with relatively high mean temperatures have been identified in the western part of the area. For the second case study area (Limassol), a different pattern (Figure 10, right) is observed, where high mean temperatures are reported practically across the broader area of investigation, with exceptions in areas close to the sea. Nicosia's area revealed approximately 3 Kelvin degrees higher mean temperature than the Limassol case study.

The NDVI index is produced for each year from 2013 through 2020 using the optical bands of Landsat sensors, while the analysis is conducted on Google Earth Engine. Annual results for this period can be found in Agapiou and Lysandrou (2021) study. The result for the Nicosia case study for the year 2020 is shown in Figure 11 (left), and the NDVI values for the same year for Limassol area are shown in Figure 11 (right). Higher NDVI values around 1 indicate places with healthy vegetation. In contrast, NDVI values less than 0.20 indicate areas that are not vegetated (e.g., urban areas). Green colour highlights vegetated regions, whereas yellow and red highlights other land cover areas. Annual differences were also visible within the Nicosia area as demonstrated in the study of Agapiou and Lysandrou (2021). For instance, in 2014, vegetation coverage was observed in the western part of the river, while in 2020, vegetation coverage for the same area was less. Changes along the shoreline in the area of Limassol may be seen in this area. These alterations should be linked to recent developments along with the city's beachfront, where high-rise buildings have been constructed.

For both case studies, the same analysis for the NDBI index was also determined (Figure 12) using the spectrum's short-wave infrared and near-infrared parts, as described in Equation (2). For each year, similar findings to the NDVI index are derived. Based on the NDBI index, land-use change has been documented for 2020. These changes are consistent with measurements of the area's mean temperatures (see high mean temperatures in Figure 12). For the Limassol case study, a similar technique was used.

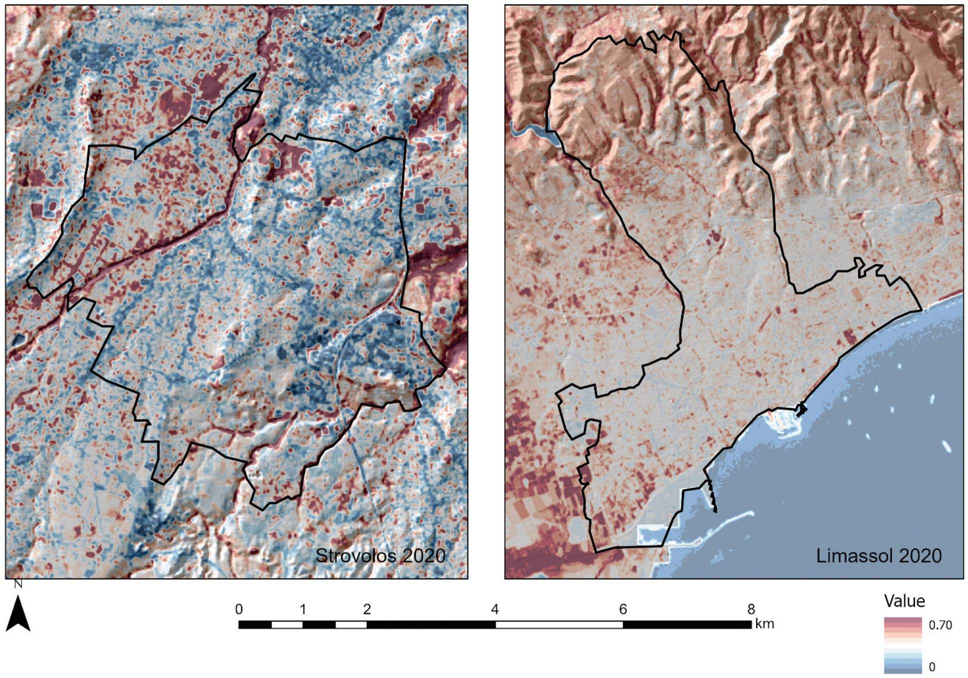


Figure 11. NDVI values Nicosia [left]; and Limassol [right] case studies for 2020

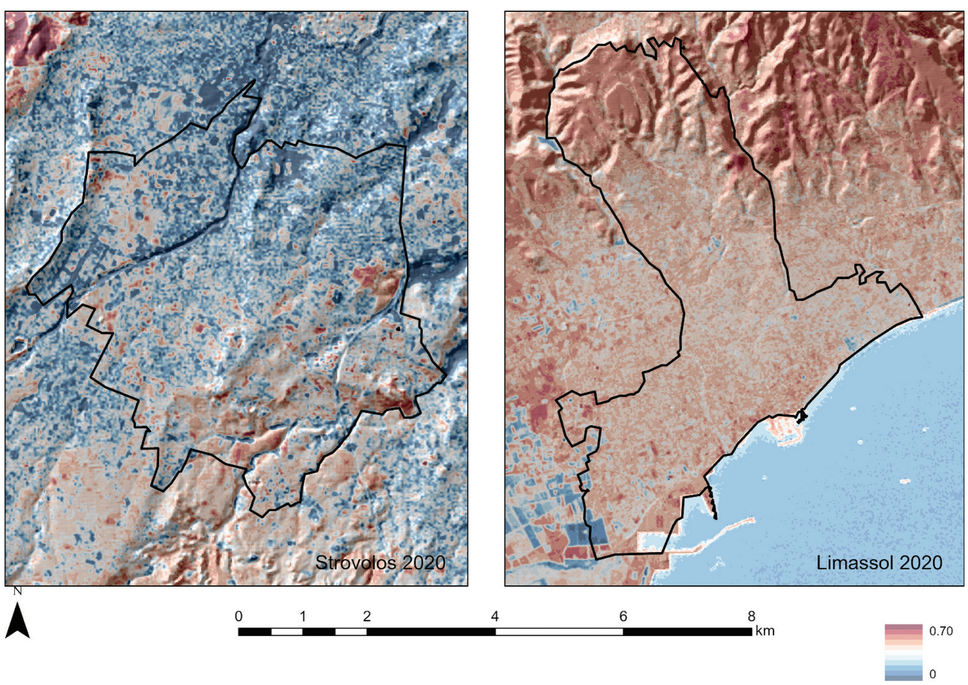


Figure 12. NDBI values for Nicosia [left]; and Limassol [right] case studies for 2020.

3.2. Analysing the weathering mechanisms of heritage buildings

The presented online platform provides information with regard to the weathering mechanisms that have affected the heritage buildings under consideration, as well as a forecasting tool for potential structural damages. This information is integrated into the HBIM, and may provide useful inside to the actors involved in required restoration activities of the building. As value-added service, the platform also allows the implementation of data analytics, which may reveal the type of weathering mechanism that may appear in a

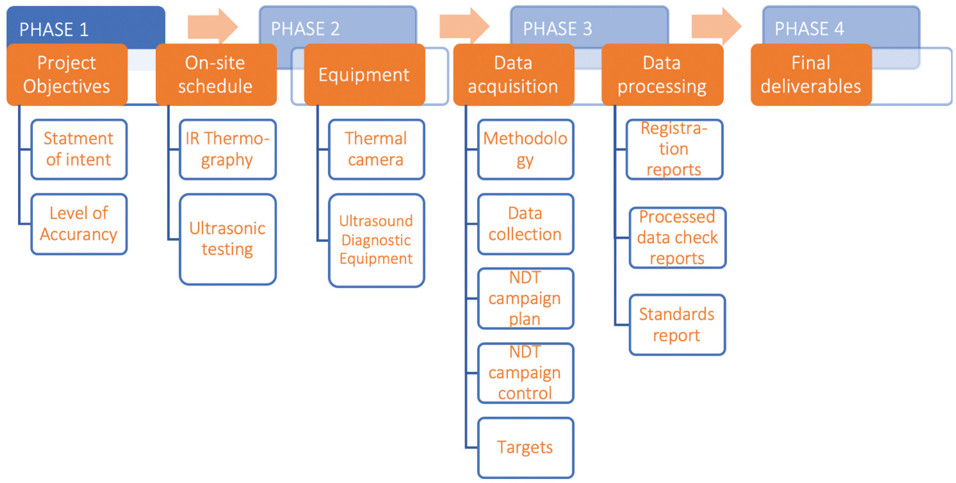


Figure 13. Non-destructive Testing (NDT) on-site Assessment Employer Information Requirements (EIR).

Table 3. Analysis of heritage buildings' landscape thermal conditions with the use of satellite images and GIS use case requirements.

Use case name	Analysis of heritage buildings' landscape thermal conditions
Intent	To introduce all required information of land surface thermal conditions to the platform. Allow the detections of thermal variations for each case study. Predict possible thermal variations based on previous and current thermal conditions knowledge.
Actors Involved	Main Actor: Engineers, Architects Other: Public Bodies, Researchers/ Academics, Tenants/Owners, Building Managers, Facilities Managers
Brief Description	Land surface Temperature obtained from sun synchronious optical sensors. Post-process of optical data. Optical products extraction characterising vegetated and built-up areas (i.e., Normalized Difference Vegetation Index-NDVI and Normalized Difference Built Index-NDBI).
Assumptions	Satellite data must be calibrated
Pre-conditions	Limited cloud coverage
Trigger	Near real-time monitoring of thermal conditions over large scale areas
Goal (Successful End Condition)	All needed data for diagnosing the thermal condition of a cultural landscape entailing individual buildings under investigation are introduced in the platform, e.g., mean land surface temperature
Post-conditions	Temporal thermal information is available for other processes and operations

heritage building, given its age, its building materials and the orientation of each building element.

For the implementation of the on-site NDT assessment of the building, an Employer Information Requirements (EIR) was developed, including all required steps for the assessor, with the aim to collect the required information. An overview of the EIR for the on-site NDT assessment is depicted in Figure 13.

The use case requirements for the value-added service of the platform, related to the prediction of the weathering mechanisms, affecting the building, are tabulated in Table 3.

In Figure 14, indicative data analytics of input related to weathering mechanisms is presented. This information was extracted by the analysis of the 19 pilot buildings under study. The weathering mechanisms were recognized in accordance with the EIR procedures developed for the purpose of the platform. Weathering refers to the natural phenomenon of the breakdown or dissolution of rocks and minerals, and this can cause deterioration of building materials, provoking the following mechanisms: wet and dry expansion, frost-induced weathering, salt crystallization, biological degradation, chemical weathering, mechanical weathering, and thermal expansion deterioration. This data allows for further forecasting of restoration needs of heritage buildings, as well as the development of a risk assessment for the structural integrity of building assets under study.

3.3. *Environmental assessment of heritage buildings*

The presented platform provides information about the environmental assessment of heritage buildings with the use of Life Cycle Assessment (LCA), focusing mainly on the building shell and on the building materials used. This information may be assessed for informed decision-making with regard to environmentally optimal conditions for buildings' restoration. The platform also allows for the extraction of metrics concerning the average environmental performance of given stock of

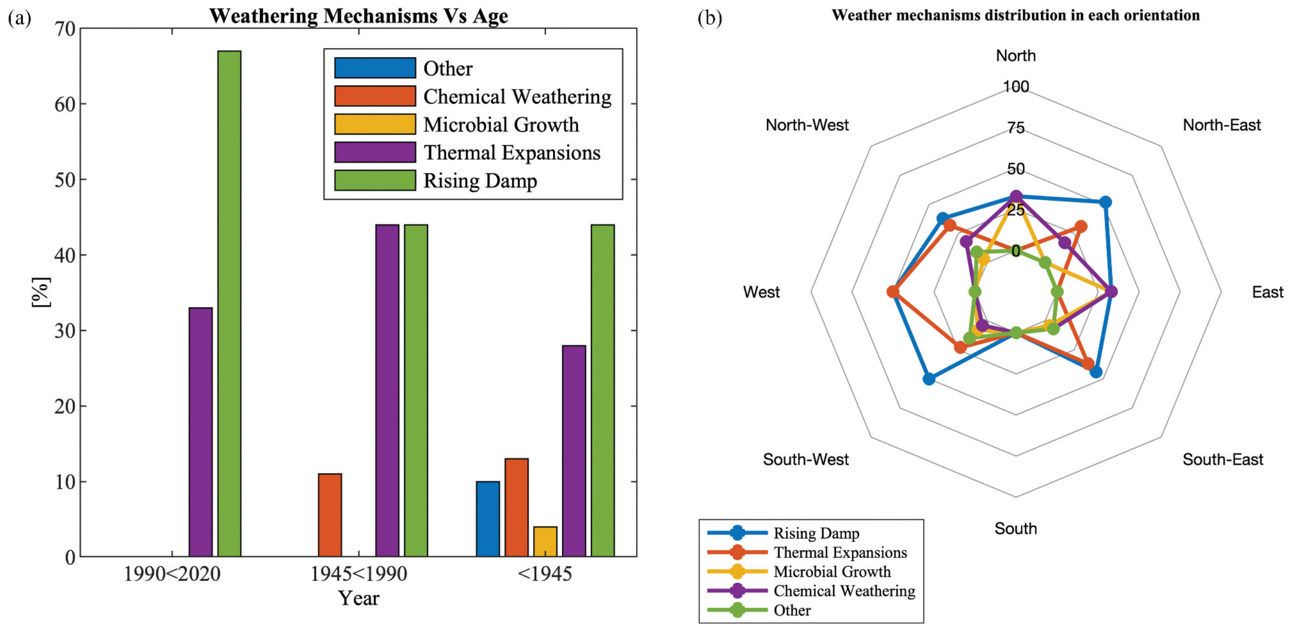


Figure 14. Indicative data analytics of information related to weathering mechanisms affecting heritage buildings per age (left) and per orientation of the building element (right).

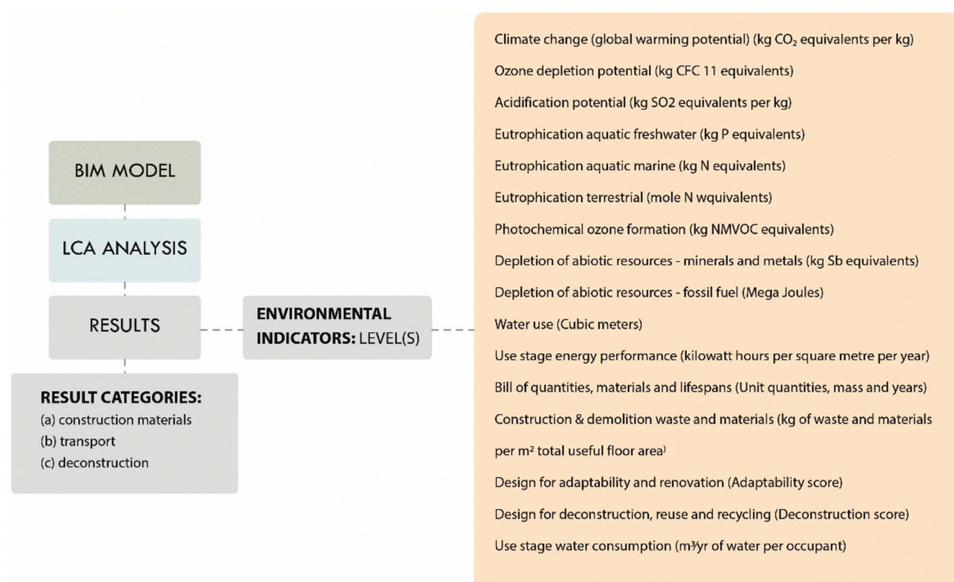


Figure 15. Life Cycle Assessment (LCA) Employer Information Requirements (EIR).

heritage buildings, enabling policy making concerning financing incentives and structural restoration measures. The analysis is based on the set of environmental indicators employed under the Level(s) scheme [27]. The implementation of the environmental assessment with the use of LCA, is conducted likewise based on a given EIR (Figure 15).

The use case requirements for the value-added service of the PERIsCOPE platform, related to the definition of the environmental indicators, is given in Table 4.

In Table 5, an indicative protocol of LCA indicators, provided for heritage buildings by the PERIsCOPE platform is provided. Here these results are extracted for one of the pilot buildings, and may be further exploited for assessing alternative restoration scenarios, based on the environmental data.

4. Discussion

The article presented through a use case, how hosting together multi-scale analysis datasets in the same online platform and data repository can provide benefits for the transdisciplinary study of built heritage. Integrating

Table 4. Analysis of heritage Life Cycle Assessment (LCA) use case requirements.

Use Case Name	Analysis of heritage buildings weathering mechanisms
Intent	To introduce all required information of climate change weathering to a BIM file and allow the prediction of weathering to heritage buildings
Actors Involved	Main Actor: Engineers, Architects Other: Public Bodies, Researchers/Academics, Tenants/Owners, Building Managers, Facilities Managers
Brief Description	PERIsCOPE platform user has access to the heritage building BIM file through smart scanning, and imports it in the platform. In case the BIM is incomplete or wrong, the user is informed. It is also possible to input (additional) data through a simplified UI, related to structural conditions, resulting from on-site NDT.
Assumptions	A BIM file is available. An on-site NDT assessment of the building is carried out.
Pre-conditions	None
Trigger	A request for structural assessment of a heritage building
Goal (Successful End Condition)	All needed data for diagnosing the structural condition of the building are introduced in the BIM document
Post-conditions	Weathering information is available for other processes and operations

Table 5. Indicative results of Life Cycle Assessment (LCA) indicators, delivered by PERIsCOPE HBIM platform.

Use Case Name	Analysis of heritage buildings Life Cycle Assessment (LCA)
Intent	To extract the LCA indicators of a heritage building from a BIM file and allow informed restoration decisions based on environmental criteria
Actors Involved	Main Actor: Engineers, Architects Other: Public Bodies, Researchers/Academics, Tenants/Owners, Building Managers, Facilities Managers
Brief Description	PERIsCOPE platform user introduces a BIM file through smart scanning, and imports it in the platform. In case the BIM is incomplete or wrong, the user is informed. It is also possible to input (additional) data through a simplified UI, related to environmental conditions. The user has access to the environmental indicators of the building.
Assumptions	A BIM file is available. Environmental Product Declarations (EPDs) of the used materials are available.
Pre-conditions	None
Trigger	A request for environmental assessment of a heritage building
Goal (Successful End Condition)	All environmental indicators of a heritage building are extracted from a BIM file and delivered in the form of a report to the user.
Post-conditions	LCA indicators are available as a decision-making information for actors involved, enabling environmentally informed decisions for heritage buildings' restoration.

results of the application of NDT methods within a platform that provides to the user access to diachronic results of earth observation monitoring can offer new possibilities in correlating high mean land surface temperatures and observed state of buildings in the area under study to professionals. Naturally, further enrichment of the online platform with new findings from other buildings in the respective areas is anticipated to deliver higher value to the users and a more reliable understanding of possible correlations between the environmental conditions and the decay of the building material.

In this paper, satellite observation multi-temporal analysis related to the retrieval of the LST, NDVI, and NDBI values over two extensive areas (i.e., two historic clusters) was carried out. This analysis documented diachronic changes in both areas, while these changes were validated with ground observations related for example to land-use changes along the coastline front of Limassol, and the respective climatic conditions, such as the lower mean temperature in proximity to coastline areas. In comparison to Limassol, higher LST values were mapped, as expected, for the inland case study (located in Strovolos, Nicosia).

Integrating data created by different disciplines of the built environment can offer new opportunities for the transdisciplinary research of heritage buildings and historic clusters in cities by means of a single point of access, a portal to a digital twin of the area under study, but it also introduces several challenges. These challenges are encountered because of two main reasons, that of visualizing information and accessing data. For instance, satellite image products are obtained in a raster format in a resolution of 60 m, which is considered too course for observing individual buildings. To overcome this drawback, a downscale resampling approach to 10-m resolution using the cubic resampling method was implemented. Despite this processing does not provide finer resolution outcomes, this can enhance the satellite imagery's visualization experience. Another challenge is related to the processing of the large volume of satellite images, which therefore was carried out externally to the platform. The results of the processing where then imported into the platform as final products.

In addition, end users' feedback was retrieved. Three rounds of testing and user evaluation (https://uperiscope.cyi.ac.cy/news-and-events) of different solutions of visualizing earth observation information at neighbourhood scale and accessing NDT methods' results per building, were conducted by the authors by means of workshops, addressing the needs of researchers, policy makers and professionals. The most favourable solution that was implemented in the design of the PERIScOPE online platform allows users to observe large-scale information about environmental data through a 3D GIS representation of the neighbourhood, while accessing per building information of material state through static documentation of conservation state analysis, like thermal photographs and a database of standardized documents. These solutions were made possible through the ArcGIS JS API and Clowder Framework. User feedback collected during series of stakeholder (academia, policymakers, municipalities and professionals) workshops corroborated the integration of tools and features available (90% as excellent or good) and the usefulness of data available on the platform (82% as excellent and 18% as good).

The presented workflow can be applied not only to listed monuments and buildings with significant cultural value but also to numerous cases of vernacular architecture, as well as to examples of architecture of the recent past that bear the identity of the place but yet are not listed. It is worth noting that while the presented workflow and methods are applied as a pilot in the analysis of sensitive historic clusters in Cypriot cities that are facing rapid urbanization challenges and the impact of climate change, the research is taking measures that will allow it in the future to become applicable at other European cities too, through the technical guidelines, workflows and instructions produced.

Acknowledgments

Project Coordinator: The Cyprus Institute; Partners: Cyprus University of Technology (Cyprus), Frederic Research Center (Cyprus), Fondazione Bruno Kessler (Italy), University of Catania (Italy), Department of Urban Planning and Housing, Municipality of Strovolos, Municipality of Limassol, HIT – Hypertech Innovations, NetU Consultations and Talos RTD.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The work presented here is from the "Portal for heritage buildings integration into the contemporary built environment" (URBAN PERISCOPE) project. The project is funded by the Cyprus Research & Innovation Foundation Restart Programs 2016–2020 "Integrated Projects". The project [Grant number: INTEGRATED/0918/0034] is co-financed by the European Regional Development Fund and the Republic of Cyprus through the Research Innovation Foundation.

ORCID

Georgios Artopoulos http://orcid.org/0000-0003-4500-1464
Paris Fokaides http://orcid.org/0000-0003-4112-3819
Vasiliki Lysandrou http://orcid.org/0000-0002-1448-7599
Panos Sabatakos http://orcid.org/0000-0003-1756-5158
Athos Agapiou http://orcid.org/0000-0001-9106-6766

Author Contributions

Conceptualization, G.A.; methodology, G.A., P.F. and A.A.; software; validation; formal analysis; investigation; resources; data curation, A.A., V.L., P.F. and M.D.; writing—original draft preparation, G.A., P.F. and A.A.; writing—review and editing, G.A., A.A., V.L. and P.F.; visualization, A.A., P.F. and M.D.; supervision, G.A.; project administration, funding acquisition, G.A. All authors have read and agreed to the published version of the manuscript.

References

Agapiou, A., and V. Lysandrou. 2019. "Remote sensing archaeology: Tracking and mapping evolution in European scientific literature from 1999 to 2015." *Journal of Archaeological Science: Reports* 4: 192–200.

Agapiou, A., and V. Lysandrou. 2021. Observing thermal conditions of historic buildings through earth observation data and big data engine. *Sensors* 21 (13):4557. doi:10.3390/s21134557.

Antonopoulou, S., and P. Bryan. 2017. *BIM for Heritage: Developing a Historic Building Information Model*. Swindon, UK: Historic England.

Arfa, F. H., H. Zijlstra, B. Lubelli, and W. Quist. 2022. Adaptive reuse of heritage buildings: from a literature review to a model of practice. *The Historic Environment: Policy & Practice* 13 (2):148–70. doi:10.1080/17567505.2022.2058551.

Artopoulos, G. 2020. Schemas for BIM interoperability: A case for linked urban data. *Scholarly Primitives - DARIAH Annual Event 2020*. doi:10.5281/zenodo.4302146.

Artopoulos, G., and M. Deligiorgi. 2021. Employer Information Requirements (EIR) for Geometric survey with aerial and terrestrial documentation techniques (Version 002). *Zenodo*. doi:10.5281/zenodo.5576322.

Barazzetti, L. 2021. Integration between Building Information Modeling and geographic information system for historic buildings and sites: Historic-BIM-GIS. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 41–48. doi:10.5194/isprs-annals-VIII-M-1-2021-41-2021.

Blundo, D. S., A. M. Ferrari, A. F. Del Hoyo, M. P. Riccardi, and F. E. G. Muiña. 2018. Improving sustainable cultural heritage restoration work through life cycle assessment based model. *Journal of Cultural Heritage* 32:221–31. doi:10.1016/j.culher.2018.01.008.

Brumana, R., S. Della Torre, D. Oreni, M. Previtali, L. Cantini, L. Barazzetti, A. Franchi, and F. Banfi. 2017. "HBIM challenge among the paradigm of complexity, tools and preservation: The basilica di collemaggio 8 years after the earthquake (l'aquila)." Ottawa, *International Archaeological Photogrammetry and Remote Sensing Spatial Information Science* XLII-2/W5: 97–104. https://doi.org/10.5194/isprs-archives-XLII-2-W5-97-2017 .

Bruno, S., A. Musicco, F. Fatiguso, and G. Dell'Osso. 2019. The role of 4D historic building information modelling and management in the analysis of constructive evolution and decay condition within the refurbishment process. *International Journal of Architectural Heritage* 15. doi:10.1080/15583058.2019.1668494.

Commission, E. 2011. Communication 711/2011. *Recommendation on the Digitisation and Online Accessibility of Cultural Material and Digital Preservation. Brussels* 27 (10):2011.

Commission, E. 2018. *European Framework for action on cultural heritage. Commission staff working document*. Luxembourg: Publications Office of the European Union. doi:10.2766/949707.

Cuca, B. 2017. The contribution of earth observation technologies to monitoring strategies of cultural landscapes and sites. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 135–40. doi:10.5194/isprs-archives-XLII-2-W5-135-2017.

Cursi, S., L. Martinelli, N. Paraciani, F. Calcerano, and E. Gigliarelli. 2022. Linking external knowledge to heritage BIM. *Automation in Construction* 141:104444. doi:10.1016/J.AUTCON.2022.104444.

Dabetwar, S., N. N. Kulkarni, M. Angelosanti, C. Niezrecki, and A. Sabato. 2022. Sensitivity analysis of unmanned aerial vehicle-borne 3D point cloud reconstruction from infrared images. *Journal of Building Engineering* 105070. doi:10.1016/j.jobe.2022.105070.

Diara, F., and F. Rinaudo. 2021. ARK-BIM: Open-Source Cloud-Based HBIM Platform for Archaeology. *Applied Sciences* 11:8770.

Dol, K., and M. Haffner eds. 2010. Housing Statistics in the European Union. The Hague: Ministry of the Interior and Kingdom Relations, Accessed January 31, 2014. http://www.bmwfj.gv.at/Wirtschaftspolitik/ Wohnungspolitik/Documents/housing_statistics_in_ the_european_union_2010.pdf

Dore, C., M. Murphy, S. McCarthy, F. Brechin, C. Casidy, and E. Dirix. 2015. "Structural simulations and conservation analysis -Historic Building Information Model (HBIM), International Archaeological Photogrammetry and Remote Sensing Spatial." *Information Science* XL-5/W4: 351–357.

ENCORE CONSORTIUM. 2021. Accessed 16 April 2022. https://encorebim.eu/

England, H. 2018. "Iain McCaig, Robyn Pender and David Pickles. Energy efficiency and historic buildings, how to improve energy efficiency." *Historic England* 12: 2022. Accessed 26 April 2023. https://www.historicengland.org.uk/advice/technical-advice/energy-efficiency-and-historic-buildings/.

FLIR 2022. "FLIR E40bx." Accessed 28 Aug 2022. https://www.flir.eu/support/products/e40bx/#Overview.

Fokaides, P. A., and S. A. Kalogirou. 2011. Application of infrared thermography for the determination of the overall heat transfer coefficient (U-Value) in building envelopes. *Applied Energy* 88 (12):4358–65. doi:10.1016/j.apenergy.2011.05.014.

Gan, V. J. L., M. Deng, Y. Tan, W. Chen, and J. C. P. Cheng. 2019. BIM-based framework to analyze the effect of natural ventilation on thermal comfort and energy performance in buildings. *Energy Procedia* 158:3319–24.

Haala, N., and M. Rothermel. 2015. "Image-based 3 D Data Capture in Urban Scenarios." *Photogrammetric Week 15*, Wichmann/VDE Verlag, Belin & Offenbach, 119–30. Accessed 26 April 2023. https://phowo.ifp.uni-stuttgart.de/publications/phowo15/130Haala.pdf.

Hellier, C. 2003. *Handbook of Nondestructive Evaluation*.

International Standardisation Organisation (ISO) 2006. ISO 14040:2006 Environmental management Life cycle assessment Principles and framework.

Kylili, A., P. A. Fokaides, P. Christou, and S. A. Kalogirou. 2014. Infrared thermography (IRT) applications for building diagnostics: A review. *Applied Energy* 134:531–49. doi:10.1016/j.apenergy.2014.08.005.

Kylili, A., M. Ilic, and P. A. Fokaides. 2017. Whole-building Life Cycle Assessment (LCA) of a passive house of the subtropical climatic zone. *Resources, Conservation and Recycling* 116:169–77. doi:10.1016/j.resconrec.2016.10.010.

Lee, J., and J. Kim. 2017. BIM-based 4D simulation to improve module manufacturing productivity for sustainable building projects. *Sustainability* 9 (3):426.

Lin, D., M. Jarzabek-Rychard, D. Schneider, and H. G. Maas. 2018. Thermal texture selection and correction for building facade inspection based on thermal radiant characteristics. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences* 42:2. doi:10.5194/isprs-archives-XLII-2-585-2018.

Logothetis, S., E. Karachaliou, E. Valari, and E. Stylianidis. 2018. OPEN SOURCE CLOUD-BASED TECHNOLOGIES FOR BIM. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII–2* (2):607–14. doi:10.5194/ISPRS-ARCHIVES-XLII-2-607-2018.

Luo, L., X. Wang, H. Guo, R. Lasaponara, X. Zong, N. Masini, G. Wang, P. Shi, H. Khattel, F. Chen, et al. 2019. Airborne and spaceborne remote sensing for archaeological and cultural heritage applications: A review of the century (1907–2017). *Remote Sensing of Environment* 232:111280.

Malovrh Rebec, K., B. Deanovic, and L. Oostwegel. 2022. Old buildings need new ideas: Holistic integration of conservation-restoration process data using Heritage Building Information Modelling. *Journal of Cultural Heritage* 55:30–42.

Martinelli, L., F. Calcerano, and E. Gigliarelli. 2022. Methodology for an HBIM workflow focused on the representation of construction systems of built heritage. *Journal of Cultural Heritage* 55:277–89. doi:10.1016/j.culher.2022.03.016.

Masciotta, M. G., M. J. Morais, L. F. Ramos, D. Oliveira, L. J. Sánchez-Aparicio, and D. González-Aguilera. 2021. A digital-based integrated methodology for the preventive conservation of cultural heritage: The experience of heritage care project. *International Journal of Architectural Heritage* 15 (6):844–63. doi:10.1080/15583058.2019.1668985.

Meng, X., J. Cheng, S. Zhao, S. Liu, and Y. Yao. 2019. Estimating Land Surface Temperature from Landsat-8 Data using the NOAA JPSS Enterprise Algorithm. *Remote Sensing* 11:155.

Mirza & Nacey Research Ltd, The Architects' Council of Europe. 2021. THE ARCHITECTURAL PROFESSION IN Europe 2020: A Sector Study. Accessed March 20, 2022. https://www.ace-cae.eu/fileadmin/user_upload/2020ACESECTORSTUDY.pdf

Panteli, C., A. Kylili, and P. A. Fokaides. 2020. Building information modelling applications in smart buildings: From design to commissioning and beyond A critical review. *Journal of Cleaner Production* 265:121766. doi:10.1016/j.jclepro.2020.121766.

Pepe, M., D. Costantino, V. S. Alfio, A. G. Restuccia, and N. M. Papalino. 2021. Scan to BIM for the digital management and representation in 3D GIS environment of cultural heritage site. *Journal of Cultural Heritage* 50:115–25. doi:10.1016/j.culher.2021.05.006.

PERISCOPE "Portal for heritage buildings integration into the contemporary built environment". February 2020. https://uperiscope.cyi.ac.cy/ Accessed 16 August 2022.

Preidel, C., A. Borrmann, H. Mattern, M. Konig, and S.-E. Schapke. 2018. Common Data Environment. *Building Information Modeling: Technology Foundations and Industry Practice* 1–15. doi:10.1007/978-3-319-92862-3.

Radanovic, M., K. Khoshelham, and C. Fraser. 2020. Geometric accuracy and semantic richness in heritage BIM: A review. *Digital Applications in Archaeology and Cultural Heritage* 19: e00166. doi:10.1016/j.daach.2020.e00166.

Rekha, K. S., T. H. Sreenivas, and A. D. Kulkarni. 2018. Remote monitoring and reconfiguration of environment and structural health using wireless sensor networks. *Materials Today: Proceedings* 5 (1):1169–75. doi:10.1016/j.matpr.2017.11.198.

Rodríguez-Gonzálvez, P., A. L. Muñoz-Nieto, S. Del Pozo, L. J. Sanchez-Aparicio, D. Gonzalez-Aguilera, L. Micoli, S. Gonizzi Barsanti, G. Guidi, J. Mills, K. Fieber, et al. 2017. "4D reconstruction and visualization of cultural heritage: analyzing our legacy through time." *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 609–16. Accessed 26 April 2023. doi:10.5194/isprs-archives-XLII-2-W3-609-20172017.

Tejedor, B., E. Lucchi, D. Bienvenido-Huertas, and I. Nardi. 2022. "Non-Destructive Techniques (NDT) for the diagnosis of heritage buildings: Traditional procedures and futures perspectives." In *Energy and Buildings*. Vol. 263, 112029. https://doi.org/10.1016/j.enbuild.2022.112029.

Vacca, G., E. Quaquero, D. Pili, and M. Brandolini. 2018. Integrating bim and gis data to support the management of large building stocks. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences ISPRS Archives* 42 (4):717–24. doi:10.5194/ISPRS-ARCHIVES-XLII-4-647-2018.

Xiao, W., J. Mills, G. Guidi, P. Rodríguez-Gonzálvez, S. G. Barsanti, and G.-A. Diego. 2018. Geoinformatics for the conservation and promotion of cultural heritage in support of the UN Sustainable Development Goals. *ISPRS Journal of Photogrammetry and Remote Sensing* (142) (389–406). doi: 10.1016/j.isprsjprs.2018.01.001.

Xystouris, K., E. Apostolidou, A. Kylili, and P. A. Fokaides. 2021. The effect of climate change on weathering: evidences from heritage buildings under subtropical conditions. *Journal of Sustainable Architecture and Civil Engineering* 29 (2):232–45. doi:10.5755/j01.sace.29.2.29425.

Yang, X., P. Grussenmeyer, M. Koehl, H. Macher, A. Murtiyoso, and T. Landes. 2020. Review of built heritage modelling: Integration of HBIM and other information techniques. *Journal of Cultural Heritage* 46:350–60. doi:10.1016/j.culher.2020.05.008.