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Integrating ecological processes into building information modelling for heritage conservation

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Building Information Modelling (BIM) is increasingly used in heritage conservation, yet biological processes such as colonisation dynamics, growth rates, succession, and biologically driven material change remain poorly integrated. We propose an Ecological BIM (E-BIM) approach that treats these processes as dynamic components of coupled biological-material-environment systems. We outline conceptual shifts, data needs, and methodological challenges involved in translating ecological knowledge into BIM-compatible variables for monitoring, scenario-based modelling, and conservation decision-making.

From BIM to HBIM in heritage science

Building Information Modelling (BIM) is a digital framework that combines geometric representations of buildings with structured information on materials, construction phases, performance, and maintenance[1]. Originally developed for architecture, engineering, and construction, BIM is now widely used to manage buildings across their life cycle, from design and construction to operation, reuse, and demolition[2].

The expansion of BIM reflects a broader transformation in the built environment, with digital models increasingly functioning as shared platforms for integrating diverse datasets and supporting decision-making. With the integration of AI, sensor networks, and digital twins, BIM has evolved from static documentation into dynamic systems supporting simulation, prediction, and adaptive management[3,4].

In cultural heritage contexts, BIM has been adapted into Heritage Building Information Modelling (HBIM), enabling the documentation, analysis, and management of historic buildings and monuments[5]. HBIM workflows commonly integrate laser scanning, photogrammetry, archival records, material characterisation, and conservation histories, supporting restoration planning and long-term monitoring[6]. These approaches improved geometric accuracy and integrated survey, historical, and conservation data within a single digital environment[4].

More recently, Scan-to-BIM workflows have been extended to include thematic mapping of decay and alteration phenomena, reinforcing HBIM's role as a platform for organising conservation-related information[6]. However, HBIM remains focused primarily on structural, geometric, and material aspects of heritage assets. Biological and other environmentally driven processes, including hydrological processes critical to understanding deterioration risks[7], are often seen as static descriptors rather than dynamic phenomena that can be analysed, modelled, and anticipated over time. This may partly explain their limited integration within current HBIM implementations, particularly when compared with data more readily expressed in parametric or numerical terms[4].

Biological colonisation as a missing dimension

Biological colonisation is a pervasive factor affecting historical buildings and monuments, with extensive research documenting the occurrence of bacteria, algae, fungi, lichens, and plants across diverse built substrates[8–12].

Biological growth alters moisture retention, salt mobilisation, mechanical stress, and surface chemistry, thereby influencing surface aesthetics, deterioration rates, the effectiveness of conservation treatments and long-term conservation outcomes. Under certain conditions, biological colonisation can contribute to surface protection through mechanisms such as thermal buffering, surface shielding, and biocementation, reducing dissolution rates and other forms of material loss[8,9,11].

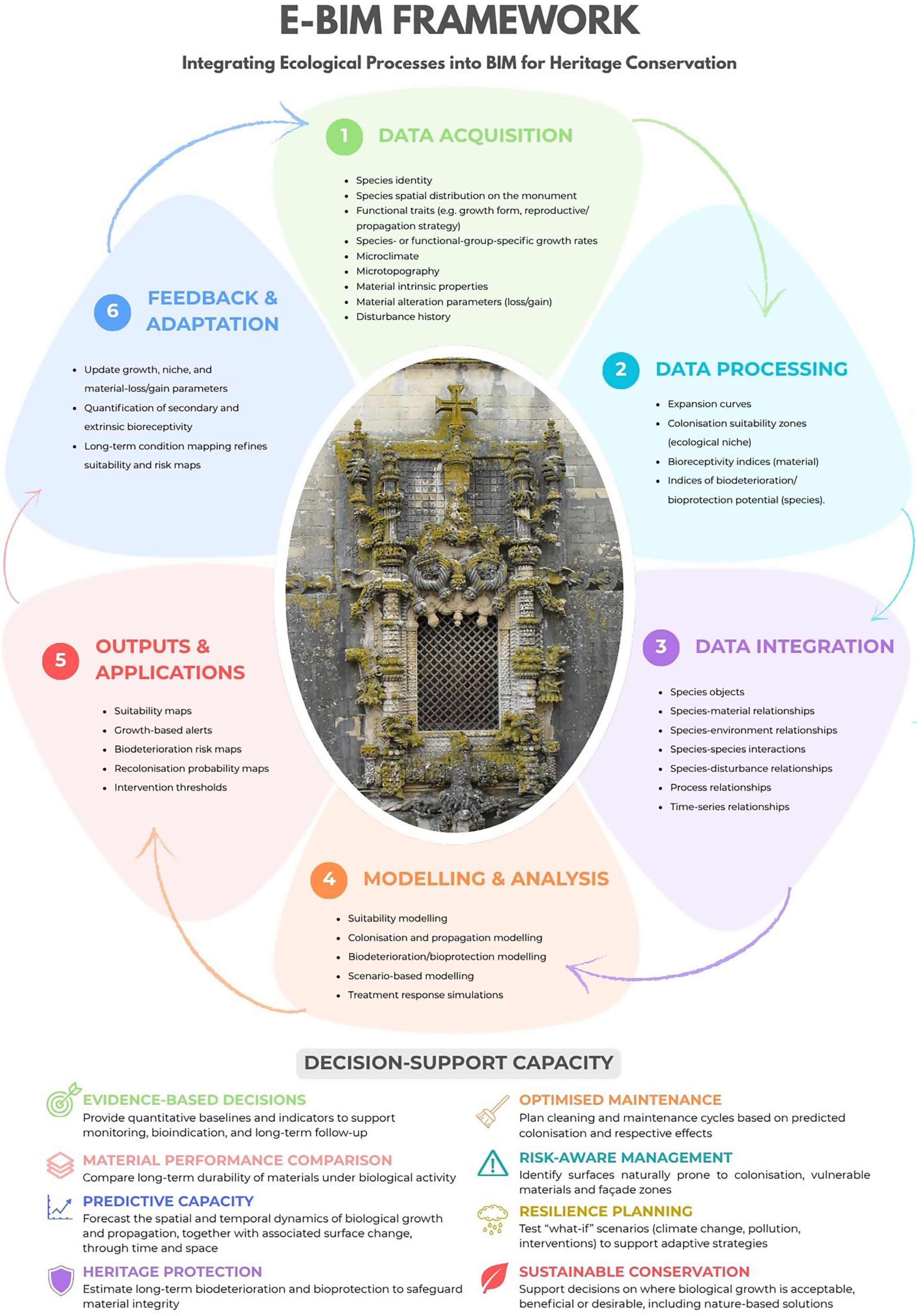
Despite this substantial body of knowledge, much research remains descriptive and does not provide the actionable, predictive information required by architects, engineers, and conservation practitioners. Within HBIM workflows, biological colonisation, when considered, is generally recorded as descriptive information (e.g., mapped decay) rather than directly addressed and treated as a dynamic process that can be quantified, modelled, or predicted.

Cooney et al. (2023) have shown how biological information can be linked to BIM-based workflows, focusing on the health-and-safety implications of microbial communities during refurbishment[13]. Such valuable pioneering efforts represent important early steps, but do not yet address process-based or scenario-oriented representations of biological dynamics essential for effective conservation planning. This underscores the need for a systematic framework that enables biological processes to be quantitatively modelled and operationalised within BIM environments.

As expectations for BIM-based decision support increase, there is a growing risk that biological data will be perceived as informative but operationally marginal. When biological information cannot be readily integrated into design, maintenance, or risk-assessment tools, it remains disconnected from the workflows that increasingly shape heritage management decisions.

Quantifying biological processes for Ecological BIM (E-BIM)

To enable meaningful integration of biological information into BIM environments, heritage science must move beyond documenting organism presence towards quantifying how biological processes operate across space and time.



E-BIM FRAMEWORK

Integrating Ecological Processes into BIM for Heritage Conservation

1 DATA ACQUISITION

- Species identity
- Species spatial distribution on the monument
- Functional traits (e.g. growth form, reproductive/propagation strategy)
- Species- or functional-group-specific growth rates
- Microclimate
- Microtopography
- Material intrinsic properties
- Material alteration parameters (loss/gain)
- Disturbance history

2 DATA PROCESSING

- Expansion curves
- Colonisation suitability zones (ecological niche)
- Bioreceptivity indices (material)
- Indices of biodeterioration/bioprotection potential (species).

3 DATA INTEGRATION

- Species objects
- Species-material relationships
- Species-environment relationships
- Species-species interactions
- Species-disturbance relationships
- Process relationships
- Time-series relationships

4 MODELLING & ANALYSIS

- Suitability modelling
- Colonisation and propagation modelling
- Biodeterioration/bioprotection modelling
- Scenario-based modelling
- Treatment response simulations

5 OUTPUTS & APPLICATIONS

- Suitability maps
- Growth-based alerts
- Biodeterioration risk maps
- Recolonisation probability maps
- Intervention thresholds

6 FEEDBACK & ADAPTATION

- Update growth, niche, and material-loss/gain parameters
- Quantification of secondary and extrinsic bioreceptivity
- Long-term condition mapping refines suitability and risk maps

DECISION-SUPPORT CAPACITY

EVIDENCE-BASED DECISIONS
Provide quantitative baselines and indicators to support monitoring, bioindication, and long-term follow-up

MATERIAL PERFORMANCE COMPARISON
Compare long-term durability of materials under biological activity

PREDICTIVE CAPACITY
Forecast the spatial and temporal dynamics of biological growth and propagation, together with associated surface change, through time and space

HERITAGE PROTECTION
Estimate long-term biodeterioration and bioprotection to safeguard material integrity

OPTIMISED MAINTENANCE
Plan cleaning and maintenance cycles based on predicted colonisation and respective effects

RISK-AWARE MANAGEMENT
Identify surfaces naturally prone to colonisation, vulnerable materials and façade zones

RESILIENCE PLANNING
Test "what-if" scenarios (climate change, pollution, interventions) to support adaptive strategies

SUSTAINABLE CONSERVATION
Support decisions on where biological growth is acceptable, beneficial or desirable, including nature-based solutions

Fig. 1 | Conceptual E-BIM framework illustrating the integration of ecological processes into BIM workflows for heritage conservation, including stages of data acquisition, processing, semantic integration, modelling and analysis, outputs/applications, and iterative feedback/adaptation. The framework highlights how biological, material, and environmental information may support monitoring, predictive modelling, and conservation decision-making within HBIM environments.

This requires treating biological colonisation as the ecological process it is, rather than as a static condition. Built heritage forms part of socio-ecological systems in which biological communities respond to material properties, (micro)climate, disturbance regimes, and management interventions, while simultaneously modifying the physical and chemical behaviour of materials, through feedbacks that evolve over time[14–17].

Disturbances such as pollution, fire, physical damage, cleaning and structural interventions can profoundly alter colonisation dynamics, triggering processes analogous to ecological succession in natural systems[18]. Different successional trajectories may coexist on the same monument, driven by fine-scale variation in microhabitat and microclimate. Although central to understanding biological change, these dynamics are rarely considered in heritage modelling frameworks, despite HBIM's unique capacity to organise, relate, and visualise them within a single system.

Early examples of the transition from description to quantification include indices linking lichen and vascular plant traits to their biodeteriogenic potential[19,20]. These approaches demonstrate how biological knowledge can be translated into structured indicators suitable for digital integration. Comparable metrics for other major biodeterioration agents, including cyanobacteria, algae, fungi and bryophytes are now needed.

The related concept of material bioreceptivity - the tendency of materials to support biological growth[17]—offers a complementary basis for E-BIM, but existing indices[21] remain fragmented and poorly aligned with BIM requirements.

For E-BIM to become operational, biological information must be translated into variables that can be associated with BIM objects and updated through time. This implies producing quantitative species- or functional-group-specific information on dispersal, growth rates, colonisation pathways, community dynamics, modes of substrate interaction, and resulting physical or chemical effects across different materials and climate conditions[15]. Future frameworks should clearly distinguish within E-BIM semantic structures between (i) colonisation occurrence and abundance on or within substrates, (ii) the biological processes operating at the surface or subsurface, and (iii) their effects on material properties. Materials, in turn, should be characterised using bioreceptivity-related attributes that complement existing material property data. Linking species-specific impact profiles with material-specific bioreceptivity parameters, reproductive and propagative potential, and environmental conditions would enable monitoring, scenario testing, and prediction of biological change under different management strategies and future scenarios. The conceptual workflow and operational structure of E-BIM are summarised in Fig. 1.

Although discussions of biological colonisation often focus on exterior surfaces, E-BIM is equally relevant to indoor environments (Fig. 1), where biofilms can strongly affect material performance, conservation outcomes, and health considerations[13,22].

Biologists working in heritage science are key contributors to E-BIM, as they are uniquely equipped to generate the species- and context-specific datasets required, explicitly accounting for variation in material properties and climatic conditions.

Integration into BIM environments will also benefit from simpler, faster, and lower-cost analytical methods capable of generating standardised datasets at scale. High costs and logistical constraints often limit sampling intensity and spatial coverage, reducing data representativeness. Affordable and time-efficient approaches are essential for generating spatially and temporally robust datasets for BIM integration across diverse heritage contexts.

Advances in molecular methods, including metabarcoding and functional omics approaches (e.g., metagenomics, metatranscriptomics, metaproteomics and metabolomics) are transforming the characterisation of biological communities on built heritage[23]. While these techniques improve taxonomic resolution and provide insights into community composition, functional potential, and biological activity, their ability to quantify ecological process rates and biodeterioration dynamics remains limited. Approaches targeting gene expression, proteins, and metabolites hold considerable promise for capturing ongoing biological processes, but their application to heritage systems is still at an early stage and has been more widely proposed than systematically explored. As a result, the integration of molecular data into predictive models remains constrained by incomplete reference databases, methodological limitations, and uncertainties in translating molecular signals into rates of biological activity and material change[24]. Moreover, the lack of standardised parameters and protocols for characterising biologically driven changes in material properties limits the development of comparable datasets and robust reference frameworks.

In summary, if a surface is colonised by a known species assemblage, colonisation rates and impact indices could be associated with corresponding surface elements within a BIM model. Combined with environmental data, at both micro and macro-scales, and material bioreceptivity parameters, this information could support simulations of future colonisation trajectories and associated material change. In this way, E-BIM would move beyond static documentation towards biologically informed monitoring and scenario-based conservation planning. These conceptual and operational relationships are further synthesised in Table 1.

Recommendations for advancing E-BIM in heritage science

1. Develop standardised bioreceptivity databases: Quantify bioreceptivity for different substrate types, while accounting for the influence of climatic context, dispersal and successional dynamics, and disturbance regimes on the expression of biological colonisation. Bioreceptivity should be treated as a dynamic, context-dependent property rather than as a fixed material attribute. Future E-BIM developments could progressively integrate interoperable bioreceptivity datasets stratified by material type, climatic context, and disturbance regime.
2. Prioritise process-based indicators over inventories: Focus on rates, thresholds, and trajectories of colonisation; interactions between species or functional groups and substrate types; community dynamics (e.g., competition, facilitation); and biogeomorphic effects (e.g., biodeterioration and bioprotection), rather than on static species lists. Process-oriented indicators are essential for modelling and comparison within HBIM environments.
3. Design HBIM-compatible data structures: Ensure that biological and ecological indicators are expressed in formats compatible with HBIM objects, property sets, and time-based simulations, allowing integration into monitoring workflows, scenario testing, and digital twins.
4. Integrate climate (including hydrology) and biology from the outset: Treat biological colonisation as an emergent property of coupled

Table 1 | Comparative overview of BIM, HBIM, and E-BIM workflows, summarising their respective core purposes, dimensional frameworks, knowledge levels, life-cycle relevance, data acquisition and processing methods, semantic integration, analytical capabilities, decision-support functions, update mechanisms, and disciplinary contributors

WORKFLOW DIMENTION	BIM	HBIM	E-BIM
Core purpose	Digital representation of built assets for design, construction, and lifecycle management	Documentation, interpretation, management and conservation of historic buildings using survey-based, archival, and diagnostic data	Integration of biological processes as dynamic, quantifiable drivers of material change
Primary processes modelled	Structural behaviour, energy performance, cost/time simulations	Material decay, historical phasing, conservation assessment and interventions	Biological colonisation dynamics, successional trajectories, biodeterioration and bioprotection processes, microclimate–biology feedbacks, disturbance-driven recolonisation
Dimensionality	3D Geometry; 4D Time; 5D Cost; 6D Sustainability; 7D Facility Management	3D Analytical Survey; 4D Historical Evolution; 5D Diagnosis; 6D Cultural Context; 7D Preventive Conservation (Castellano-Román & Pinto-Puerto, 2019)	Eco-3D Ecological characterisation; Eco-4D Temporal ecological dynamics; Eco-5D Biological risk/cost; Eco-6D Ecological performance (e.g., bioprotection, nature-based solutions); Eco-7D Scenario-based ecological trajectories under climate change, pollution, cleaning, and structural interventions
Levels of Development/ Knowledge	LOD100–500 — conceptual → schematic → detailed → fabrication → as-built	LOK1–5: Identification → Protection & Dissemination → Advanced Research → Conservation & Intervention → Comprehensive Management (Castellano-Román & Pinto-Puerto, 2019)	E-LOK1–5: Diversity (identification) → Distribution (spatialisation) → Processes (bioreceptivity, growth, propagation, alteration) → Interactions (competition, facilitation) → Scenario-based ecological modelling
Life-cycle relevance	Design, construction, operation, maintenance, demolition	Documentation, conservation, monitoring, maintenance	All life-cycle stages where biological processes influence material performance (dispersal, colonisation onset, growth/persistence, treatment response, recolonisation cycles, long-term ecological trajectories)
Data acquisition	Design models; construction records; sensor data	Laser scanning; photogrammetry; archives; material surveys; condition mapping	Spatially explicit biological surveys; material and microclimate characterisation; biologically relevant condition mapping
Data processing	Geometric modelling; parametric object generation; interoperability workflows; sensor-data processing	Scan-to-BIM; geometric reconstruction; historical data interpretation; condition-map processing; custom heritage object generation	Ecological parameterisation; microhabitat suitability and bioreceptivity analysis; growth modelling; biodeterioration/bioprotection index generation; ecological relationship modelling; uncertainty quantification
Data Integration	BIM objects (walls, roofs, MEP, materials) with spatial (containment, adjacency), parametric (constraints), topological (connectivity), and semantic (documents, schedules) relationships	Heritage objects (elements, stratigraphic units, decorative features, conservation records) with diachronic (phasing), stratigraphic (superposition), authenticity (original/ restored), and documentary (archives, iconography) relationships	E-BIM objects (species, functional groups, ecological indicators) with ecological relationships (species–material, species–environment, species–species, species–disturbance), temporal relationships (colonisation cycles), and semantic links to monitoring, treatments, and environmental data
Analytical capabilities	Structural, energy, cost, scheduling, lifecycle analysis	Conservation planning, deterioration mapping, diagnostic assessment, monitoring	Ecological suitability assessment; colonisation and recolonisation modelling; biodeterioration/ bioprotection assessment; scenario-based ecological modelling; ecologically informed conservation planning
Decision support	Design optimisation, construction coordination, asset management	Conservation planning and maintenance prioritisation	Adaptive conservation, ecological risk assessment, intervention timing, ecological monitoring, scenario-based management
Update mechanisms	As-built revisions; sensor updates; digital twins	Conservation records and monitoring updates	Iterative updating through ecological monitoring, environmental sensing, disturbance history, and intervention feedback
Main contributors	Architects, engineers, contractors, BIM managers, manufacturers, facility managers, software developers	BIM contributors + archaeologists, historians, conservators-restorers, heritage managers	BIM/HBIM contributors + biologists/ecologists, conservation scientists, environmental scientists, geoscientists

HBIM dimensionality and Levels of Knowledge (LOK) terminology reproduced from: Castellano-Román, M.; Pinto-Puerto, F. Dimensions and Levels of Knowledge in Heritage Building Information Modelling, HBIM: The model of the Charterhouse of Jerez (Cádiz, Spain). Digital Applications in Archaeology and Cultural Heritage 14 (2019), e00110. https://doi.org/10.1016/j.daach.2019.e00110.

biological-environmental systems by explicitly linking biological data with climatic and microclimatic conditions, as well as hydrological processes such as moisture transport, wetting-drying cycles, and water availability at material surfaces. Where detailed sensor data are sparse or uneven, E-BIM should incorporate proxy variables, modelled parameters, and contextual information on exposure, materials, and disturbance history.

5. Promote interdisciplinary co-design: Ensure that ecologists, heritage scientists, HBIM developers, and practitioners jointly define which biological data are relevant and usable within HBIM-based decision-making workflows.
6. Strengthen spatial and temporal sampling strategies: Biological and ecological data intended for HBIM integration must be collected using sampling designs that represent the spatial heterogeneity and temporal dynamics of individual buildings and monuments. Capturing and modelling colonisation dynamics and impacts on material properties requires environmental data at spatial and temporal resolutions rarely available in current heritage monitoring and HBIM workflows. Opportunistic or isolated sampling points are insufficient to characterise complex processes operating across diverse microhabitats and environmental gradients, particularly where successional dynamics and disturbance-driven change are involved. Higher spatial and temporal resolution must be balanced against the challenges of analysing large datasets and developing robust, interpretable, and computationally efficient predictive models.
7. Promote scale convergence between ecology and HBIM applications: Ecological processes relevant to material deterioration and surface change operate at fine spatial and temporal scales, while many current HBIM applications prioritise coarser structural, functional, or asset-management perspectives. Advancing E-BIM, therefore, requires convergence between these approaches, with HBIM workflows increasingly accommodating fine-scale biological and environmental processes, and ecological data being structured in ways that are meaningful and usable within HBIM environments. This may involve hierarchical spatial organisation, in which fine-scale ecological observations are associated with broader architectural or management units through nested relational structures. Aligning scales is essential for integrating ecological processes into modelling and decision-making without overburdening workflows. Where HBIM questions operate primarily at larger structural or urban scales, ecological data can still contribute through the integration of broader biological and environmental drivers, including long-term climatic trends and scenario-based projections.

E-BIM should not be understood as an additional layer of complexity, but as a translation effort, converting biological knowledge into a form that can actively inform design, conservation, and long-term management decisions. Embracing ecological concepts such as disturbance, succession, and scale-dependence is essential if E-BIM is to move beyond descriptive layers and become a meaningful tool for anticipating biological change in heritage environments.

Extending E-BIM beyond heritage

The conceptual framework of E-BIM is not restricted to heritage contexts and has the potential to contribute broadly to contemporary architecture and urban development. As buildings increasingly incorporate bio-integrated design strategies, such as green façades, living roofs, nature-based solutions, and bioreceptive materials, there is a growing need to understand, model, and manage biological processes as integral components of the built environment.

In new construction, biological growth is often intentionally promoted to improve thermal performance, reduce energy demand, mitigate climate change impacts, and enhance urban biodiversity[25]. As in heritage contexts, the effectiveness and long-term behaviour of these interventions depend on species traits, material properties, microclimatic conditions, disturbance, and management regimes. E-BIM provides a structured framework to link biological dynamics with material and environmental data, enabling simulation, monitoring, and adaptive management through time.

Heritage environments, where biological colonisation is unavoidable, long-term, and frequently constrained by conservation requirements, offer a particularly demanding testing ground for developing ecological indicators, data structures, and modelling approaches. Insights gained from these contexts, especially regarding process-based indicators, bioreceptivity, and the coupling of biology with microclimate, are therefore directly transferable to wider BIM applications in contemporary construction and urban systems.

In this sense, E-BIM should be understood not as a niche extension of HBIM, but as a generalisable approach for integrating ecological processes into digital representations of the built environment, supporting more resilient and ecologically informed design and management practices.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

J.M. conceived the article and led the drafting of the manuscript. S.V. and H.V. contributed to the development of the ecological and heritage science concepts and critically revised the text. All authors contributed to discussion, reviewed the final manuscript, and approved the submitted version.

Competing interests

The authors declare no competing interests.

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