



BIM-based framework for estimating service life duration of wood construction elements under environmental exposure

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ABSTRACT

As the construction industry adopts more data-driven and sustainable practices, Building Information Modelling (BIM) is increasingly used for energy analysis, lifecycle management, and maintenance planning. However, its integration with service life performance analysis especially for wood, a material susceptible to environmental degradation remains limited. This study presents a BIM-based framework that incorporates wood-specific parameters such as environmental exposure, material properties, and design detailing to estimate the service life of wood construction elements. The framework is structured using ISO 15,686-4 principles and implemented through custom Industry Foundation Classes (IFC) property sets. A Revit plugin developed in C# integrates the model into the BIM environment. A case study of a wooden playhouse is used as a proof-of-concept to demonstrate the framework's ability to evaluate the impact of design, material, and environmental factors on service life. The results confirm that the framework supports service life prediction and enhances decision-making for wood-based construction. Twenty-one-month observations align with predicted results. However, long-term (2–9 year) predictions remain unvalidated, requiring extended monitoring. By integration of the service life prediction for fungal decay into BIM it offers a practical and scalable tool to support service life-informed design and planning for wood structures.

1. Introduction

Wood is increasingly recognized as a fundamental material in sustainable construction, valued for its renewable nature, environmental benefits, structural versatility, and economic efficiency [1]. Unlike conventional materials such as concrete and steel, wood sequesters carbon, reducing the high carbon footprint of the construction industry and contributing to global climate mitigation efforts [2]. Its aesthetic appeal, adaptability, and ability to enhance indoor environmental quality further reinforce its significance in modern architecture and engineering. Recent evaluations of real-world timber buildings further confirm wood's effectiveness in lowering environmental impacts compared to conventional construction practices [3]. However, its performance is highly dependent on external environmental factors, including moisture [4], temperature–moisture interactions [5], UV radiation [6], and biotic agents such as fungi and insects [7]. These environmental factors introduce complexity into predicting wood durability across diverse construction contexts. As a result, service life estimation (SLE) plays a key role in informing design and maintenance

strategies that extend material lifespan and reduce premature replacement [8,9].

Despite its growing importance in sustainable construction, service life estimation (SLE) remains insufficiently integrated into contemporary design and construction workflows [10]. In the field of wood construction, professionals still rely heavily on historical data, expert judgment, or generalized assumptions, rather than project-specific performance modelling. This is evident in life cycle assessment (LCA) studies, where standardized service life values typically ranging from 30 to 50 years for wood are frequently adopted [10], often without adequate consideration of environmental exposure, design detailing, or end-of-life modelling limitations [11]. Similarly, Davis et al. [12] identify 50 years as the most frequently used default service life. Recent LCA studies of real-world timber buildings continue to rely on generalized service life assumptions, largely due to the limited integration of project-specific durability modelling [3]. These simplified assumptions are not only used in LCA but also dominate life cycle costing (LCC) and maintenance planning models, where they are often applied without adjusting for contextual variables such as climate, material degradation

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behaviour, construction detailing, or maintenance regimes [13,14]. This lack of detailed estimations introduce uncertainty into long-term cost projections, durability expectations, and environmental assessments [14,10].

Various research initiatives have advanced service life modelling for wood construction [15]. The TimberLife Project introduced probabilistic models for timber durability, while WoodExter refined above-ground service life prediction using a dose-response approach aligned with Eurocode 5 [16]. The BIO4ever project focused on the performance of biomaterials during the service life, while also considering the end-of-life scenario [17]. Other initiatives, such as WoodBuild and DuraTB, focused on outdoor applications and timber bridges, respectively. The CLICKdesign project [18] developed digital tools for specifying wood performance in design workflows. WoodLCC project extends previous work by creating an LCC framework that integrates advanced service life prediction models into BIM.

In addition to contributions from large-scale projects on service life modelling (SLE) of wood, individual studies have addressed critical knowledge gaps through focused, empirical research. Key among these are investigations into biological decay mechanisms. Schrader et al. [19] detailed the microbial communities responsible for wood degradation, while Isola et al. [20] and Tatum [21] highlighted fungal decay processes and diagnostic tools, extending insights from the microstructural to structural scales. Moisture dynamics which are a key decay driver, have also been examined in depth. Brischke et al. [22] demonstrated intra-species variability in moisture behaviour, challenging the use of generalized material properties in predictive models. Their subsequent studies evaluated the performance of treated and modified wood under decay stress [23] and refined durability classifications using statistical methods [4]. Recent work also integrates climatic data into decay risk models. van Niekerk et al. [24] mapped fungal decay hazards across Europe using ERA5-Land data, while a companion study by van Niekerk et al. [15] projected an increase in-ground fungal decay hazard zones in Germany under recent climate shifts, highlighting the implications of long-term climatic changes on decay modelling. However, the latest studies on the bioreceptivity of wood and other bio-based materials emphasize that microbial colonization alone does not necessarily indicate material deterioration or decay [25]. These highlight the need for geographically adaptive, climate-sensitive modelling. Other contributions apply SLE in practical contexts. Gaspari et al. [26] modelled decay risk in timber balconies, and Anastasiades et al. [27] developed reusability models aligned with circular construction. Together, these studies provide essential insights into biological decay, environmental sensitivity, and predictive modelling, forming the basis for more detailed digital integrated SLE tools like the BIM-based framework proposed in this study.

Despite progress in developing service life estimation (SLE) models, their integration into digital design workflows remains limited due to the lack of harmonized tools, localized datasets, and regulatory standards. While BIM has been successfully adopted for structural performance analysis, life cycle analysis [28] energy efficiency assessment, and life cycle costing [29], its application in service life estimation for wood construction is still underdeveloped. This digital disconnect is especially problematic in wood-based construction, where material performance is highly sensitive to environmental conditions. As a result, professionals face challenges in applying SLE insights during design, leading to over- or under-engineered solutions, inefficient maintenance strategies, and reduced asset reliability [30,31].

To address these research gaps, this study develops a BIM-based framework that integrates wood-specific factors, including environmental conditions, material properties, and design details, to estimate the service life duration of wood construction elements. Conducted within the scope of the WoodLCC project [32], this proof-of-concept study proposes a BIM-based application that enhances service life prediction by incorporating these key parameters into modern construction workflows, enabling predictive planning, material optimization, and

fungal decay performance-driven decision-making. The novelty of this work lies in operationalizing existing dose-response models within a professional BIM authoring tool (Revit), enabling service life estimation and IFC-based data export. This practical integration marks one of the first efforts to embed wood decay modelling directly into digital design tools, offering a foundation for incorporating future advances in service life performance modelling into BIM environments.

2. Methodology

2.1. Service life prediction model

The prediction of service life for wood construction elements fundamentally relies on comparing two critical values. These include material resistance which is the wood's ability to resist environmental degradation and the exposure dose which is the environmental stress imposed on the wood. To estimate how long a wooden structure will last, it is essential to determine whether the wood's resistance exceeds its exposure to environmental factors. The fundamental mathematical relationship underpinning this principle is presented in Eq. (1), as derived from experimental research [33–35]:

$$SL \geq D_{Rd}/D_{Ed} \quad (1)$$

where:

SL = Service Life (years), the expected duration (onset of decay).

D_{Rd} = Material resistance Dose (days), quantifying the wood's inherent or enhanced capability to resist degradation due to its natural durability or protective treatments.

D_{Ed} = Exposure Dose (days/year), representing the annual cumulative impact of environmental factors that accelerate the degradation process.

This provides a scientific method for predicting the threshold (onset) at which decay becomes a concern which aligns with ISO 15,686. Although the relationship between resistance and exposure is simplified as linear, this formulation is grounded in established dose-response models and is purposely adopted to ensure computational efficiency and seamless integration into BIM workflows, which was a primary objective of this study.

Calculation of material resistance dose

Material resistance dose (D_{Rd}) represents the ability of wood to resist fungal decay under environmental exposure. In this study, D_{Rd} values for 170 wood species and treatments are adopted from datasets developed within the CLICKdesign [18] project and the multi-part study by Alfredsen et al., [38], Brischke et al. [39]. The material resistance dose (D_{Rd}) is presented in Eq. (2).

$$D_{Rd} = D_{crit} * k_{wa} * k_{inh}[d] \quad (2)$$

where:

D_{crit} = the critical dose required to initiate slight decay (days),

k_{wa} = the wetting ability factor derived from tests on moisture uptake and drying behaviour (dimensionless),

k_{inh} = the inherent durability factor reflecting fungal resistance based on extractive content and cell wall properties (dimensionless).

The dataset incorporates results from standardized lab decay tests (EN 113–2), semi-field terrestrial microcosms, and long-term above-ground/in-ground field exposures. Part 1 of the series established baseline conversion factors between European reference species and outlined the role of material variability in resistance modelling [36]. Part 2 validated and optimized the Meyer-Veltrup model using broader datasets, including treated and modified wood, and refined the upper

thresholds for the k_{wa} and k_{inh} parameters [37]. Part 3 compiled a global dataset covering over 300 wood species and treatment systems, distinguishing between in-ground and above-ground exposure conditions and allowing for resistance mapping across regions [38]. In our implementation, details of the 170 wood species and treatment data is taken from these sources and assembled using Eq. (2). The intrinsic durability values used here were not re-validated in this study. The data schema is extensible, allowing straightforward integration of additional species or treatments when characterization data are available.

Calculation of exposure dose

The exposure dose (D_{Ed}) represents the annual environmental impact on a wooden element based on moisture and temperature conditions, i.e. the material climate. The relevant environmental influences depend on whether the wood is exposed in-ground or above ground. In above ground conditions, the estimation of exposure dose accounts for factors such as rainfall, wind-driven rain, local climate, design detailing, sheltering conditions (e.g., roof overhangs), and proximity to the ground. For in-ground conditions, the exposure dose is described as a fixed value per location, which has accounted for the actual soil conditions. For above ground conditions, the annual exposure dose ($D_{Ek} = D_{Ed}$) is calculated by applying a set of environmental and design-related multipliers to a reference value. This is expressed in Eq. (3) as:

$$D_{Ek} = k_{E1} * k_{E2} * k_{E3} * k_{E4} * k_{E5} * D_{E0} \quad (3)$$

where:

- D_{Ek} = Factorized characteristic exposure dose (days/year)
- D_{E0} = Reference annual exposure depending on different geographical locations (days/year)
- k_{E1} = Effect of wind driven rain on surfaces (dimensionless factor)
- k_{E2} = Local climate conditions (dimensionless factor)
- k_{E3} = Effect of sheltering (dimensionless factor)
- k_{E4} = Effect of distance from ground (dimensionless factor)
- k_{E5} = Design-specific factors e.g., grain orientation, connections, exposure and contact with other elements (dimensionless factor)

D_{E0} is the reference annual exposure dose expressed in units of days/year and represents the equivalent number of days per year when climatic conditions (wood moisture content and temperature) are ideal for facilitating fungal decay in wood. The values applied in this study are derived by first conducting moisture simulations for a statistically average year at each location based on climatic data. In this study, these reference doses have been quantified through climatic analyses and are compiled into two distinct datasets (for in-ground and above-ground conditions) for 533 distinct locations across Europe. For above-ground conditions, the parametrisation of reference dose, as well as the factors accounting for detailing and sheltering, are based on analysis of statistical average years [34]. For in-ground conditions, the reference values are modelled by soil-specific decay response functions incorporating soil temperature, moisture, and water-holding capacity ([39] and [40]). The latter presents an independently validated dose-response model for predicting decay in European beech, achieving an $R^2 = 0.65$ in an independent dataset of 480 specimens exposed to fluctuating soil temperatures, supporting its applicability for practical risk assessments.

Geographic hazard mapping methods and future climate scenarios were applied following the methodologies outlined by [16] to assign location-specific decay potential. For in-ground conditions, all additional adjustment factors (k_{E1} to k_{E5}) are set to 1, as they do not affect the modelling of in-ground wood decay. These datasets, developed within the CLICKdesign [18], and WoodLCC [41] projects, provide geographically resolved, exposure-type-specific inputs for performance-based service life prediction.

Effect of wind driven rain factor (k_{E1}) is a factor to adjust exposure based on the intensity of wind-driven rain (WDR) impacting the wood

surface. The local climatic factor k_{E2} adjusts the exposure dose to reflect local environmental conditions such as terrain and nearby buildings. These influence the severity of exposure to wind and moisture. According to [35], the value of k_{E2} ranges between 0.8 and 1.0 as presented in Table 1.

In this study, we assumed the elements are fully exposed, meaning no surrounding protection from terrain or buildings was considered. Therefore, we used a fixed value of $k_{E2} = 1$. This assumption simplifies the model while still aligning with realistic worst-case exposure conditions for outdoor wooden elements. The sheltering factor (k_{E3}) adjusts the exposure dose based on how protected a wooden element is from rain by features like roof overhangs or balconies. Greater shelter reduces moisture impact and decay risk.

In this study, the effects of wind-driven rain and sheltering were combined into an adjusted exposure dose (η) using an interpolation approach instead of applying them as separate multipliers, the exposure dose was interpolated between two reference cases: a fully exposed surface and a fully sheltered surface. This approach assumes that sheltering reduces the fraction of rain reaching the surface, particularly for above-ground elements. In this approach, the effect of wind driven rain (η_1) is the ratio of rain striking the surface in question to that of a horizontal surface. The amount of rain striking the surface in question depends on both the amount of WDR at the location and whether shelter is present. The former ratio is presented in Eq. (4):

$$\eta_1 = R_{wdr} / R_h \quad (4)$$

Where R_h is the reference horizontal rainfall and R_{wdr} is the wind-driven rain on the vertical surface, calculated using the established WDR formula from [42] and [43]:

$$R_{wdr} = (R_h * 0.222 * U * \cos(\varphi)) / V_t \quad (5)$$

Where:

- R_h = Rainfall rate striking the ground plane (mm/h)
- U = Wind speed (m/s)
- V_t = Terminal velocity of raindrops (typically 4.5 m/s for light to moderate rain) (Blocken and Carmeliet, 2004)
- φ = Angle between the wind direction and the surface normal.

The effect of shelter is calculated using a geometric formula (Eq. (6)) that considers the overhang depth and vertical distance to the element [33]:

$$\eta_2 = 1 - (e / d) \quad (6)$$

Where:

- e = horizontal length of the overhang (cm)
- d = vertical distance from the overhang to the wood element (cm)

When e is large and d is small (i.e., the overhang is wide and the element is close to it), the value of k_{E3} becomes smaller, indicating better protection. For a fully protected surface ($e/d = 0.5$, i.e., a 45° shelter), exposure is negligible. For an unprotected member, exposure remains at its full value ($k_{E3} = 1$) and for intermediate cases, linear interpolation is used to approximate the effect of sheltering [33]. The effect of wind driven rain (η_1) and the effect of shelter (η_2) are combined to calculate the ratio of rain striking the surface in question to that of a horizontal

Table 1
Determining k_{E2} Based on Local Exposure Conditions (adapted from [35]).

Exposure Level	Site Conditions	k_{E2}
Low	Protected by both terrain and surrounding buildings	0.8
Moderate	Protected by either terrain or buildings	0.9
High	No protection from terrain or buildings (fully exposed)	1.0

surface is expressed as the adjusted exposure dose for rain and shelter ($\eta = \eta_1 \eta_2$) and presented in Eq. (7).

$$\eta = (D_s + (\eta_1 * \eta_2) * (D_{E0} - D_s)) / D_{E0} \quad (7)$$

Where:

- η = Adjusted exposure dose after accounting for rain and sheltering
- D_s = Dose under fully sheltered condition (pre-computed for different locations)
- D_{E0} = Reference dose under fully exposed condition (pre-computed for different locations)
- $D_{\text{delta}} = (D_{E0} - D_s)$ = Dose difference between exposed and sheltered conditions
- η_1 = Rain exposure factor (pre-computed for different locations) as presented in Eq. (4)
- $\eta_2 = 1 - \frac{g}{d}$ = geometric sheltering factor as presented in Eq. (6)

By expressing sheltering as a proportional reduction of incident rain, the method captures the net effect on surface wetting in a straightforward way. This simplification allows for element-specific adjustments while ensuring practical applicability, making the approach well-suited for comparative assessments. It should be emphasized, however, that the method does not capture the complex fluid dynamics of rain impact.

The distance from ground factor (k_{E4}) accounts for the impact of the vertical distance between a wooden element and the ground surface on its moisture exposure and corresponding risk of fungal decay. Elements positioned closer to the ground are more prone to splash water, capillary moisture, and reduced air circulation, increasing their exposure to wet conditions. Conversely, elevated elements benefit from better ventilation and reduced moisture accumulation. This is mathematically presented in Eq. (8):

$$k_4 = \begin{cases} 2 & a \leq 100 \\ a/200 + 0.5 & 100 < a \leq 300 \\ 1 & a > 300 \end{cases} \quad (8)$$

where a is the distance from the ground (in mm).

As presented in Table 2, This formulation is based on [35] and linear interpolation, ensuring that timber elements close to the ground receive a higher exposure rating, improving decay risk assessments.

The detail design factor (k_{E5}), based on [16], categorized details by absorption mode (end-grain vs. side-grain) and whether a surface was in contact with another member. These design-specific features influence the rate of moisture accumulation and drying, which are critical drivers of wood decay. Unlike fixed-value models, this study adopts a dynamic, data-driven approach based on the work of Niklewski et al. [34], where each detailing configuration is assigned a location-specific dose adjustment factor ($k_{\text{trap}1}$ to $k_{\text{trap}5}$) derived from climatic simulations and empirical moisture risk studies. This is presented in Table 3.

$$k_{E5} = f(g, c) \quad (9)$$

where:

Table 2

Distance from Ground Factor (k_{E4}) Based on Element Height Above Ground (Adapted from [35]).

Distance from Ground (a)	Value	Description
$a \leq 100\text{mm}$	2.0	Very high exposure due to splash water and poor drying
$100 < a \leq 300 \text{ mm}$	1.0 – 2.0	Gradual reduction with value decreases linearly with a
$a > 300 \text{ mm}$	1.0	Normalized exposure due to improved ventilation

Table 3

Detailing Conditions and Corresponding $k_{\text{trap}1}$ to $k_{\text{trap}5}$ Values pre-computed for the different locations.

Grain Orientation	Contact Condition	Factor Name	Description
Side-grain	No contact or gap > 5 mm	1.0	Reference case (low exposure)
Side-grain	Partially ventilated surface	$k_{\text{trap}1}$	Moderately increased dose
Side-grain	Direct contact or insufficient ventilation	$k_{\text{trap}2}$	Highest exposure for side-grain
End-grain	No contact or gap > 5 mm	$k_{\text{trap}5}$	High dose due to exposed end-grain
End-grain	Partially ventilated surface	$k_{\text{trap}3}$	Very high exposure
End-grain	Direct contact or insufficient ventilation	$k_{\text{trap}4}$	Extreme exposure and moisture retention

g = the grain orientation, either side-grain or end-grain.

c = the contact type, which refers to the interface conditions such as no contact, partially ventilated, or direct contact.

All datasets referred to were pre-computed within the CLICKdesign [18] and WoodLCC [41] projects with public access together with source code on Zenodo and Github [44].

The model specifically estimates the time until the onset of decay but not complete degradation of the material. This means that the predicted service life represents the point at which environmental exposure is sufficient to trigger fungal activity and initiate decay processes, rather than the total functional lifespan of the element. By focusing on decay initiation, the model provides a proactive risk assessment tool, allowing for early design interventions, preventive treatments, and optimized maintenance planning to extend the actual functional service life of wood construction elements.

It should be emphasized that the Meyer-Veltrup decay model as adopted in this research, does not fully align with the progressive degradation lifecycle framework outlined in ISO 15,686. While ISO 15,686 emphasizes a comprehensive approach to service life planning including the full trajectory of material performance, deterioration, and maintenance. The Meyer-Veltrup model defines service life duration primarily as the onset of biological decay. It does not account for the subsequent progression of deterioration, which is often non-linear and influenced by a wide range of biotic and abiotic factors; in particular, it excludes deterioration mechanisms not related to moisture such as those driven by solar radiation or thermal stress further constrains the model's ability to comprehensively describe deterioration kinetics. As a result, the values predicted by the proposed BIM tool should be interpreted as approximations useful for early-stage design decisions and risk assessment. The tool offers valuable insights, but its outputs should be complemented by professional judgment and ongoing condition monitoring.

2.2. Conceptual framework for BIM-Integrated service life prediction

The framework aims to incorporate wood-specific data into a BIM environment, allowing the prediction of service life duration based on material properties, environmental exposure, and design factors. As presented in Fig. 1, the framework is structured into four core phases.

Phase 1: multisource data acquisition and integration

The first phase involves collecting, organizing, and formatting all necessary data required for service life estimation. This includes material data (e.g., species, treatment methods), environmental exposure parameters (e.g., wind-driven rain), design-specific detailing (e.g., overhang dimensions, ground proximity, grain exposure conditions) and location specific data. To ensure compatibility and interoperability with BIM platforms, all parameters are structured according to ISO 15,686–4 guidelines and mapped into customIFC4 property sets, such as

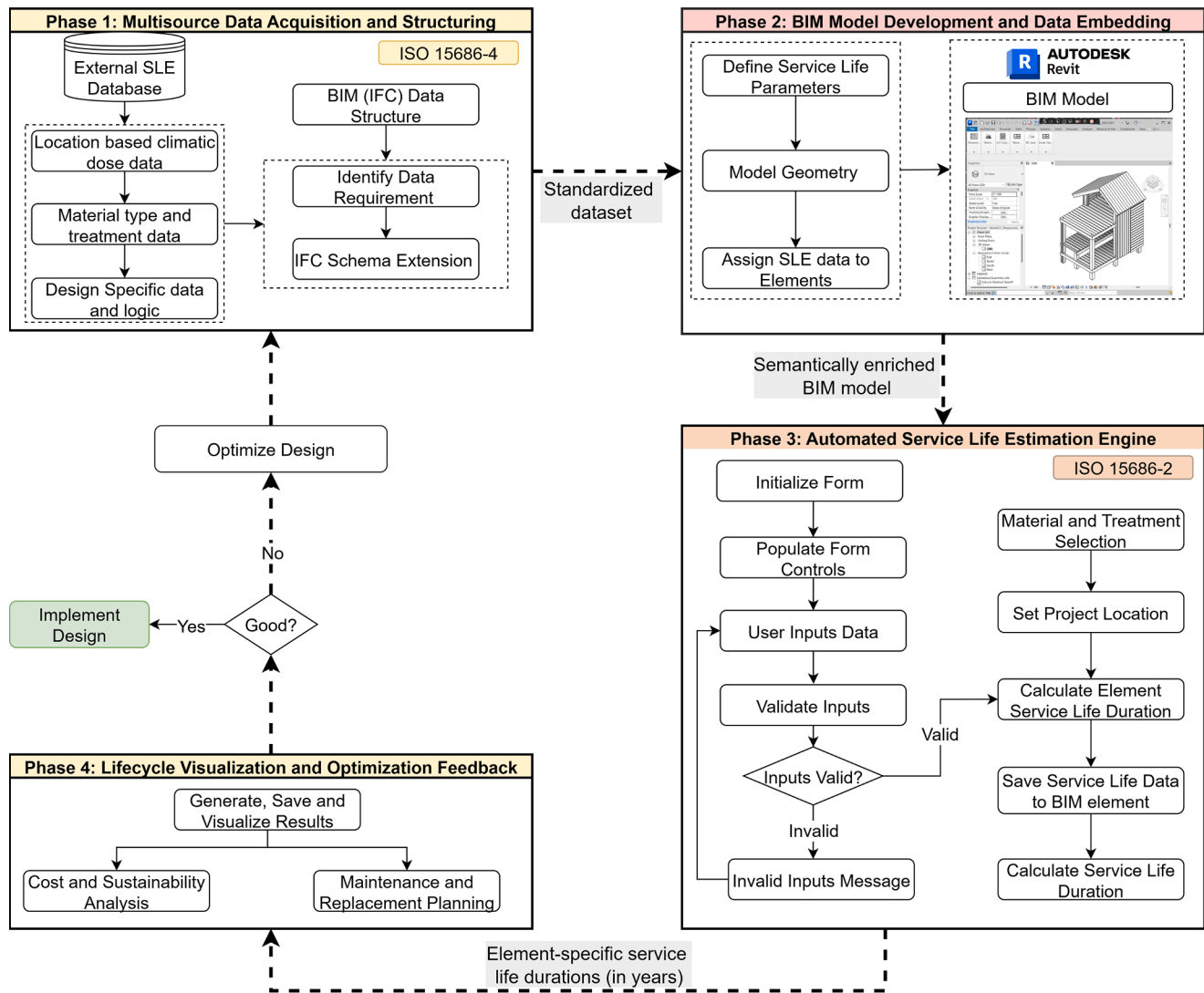


Fig. 1. Four-phase BIM-integrated framework for estimating and optimizing service life duration of wood construction elements.

ServiceLifeData Pset and MaterialWoodTreatment Pset. External datasets are handled using JSON serialization, allowing for flexible updates and seamless integration with the plugin's backend logic. Key output is a standardized dataset of SLE parameters, prepared for assignment to BIM elements.

Phase 2: BIM model development and data embedding

In this phase, the data generated in Phase 1 is integrated into the 3D BIM model. Using Autodesk Revit as the host environment, element geometries are defined or imported and structured SLE data is assigned to each relevant wood component. The RevitWoodLCC plugin provides an interface for users to input project-specific values such as material type, treatment level, location, and shelter conditions which are then stored as custom parameters within the BIM model. These parameters are embedded at the element level, ensuring they persist across model revisions and IFC exports. Key output is a semantically enriched BIM model in which each wood element carries its own service life prediction input data.

Phase 3: service life estimation engine

The third phase focuses on calculating the predicted service life of each wood element. This is achieved through a factor-based algorithm implemented in the backend of the plugin using C#. The model considers material resistance, climate conditions, moisture exposure,

intersection conditions, and design detailing logic. Core estimation calculations are based on an exposure-resistance model, where the service life is computed as the ratio between material resistance dose and characteristic exposure dose. Factors such as driving rain index, sheltering effects, ground proximity, and grain orientation are included using equations validated in prior research (e.g., [33,34]). Real-world exposure variables are localized using site-specific data. Output of this phase is an element-specific service life durations (in years), stored as parameters in the BIM model.

Phase 4: lifecycle visualization and optimization feedback

In the final phase, the estimated service life values are transformed into actionable insights to support design refinement, maintenance planning, and lifecycle assessment. These results are visualized directly within the Revit using the Analysis Visualization Framework (AVF) with color-coded overlays, enabling users to easily identify high decay risk areas or elements. The visual feedback facilitates iterative design by allowing users to modify design details such as roof overhangs and contact details or optimize material selection and treatments. This allows users to re-evaluate their impact through re-simulation in the same BIM project delivery environment. The framework enables integration of service life predictions into LCA and LCC workflows, supporting durability-informed environmental and cost assessments. Outputs from this phase are exported in IFC format with embedded custom property

sets, ensuring compatibility with external tools and stakeholders for downstream decision-making. The key deliverables include a visual durability map of the structure, optimized detailing recommendations, and interoperable IFC data for integration with broader lifecycle management processes.

The framework is designed as a closed-loop system, enabling iterative refinement of service life predictions throughout the design and construction process. As new data becomes available such as updated climate models, material performance tests, or design revisions it can be reintroduced into the workflow. This iterative capability supports continuous improvement such as automation and optimization of routines, helping architects and engineers to make informed decisions.

2.3. Architecture of the BIM-based application development process

In this study, Autodesk Revit was chosen as the BIM software for which the plugin was developed. The architecture of the BIM-based application is designed to seamlessly integrate service life estimation (SLE) functionality into the Autodesk Revit environment. The plugin was programmed using C# language in the .NET Framework (version 4.8.1). For the plugin development, the core Revit API references used are RevitAPI.dll and RevitAPIUI.dll. RevitAPI.dll provides access to Revit's data model, allowing manipulation of elements and parameters within a Revit project. In the context of this study, RevitAPI.dll is, for example, used to create material and set SLE-specific parameters using the Material class and Parameter class. RevitAPIUI.dll, on the other hand, was used to handle the user interface component within Revit. In the context of this study, the RevitAPIUI.dll is used together with WPF (Windows Presentation Foundation) to create the interactive user interface. The backend implements algorithms to calculate the service life duration of wood construction elements based on ISO 15,686–4 standards. These calculations consider factors like environmental doses, material resistance, exposure conditions, and intersection types. External data sources, such as JSON files, are used to load predefined material properties and environmental factors into the plugin. This ensures that calculations are based on context-specific data. The complete source code of the RevitWoodLCC plugin, including the implementation of all functionalities as well as data for environmental conditions, is publicly available on Zenodo and GitHub [44].

2.4. IFC data extension for service life duration

To support the integration of wood-specific service life data into BIM workflows, this study introduced custom IFC-compliant property sets, including MaterialWoodTreatment_Pset and Service-LifeDurationData_Pset. These property sets capture critical attributes such as wood treatment type and predicted service life, structured in line with ISO 15,686–4 guidelines. These allow for seamless interoperability across different BIM platforms, ensuring that service life performance data are adequately represented and exchanged. The implementation enhances data consistency and enables lifecycle management for wood construction elements through IFC-based information exchange.

2.5. Case study description

The WoodLCC Playhouse located in Izola, Slovenia, was used as a test model to evaluate the service life performance of wood structures under real environmental conditions. The playhouse was intentionally designed with moisture traps and decay-prone details to simulate common wood construction vulnerabilities. To support continuous data collection, a weather station is installed on the structure, measuring environmental climatic factors such as rainfall, wind speed, wind direction, temperature, relative humidity, and UV exposure. Additionally, embedded sensors within the wooden elements monitor moisture content and temperature fluctuations, capturing critical data for assessing material degradation over time.

This case study provides valuable validation data for the BIM-integrated service life estimation framework, enabling the predictions of wood performance under real-world conditions. Fig. 2 presents the case study building.

3. Results

3.1. User interface, functionalities and workflows

Fig. 3 presents the key functionalities and UI for the Service Life Estimation (SLE) plugin developed for Revit. The UI layout consists of multiple functionalities, including Add WoodLCC Parameters, Set Project Location, Material Manager, Service Life Estimation and Visualize SLE Results. The Add WoodLCC Parameters allows users to assign predefined specific parameters that are not natively available in Revit but are required for estimating service life duration. The Set Project Location tool enables users to define the geographical location of the project, which is critical for assessing environmental dose and underground conditions. The Material Manager provides options to specify wood material properties, including species and treatments, ensuring that the service life calculations incorporate material-specific degradation factors. The Service Life Estimation feature opens the main interface for inputting parameters like material, treatment, exposure conditions, and project location, allowing users to calculate and save the estimated service life of wood elements. The Visualize SLE Results feature provides color-coded 3D previews, enabling users to assess service life outcomes within the Revit environment.

The workflow of the plugin, as shown in Fig. 4, follows a structured step-by-step process for service life estimation. It begins with element selection (①), followed by defining the project location (②), material type (③), and treatment (④). The decision tree then determines whether the element is in-ground or above-ground (⑤), influencing further service life calculations. For above-ground elements, additional factors such as end-grain/side-grain exposure (⑥), intersection conditions (⑦) and shelter conditions (⑧) are determined. The lower section of Fig. 4(b) presents the user interface, where users make the selections as explained above (①–⑧). Following the parameter selections, the SLE results are computed with the estimate (⑨) button. The save service life duration (⑩) button stores the results as a data input in the BIM model. The plugin also features an interactive 3D visualization (Fig. 4c) that provides multiple views: position in the structure, interaction with neighbouring elements, and an isolated component view.

For each BIM element, the tool reads the user selected parameters and retrieves the material resistance (DR_d) from the database. If the element is in-ground, the exposure dose (DE_d) is taken directly from the location dataset and $k_{E1}-k_{E5} = 1$, then $SL = DR_d/DE_d$. If the element is above-ground, the tool first retrieves the site's reference doses for a fully exposed surface and a fully sheltered surface, then derives a combined rain/shelter factor that reflects k_{E1} (wind-driven rain) and k_{E3} (shelter). It next applies the local exposure class (k_{E2}), the distance-to-ground effect (k_{E4}), and the detailing factor k_{E5} selected categorically from the UI choices for grain exposure and contact/ventilation. These detailing choices map to the location-specific categories $k_{trap1} - k_{trap5}$ based on Table 3 and the database which is publicly available on Zenodo and Github [44]. Multiplying these factors by the reference dose yields exposure dose (DE_d) for the element, and the tool then reports $SL = DR_d/DE_d$.

3.2. Interoperability and data integration results

The results from implementing the IFC schema extension demonstrate the effectiveness of the proposed framework in ensuring interoperability and seamless data integration within the BIM environment. Fig. 5 illustrate an IFC model visualization in BIM Vision IFC viewer. The figure shows a beam exported from the test structure modelled in Revit and used to test the plugin developed in this study. The figure illustrates

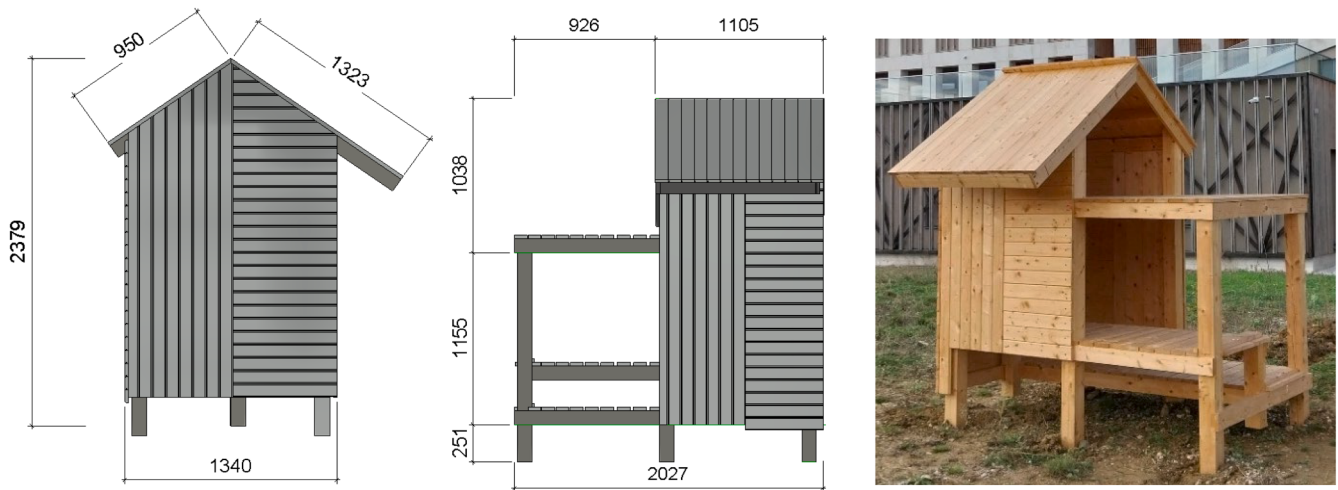


Fig. 2. WoodLCC Case Study Structure in Izola, Slovenia.

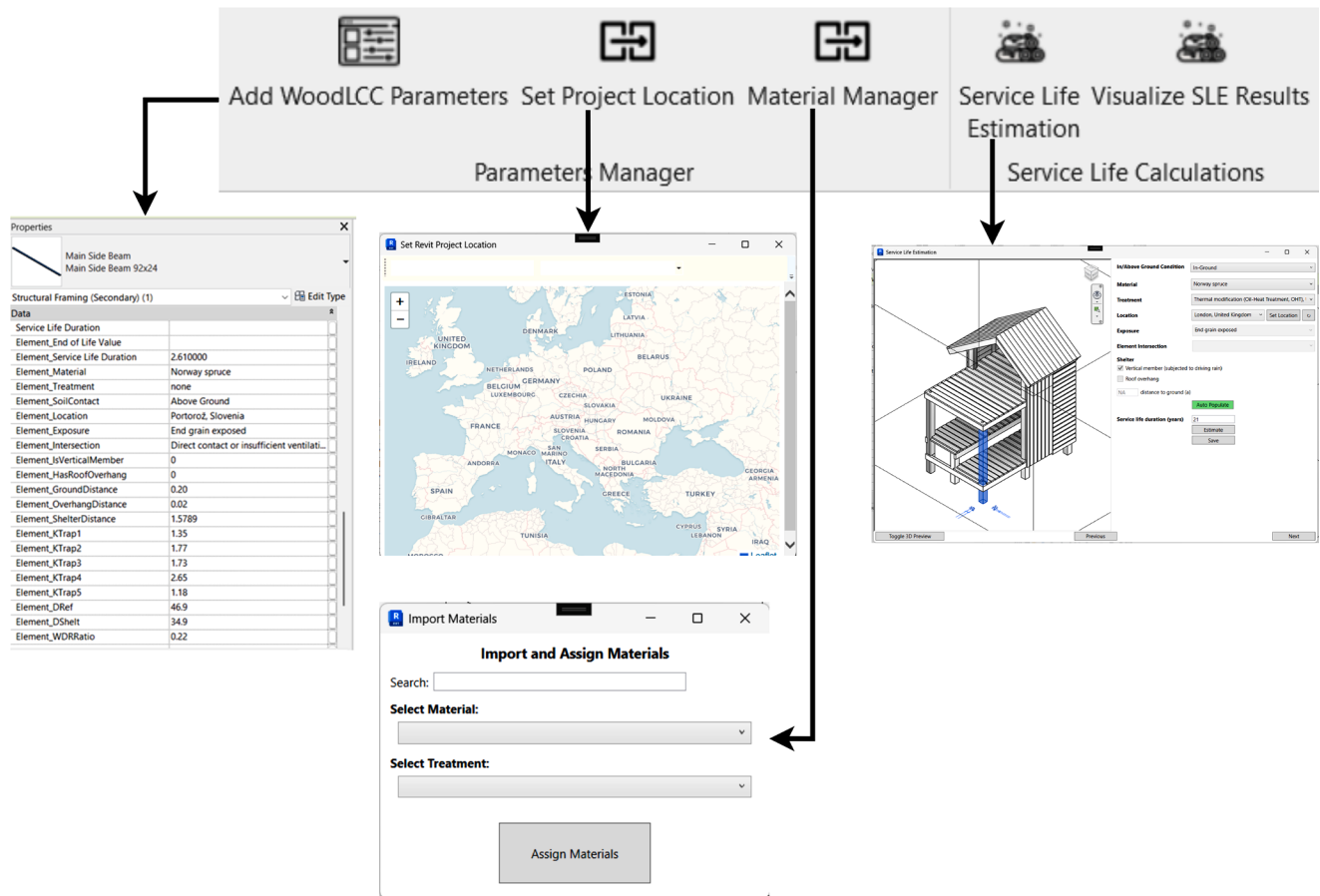


Fig. 3. Entry point user interface (UI) of the BIM-based WoodLCC plugin for service life estimation.

how the custom property sets, such as MaterialWoodTreatment_Pset and ServiceLifeData_Pset, were successfully mapped to the existing IFC data structure using BIM Vision software. By integrating these wood-specific service life attributes directly into the IFC schema, the developed application enhances the ability of various BIM tools to exchange, interpret, and utilize detailed service life information consistently across different platforms.

Fig. 5 shows how the BIM data for a horizontal beam was enriched with relevant service life parameters, including environmental

exposure, preservative treatments, and durability factors. These attributes were stored using custom property sets that conform to the guidelines outlined in ISO 15,686–4. This extension ensures that all necessary data for predicting the service life of wood elements is captured and can be properly transferred between different BIM applications without data loss or misinterpretation.

Furthermore, the results validate the practicality of using customized IFC properties for service life estimation, enabling the developed tool to operate seamlessly within standard BIM workflows and ensuring that

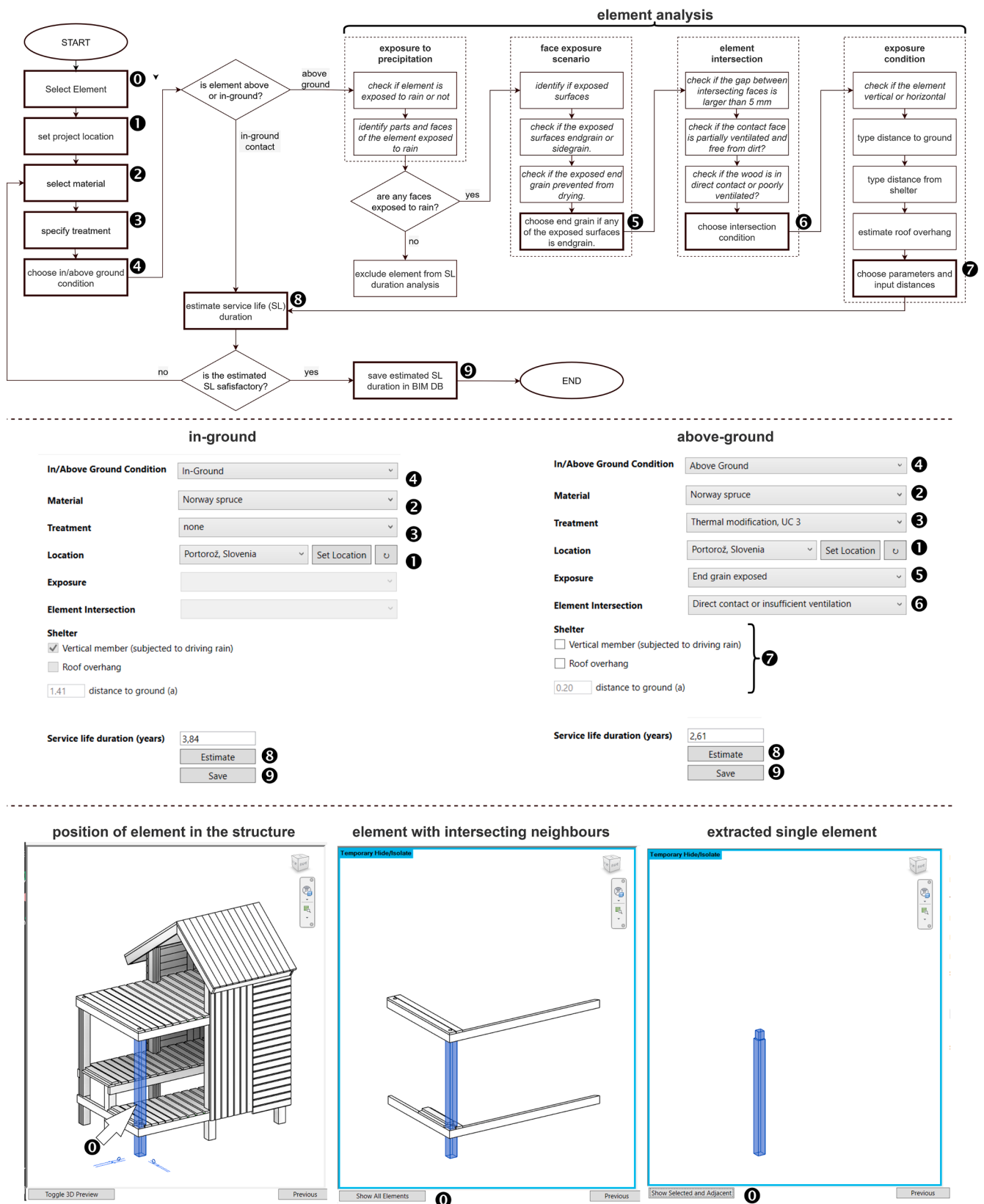


Fig. 4. Overview of the BIM-based tool for service life estimation. (a) Workflow illustrating the decision logic for calculating service life. (b) User interface for inputting material, treatment, and environmental parameters. (c) Interactive 3D preview for visualizing the element's position in the structure and its intersections with neighbouring elements.

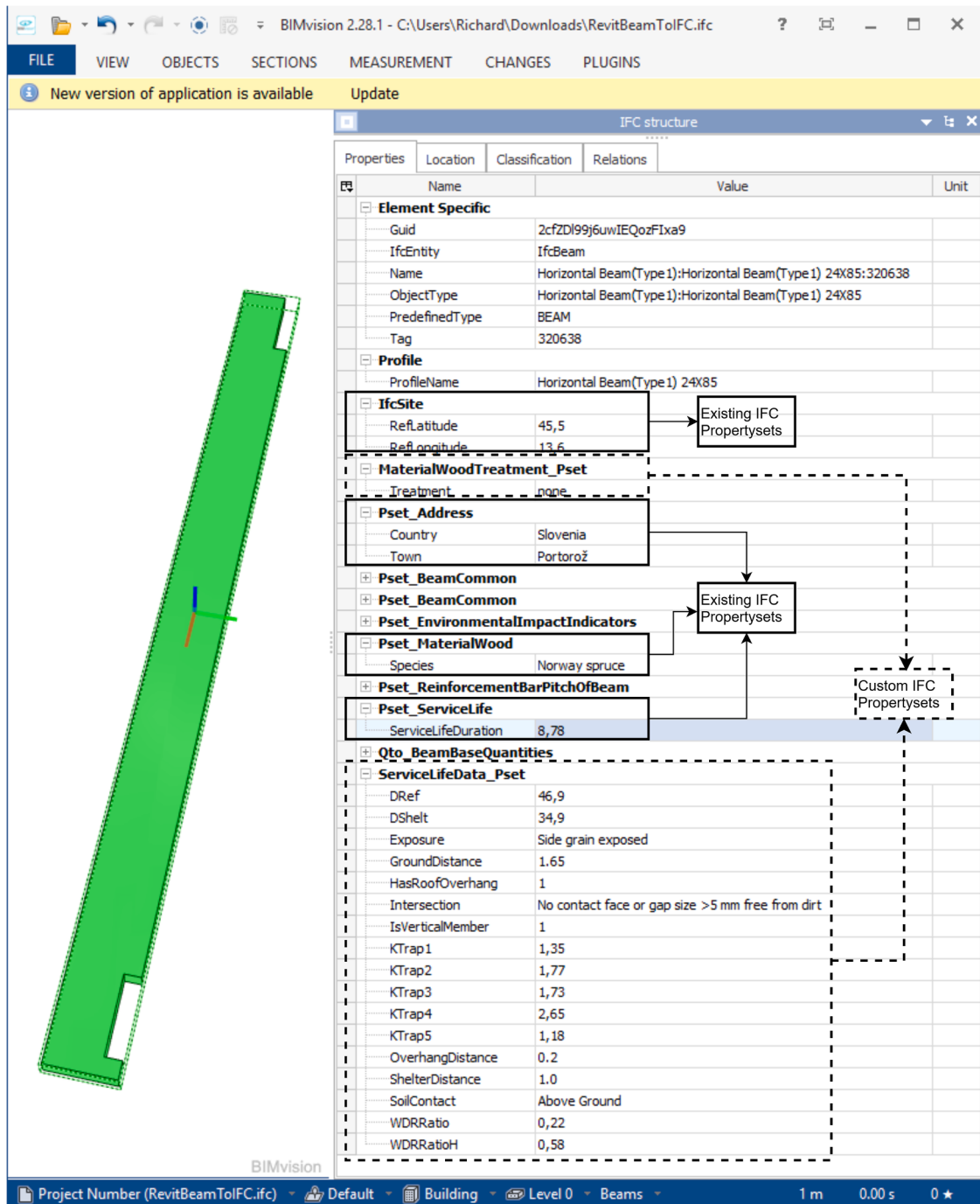


Fig. 5. IFC data structure of a horizontal beam visualized in BIM Vision. The view shows how BIM-based service life parameters are structured within the IFC schema.

complex service life data is accessible to multiple stakeholders of the wood construction project. This structured data model supports data consistency, improves the accuracy of service life predictions, and facilitates a more integrated approach to lifecycle management, thereby addressing an important gap in existing BIM implementations for wood construction. The successful integration of these properties into the BIM environment also sets the foundation for extending the framework to other material types and construction scenarios, promoting broader adoption of service life estimation methodologies within digital construction workflows.

3.3. Testing the plugin with case study

The service life estimation (SLE) of the case study structure was conducted using the BIM-integrated plugin, evaluating the service life duration of individual wood elements under real environmental conditions. The results highlight variations in service life duration based on material properties, exposure conditions, and design detailing, providing critical insights into potential fungal degradation risks. In the plugin test on the case study BIM model, the service life of each element varied based on environmental exposure, material properties, and orientation. The SLE tool visualized these variations using a color-coded scheme ranging from 2 to 9 years (onset of decay), with lower values

indicating higher susceptibility to fungal decay. The results from the original model are summarized below:

Roof Elements (Fig. 6): The roof elements, represented in green, exhibited a service life range of up to 6 years. Despite being unsheltered, their inclined orientation facilitated quick moisture drainage, allowing these elements to dry rapidly and minimizing decay risks. The inclination plays a role in maintaining the integrity of the roof elements under environmental exposure.

Siding Elements (Figs. 6a and Fig. 6e): In Fig. 6a, the left side and lower right side of the wall is depicted in green, indicating a service life of up to 6 years. The top right side is purple representing service life range of up to 9 years. This high service life duration is because these elements are sheltered by the roof overhang. In Fig. 6e, the wall panels exhibit a similar result. The green section on the left side and lower right sides indicates service life of up to 6 years. Having shorter roof overhang that offers some shelter but not as much as in Fig. 6a. Fig. 6e have fewer elements at the top purple section shows a high service life (up to 9 years), reflecting partial sheltering under its shorter roof overhang.

Siding Elements (Figs. 6b): The wall panels are visualized with green and blue colours, representing a service life range from up to 6 years and up to 8 years respectively. The green section (left and bottom right side of Fig. 6b) has service life duration of up to 6 years. The top right section of Fig. 6b (blue) indicates a moderate service life (up to 8 years) as its end-grains are not exposed to the environment giving it some level of protection but is still exposed.

Wood Decks (Figs. 6c and 6d): The sections directly beneath the roof (Fig. 6c and 6d) are represented in purple, indicating a service life range of up to 9 years. These elements benefit from maximum shelter provided by the roof above, minimizing exposure to rain and weathering, and allowing them to maintain their integrity over an extended period. The most exposed decking areas, fully outside the protective zones, are displayed in red, indicating a service life of up to 3 years. These areas experience frequent wetting and slower drying rates, making them high decay risk zones.

The variations observed in the model illustrate the critical role of architectural detailing in influencing the service life of wood elements. Design decisions such as roof inclination and overhangs influences durability by providing varying levels of shelter and protection from environmental conditions.

The service-life outputs are point estimates; prediction uncertainties arise from variability in the resistance data used, approximations of local exposure conditions, and subjective user choices when classifying detailing and shelter. In addition, the model reports time to first onset of decay using a simplified linear relationship rather than the full deterioration path that considers factors such as UV exposure, thermal stress and insect activity.

Fig. 7 presents the visual condition of the case study structure after twenty-one months of outdoor exposure (Fig. 7b), compared to its initial state at the time of construction (Fig. 7a). While the RevitWoodLCC Plugin predicted service life durations (indication of onset of decay) ranging between 2 and 9 years for different components of the structure, no visible signs of decay have yet been observed within the current exposure period. This aligns with expectations, as decay processes in wood typically progress over extended timeframes. However, clear early-stage weathering effects, such as discoloration, surface roughening, and moisture-related staining, are evident, particularly on exposed decking and wall panels, validating the plugin's identification of high-risk areas. In addition, subtle indicators of fungal susceptibility were documented (Fig. 7c and d), including UV-induced greying and wood erosion, moisture-induced surface softening and fibre swelling, microbial biofilm formation, and microcracks along the grain. Though not conclusive evidence of decay, these are established precursor conditions in the literature [6,22,32,19] that enhance fungal access and colonization. Their presence reinforces the plugin's ability to identify environmentally vulnerable areas (onset of decay) before visible decay occurs and illustrates the practical benefit of integrating decay risk modelling into BIM workflows.

To complement these visual observations, a mid-term microbiological analysis was conducted after 15 months to assess the relationship between the predicted decay onset from the RevitWoodLCC Plugin and the actual biological and environmental condition of the structure. A

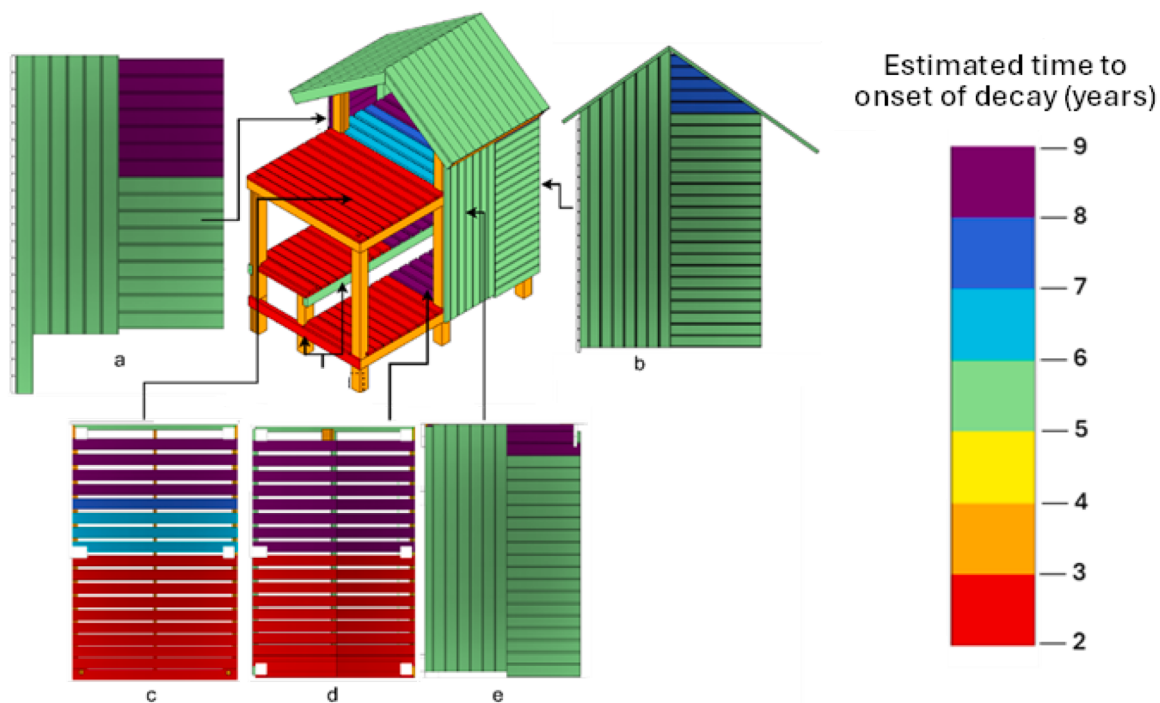


Fig. 6. Visualization of service life estimation results for the wooden test structure. Colour gradients represent predicted service life durations for individual components, highlighting variations due to exposure conditions, detailing, and material treatment.



Fig. 7. Visual comparison of the wooden playhouse at construction (a) and after 21 months of exposure (b), showing early signs of weathering. Close-ups (c1–c3, d1–d2) highlight cracks, moisture-related staining, discoloration, and surface roughness in vulnerable areas.

microbial swabbing was performed at representative locations that covered a range of orientations, exposure intensities, and protective conditions.

The results revealed a clear correspondence between the predicted decay risk levels and microbial colonization patterns. Areas with higher predicted risk, such as horizontal decking and ground-contact zones, displayed greater microbial activity or abiotic surface degradation. Areas with lower predicted risk, including roof sections and vertical cladding, exhibited minimal microbial growth. Importantly, the fungi identified, *Aureobasidium pullulans*, *Aureobasidium melanogenum*, *Cladosporium* sp., *Alternaria alternata*, *Penicillium* sp., and *Aspergillus* sp., are known early colonizers that are primarily associated with aesthetic discoloration and surface weathering rather than structural decay. Their presence indicates early bioreceptivity rather than material deterioration.

Overall, the spatial distribution of these microorganisms supports the model's predicted vulnerability map. High-risk areas show either fungal overgrowth or strong abiotic stress, while low-risk areas remain largely uncolonized. Zones with longer predicted service life exhibited diverse but balanced microbial consortia, which suggests ecological stabilization that mitigates rapid biodeterioration.

While full biological degradation is not yet evident, the early differentiation in exposure-driven surface aging supports the reliability of the predicted risk levels. The structure remains under continuous monitoring, and ongoing assessments will provide long-term insights into the correlation between predicted and actual service life outcomes.

It is important to note that this case study serves primarily to demonstrate the integration and visualization capabilities of the plugin within a BIM workflow, rather than to statistically validate long-term predictions. The dose–response model applied in this study is deterministic and based on established empirical frameworks previously validated in the literature (e.g., [37,40]). These studies confirm the reliability of the core models used here, with Brischke et al. [37] validating the Meyer–Veltrup resistance dose model for a wide range of materials, and Marais et al. [40] validating the exposure-dose decay model under in-ground conditions using an independent experimental dataset.

4. Discussion, limitations and future directions

This study introduces a practical, interoperable framework for estimating the service life of wood construction elements in a BIM environment. The results of the case study highlight how the BIM-integrated service-life estimation framework can influence construction practice and professional decision-making. By visualising exposure-driven degradation within the model, the tool enables designers and facility managers to identify vulnerable components early in the design process and to explore how detailing choices such as overhang length, material selection, or end-grain protection affect durability. This supports design optimisation by promoting preventive detailing and material specification while also informing maintenance planning through the identification of components that may require earlier inspection or replacement. In this way, the tool links design and maintenance

decisions within the same digital workflow. Given the current validation status, predictions should be used primarily for design optimisation and risk ranking, while their role in maintenance planning should focus on prioritising inspections and preventive actions, not on setting guaranteed replacement intervals or warranty lifetimes.

However, several limitations should be noted. Though wood degradation follows complex, non-linear dynamics [45], this study addresses only moisture-induced fungal decay and does not include other degradation mechanisms such as UV exposure, thermal stress, crack formation or insect activity. Additionally, exposure estimates are based on static, precomputed climate datasets, which may not fully capture local or seasonal variability [35]. However, the underlying datasets can be updated or refined without altering the core structure of the framework. The model's validation is currently limited to early-stage monitoring (21 months), and we do not yet provide statistical uncertainty (e.g., confidence intervals or error bands) for service-life estimates. In practical terms, outputs should be treated as decision-support for relative ranking and early design/maintenance planning, not as extensively validated or liability-critical predictions. Another limitation is that predictions are particularly sensitive to user-defined design parameters, including exposure (e.g., end-grain or side-grain) and sheltering (e.g., overhang), because these settings directly influence the assumed exposure. This introduces subjectivity, and small misclassifications can shift service-life estimates. Finally, the models used in this study are based on dose-response approaches developed over the past decades and still being refined by researchers (including [32,46,47,24,23,22]). Since this study prioritizes novel BIM integration, more complex refinements such as non-linear decay dynamics, uncertainty quantification, error propagation and modelling progressive degradation beyond onset of decay were outside its scope but remain active areas of further development.

These limitations offer clear pathways for future research. Upcoming development will focus on integrating uncertainty quantification and reporting confidence intervals for service-life estimates, automating design parameter detection from BIM geometry, and expanding the model to cover additional factors that affect wood service life performance. The plugin architecture and IFC schema can be extended to support other construction materials, enabling cross-material comparisons and broader adoption in mixed-material projects. Longer-term validation based on continued monitoring of case study structures will be done to further strengthen the model's reliability. Ultimately, this work lays the foundation for a more comprehensive digital durability planning toolkit aligned with BIM and digital twin workflows.

5. Conclusions

This study presents a framework that integrates BIM with SLE specifically designed for wood construction elements. By developing a BIM-compatible approach that utilizes wood-specific factors such as environmental conditions, material properties, and design detailing, this research enhances the predictive capabilities of BIM for durability and lifecycle management of wood-based building components. The framework follows ISO 15,686-4 standards, ensuring that the integration of service life data into BIM aligns with internationally recognized best practices. The case study demonstrates the framework's practical implementation. The 21-month observations qualitatively align with predicted high-exposure hotspots, supporting the framework's ability to identify onset of decay risk at design stage. While long-term validation is ongoing, the results highlight the framework's potential to support more informed planning by identifying areas with elevated decay risk. The tool's capacity to visualize and estimate the impact of design changes in real-time offers an advantage, allowing architects, engineers, and construction managers to optimize their designs and plan for maintenance. This dynamic approach to service life prediction moves beyond the traditional reliance on assumptions based on universal commonly used service life duration values and providing a more accurate, project-specific methodology. Furthermore, the study extends the IFC schema

by introducing custom property sets tailored for wood construction elements, thereby enhancing BIM interoperability and compatibility with various platforms. This extension ensures that service life duration estimates are seamlessly integrated and can be effectively communicated and used throughout the project lifecycle. This approach operationalizes existing dose-response models in a project-specific BIM context, offering a more accessible and visually guided method for evaluating exposure-driven degradation of wood elements. In conclusion, this study offers a scalable, interoperable methodology for embedding service life intelligence into digital design processes.

CRedit authorship contribution statement

Richard Acquah: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jonas Niklewski:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Anna Sandak:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Jakub Sandak:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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