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Artificial Intelligence as a Decision Support Tool in Digital Technologies of Construction 4.0: Simulation Model of Green Facade Maintenance

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Abstract

Integrating artificial intelligence (AI) into the design and management of vegetative elements in green architecture offers new opportunities to optimize their life cycle. This study examines how AI can generate input parameters for simulating the post-construction phase of green facades with BIM-based tools. A selected modular system was modeled and simulated in the BEXEL Manager environment, utilizing AI-generated data on component lifespan, operational requirements, as well as maintenance frequency and duration. Results show that AI enhances simulation accuracy and planning efficiency while addressing the limitations of current BIM libraries in sustainable design. The presented approach integrating AI into BIM modeling reflects the principles of Construction 4.0 and supports sustainable solutions in digital construction.

Keywords: green facade, Artificial Intelligence, BIM modeling, BEXEL, Construction 4.0

1 Introduction

Green elements in architecture are playing an increasingly significant role in achieving sustainable development goals. Their integration into construction projects addresses the need to mitigate the negative impacts of climate change, improve the quality of urban environments, and enhance the energy efficiency of buildings throughout their life cycle. According to Radić et al. [1], the key elements of green architecture primarily include vegetative systems in the form of exterior (green roofs, green façades) and interior (green walls) installations, which contribute not only to microclimate regulation but also to the ecological and aesthetic value of buildings.
In addition to emphasizing the integration of vegetative elements as key components of green architecture, the construction industry is also undergoing a significant transformation driven by the digital era, known as Construction 4.0. This new phase is fundamentally changing the way buildings are designed, constructed, and managed throughout their life cycle. Construction 4.0 builds on Industry 4.0 principles, linking the physical and digital worlds through smart technologies. Digital technologies currently used in construction and reflecting this trend can

be divided into the following categories [2,3]: (i) digital modeling technologies, including 3D to xD BIM and parametric design, (ii) collaboration and construction management technologies, such as cloud platforms, scheduling software, and data-sharing tools (e.g., BIMcollab, PlanRadar), (iii) automation and robotics technologies, including robots and automated construction systems used directly on-site, (iv) augmented, virtual, and mixed reality technologies (AR/VR/MR) for design, training, and stakeholder communication, (v) performance monitoring and environmental management technologies, such as sensors and IoT, (vi) training and simulation technologies for construction processes, such as machinery or maintenance process simulators, and (vii) other innovative technologies, such as 3D printing, digital twins, smart materials, and data collection drones.

These technologies enable more precise modeling, more efficient construction coordination, and optimized data-driven decision-making. Within the context of Construction 4.0, Building Information Modeling (BIM) is the most widely adopted of these technologies. Despite the widespread use of BIM platforms, vegetative elements are often only marginally represented in available BIM libraries, lacking detailed data on their life cycle or operational requirements. This limitation hinders accurate planning and the ability to simulate their behavior in various phases of the life cycle within a digital environment.

In this context, artificial intelligence (AI) appears to be a promising solution that can significantly streamline the collection and processing of input parameters for the design, management, and simulation of vegetative systems. AI can help define system longevity, irrigation and maintenance needs, or predict environmental performance. The aim of this paper is to assess to what extent AI can support the creation of realistic, data-based models in BIM tools, and subsequently enable their use in simulation platforms such as BEXEL Manager. The outcome is a demonstration of AI's contribution to more accurate planning of the operational demands of vegetative elements in the post-construction phase, as well as highlighting the potential of this approach in improving work with BIM objects within the framework of sustainable construction and the Construction 4.0 concept.

2 Methods

A knowledge-based system was chosen as the foundational model for data processing and management. This tool effectively integrates the evaluation of both graphical and non-graphical data and serves as a platform for the systematic collection, classification, and further processing of information on green architectural elements. It also provides a solid informational foundation for integrating artificial intelligence in generating inputs for digital simulation technologies.

The knowledge-based system is designed to process, store, and evaluate expert information for autonomous problem-solving through machine learning. The *knowledge base* forms its core, collecting essential information relevant to the field.

In addition to this, the system also includes so-called *problem-specific knowledge*—that is, concrete data related to solving specific tasks, stored in the database layer. A special category is formed by *metaknowledge*, which gathers information about the structure and relationships between individual knowledge elements and is managed in a dedicated part of the system. A key component is the *inference mechanism*, which integrates and connects all types of knowledge to ensure effective decision-making and problem-solving within the domain [4].

From the perspective of addressing the research goal of this paper, the *knowledge base* serves as the starting point for processing information on vegetative elements. It is grounded in widely known insights from green infrastructure, construction systems (graphical information), as well as sustainability parameters for environmental assessment (non-graphical information). These insights were processed, classified, and organized to create a systematic database usable across various categories of digital technologies mentioned in the introduction.

Metaknowledge plays a critical role in transforming this information into a format usable for AI. It enabled the identification of relationships between individual inputs, as well as the determination of logical connections between system behavior and its needs throughout the life cycle. Through metaknowledge, it was possible to prepare data inputs that were later used in simulating the post-construction phase, i.e., the use phase of the green element based on a generated system timeline.

The *inference mechanism* functioned as an analytical module that, based on a combination of knowledge and rules, evaluated appropriate development scenarios, predicted possible situations, and defined recommended interventions (e.g., in the area of maintenance or irrigation). At the same time, this mechanism served as a connecting element between the knowledge base, the BIM model, and the simulation software, thereby ensuring the continuity of information throughout the entire process. Based on this theoretical framework, a methodological procedure was developed to achieve the research objective, comprising four sequential steps:

1. *Evaluation of the knowledge base with regard to the potential of AI application.* The first phase involved exploring the possibilities of applying AI within the categories of Construction 4.0 digital technologies. Technologies were divided into seven categories: (i) digital modeling, (ii) construction management and coordination, (iii) automation and robotics, (iv) augmented and virtual reality, (v) performance monitoring and management, (vi) training and simulation, and (vii) other innovative technologies. For each category, the potential of using AI to support the design, operation, or maintenance of specific vegetative elements was assessed.

2. *Development of a BIM model as a platform for the inference mechanism.* This step involved the creation of a model of the selected green vegetative element in BIM software, containing technical, structural, material, and environmental data obtained from real system analysis, product specifications, and academic publications.

3. *Identification of metaknowledge and definition of AI inputs for simulation*. In the third step, metaknowledge was identified. Based on it, input parameters for AI were defined—such as estimated lifespan, intervention frequency, irrigation requirements, or operational scenarios which were subsequently linked with one of the digital technologies.

4. *Application of AI to create a simulation of the post-construction phase of the green element.* The final step involved the implementation of the processed inputs into the BEXEL Manager environment, where a simulation of the post-construction phase of the selected vegetative element was created. The simulation used AI-generated inputs and enabled the visualization and analysis of the system, including the prediction of mechanical damage and other phenomena that may arise along the timeline during the life cycle of the green element.

3 Results and discussion

In the first stage of the research, the knowledge base was analyzed with the aim of identifying the potential for applying artificial intelligence (AI) in the context of Construction 4.0. According to Baduge et al. [1], AI has the capability to support the entire life cycle of a construction object. In the design phase, AI enables the generation of optimized designs, cost prediction, and energy performance simulation. During the construction phase, it supports progress monitoring, planning optimization, and the identification of potential risks. In the post-construction phase, AI has the potential to support predictive maintenance and environmental management based on data from IoT sensors, which is crucial for the long-term sustainability of buildings.

AI functions as an intelligent component that enhances and streamlines technologies such as Building Information Modeling (BIM), the Internet of Things (IoT), augmented reality (AR), automation, and big data. The integration of AI with BIM systems enables, for instance, the analysis and processing of complex data inputs, simulation of construction processes, or prediction of the environmental performance of vegetative elements. In combination with AR and MR technologies, AI allows for real-time and spatial simulation of the behavior of construction elements even before the actual implementation.

An analysis of the potential applications of AI across the digital technologies of Construction 4.0 is presented in Table 1.

Table 1: Analysis of AI potential for information mining on green elements across the digital technologies of Construction 4.0 (Source: Authors)

Digital technology	**Possibility of integrating green elements into the digital technology**	**Potential for AI integration into the digital technology**
Digital Modeling	Sandwich constructions and library objects as part of a 3D model, extended to 4D (time), 5D (cost), and 6D (sustainability)	Optimalization of green elements design with automatic design generation
Construction Management and Coordination	Coordination of elements, clash detection, assignment of elements to specific tasks, team sharing of elements	Error and clash detection, real-time project and element modification proposals, data analysis for decision-making
Automation and Robotics	Control of robotic systems and machinery for producing components (planer modules), automated on-site installation of elements	Robot control for system implementation and green maintenance, growth monitoring, adaptive interventions (irrigation)
Virtual, Augmented and Mixed Reality	Presentation of elements in real space, selection of suitable elements directly on the building façade/roof at a 1:1 scale in Mixed Reality	Simulation of plant growth, system implementation progress, user interaction analysis

Performance Monitoring and Environmental Management	Integration and connection of element layers with sensor data (humidity, temperature, lighting, etc.)	Sensor data management, predictive maintenance, system optimization based on environmental data
Education and Training	VR simulation of element maintenance, interactive training for technical support/ students/users on installation manuals or maintenance procedures	Optimization of workflows. Error prediction in realization and postrealization phases
Other Technologies and Applications	3D printing of structural prototype, creation of a digital twin for life cycle monitoring of the lement	Autonomous data collection using drones, vegetation condition analysis, data optimization for the system´s digital twin

As noted by Faraji et al. [4], although AI introduces new dimensions of efficiency into the construction sector, its implementation faces several challenges. The main obstacles include a lack of high-quality data, limited interoperability between tools, and low awareness of AI technologies among industry professionals. Nevertheless, it can be concluded that artificial intelligence holds strategic potential for transforming the construction sector toward digital, predictive, and environmentally optimized building, in line with the principles of Construction 4.0.

In the next step, it was necessary to prepare digital materials that would enable the practical application of AI, specifically through the development of a BIM model of a selected vegetative element, serving as a carrier of technical and environmental data for subsequent simulation. For this purpose, a digital model of a green facade with a planter system was created [5,6]. The model was developed in SketchUp 2024, based on technical, structural, and material data obtained from available documentation, manufacturing specifications, and academic sources. The finished model, in .SKP format, was imported into ArchiCAD 26, where it was transformed into a BIM library object. In ArchiCAD, basic parameters were assigned to the object, and a structure was prepared for non-graphical information, such as material and environmental characteristics. This resulted in a comprehensive BIM model, serving as a platform for subsequent data processing and simulations (Fig. 1).

Figure 1: Preparation of the BIM model of the green façade in ArchiCad 26 software (Source:Authors)

After importing the prepared BIM model into the BEXEL Manager environment, the key phase of the project followed—the integration of artificial intelligence (AI). The life cycle of green vegetative systems involves a number of variables that influence their functionality and sustainability—particularly the need for regular maintenance, potential failure of structural and technical components, changing climatic conditions (e.g., extreme temperatures, precipitation fluctuations), and dynamic biological processes associated with growth, seasonality, or vegetation degradation [7–10].

The task of AI [11] was to analyze input parameters and identify potential phenomena during the operation of the green facade. Using the BIM model, expert inputs, and predictive algorithms, the AI generated a comprehensive post-construction simulation reflecting key factors influencing long-term performance. Table 2 presents these predicted interventions, which the authors reviewed and adjusted to align with realistic maintenance practices reported in studies [1–10]. The citation [11] refers solely to the AI-based prediction process, while comparative interpretations were developed by the authors.

AI identified the need for regular annual maintenance of the vegetation, including activities such as irrigation, pruning, replanting, and fertilization, as well as seasonal technical inspections of the irrigation system during spring and autumn. It also accounted for the gradual loss of vegetation due to the natural degradation of the system, which results in an annual decrease in plant coverage, and possible mechanical failures of vegetative modules, requiring the replacement of damaged components.

The simulation also incorporated risks such as water infiltration into the façade caused by waterproofing or irrigation system failure, and the need for major renovation of the vegetative layer, including substrate replacement and replanting. For each of these phenomena, AI assigned a predicted frequency of occurrence and an estimated duration for fault elimination or intervention execution, creating a comprehensive time-based model of the green facade's operation. This model can be used for maintenance planning and life cycle management of the vegetative system (Table 2).

Table 2: Proposed interventions during the postrealization phase of the facade. AI-generated predictions validated and adjusted by the authors based on literature data (Source: ChatGPT Artificial Intelligence, Authors) [11]

Intervention or maintenance process	Type of intervention/ Nature of activity	Frequency of occurrence	Estimated duration
Annual vegetation maintenance	Preventive maintenance (irrigation, pruning, replanting, fertilization)	Once a year	1 day
Seasonal irrigation system inspection	Preventive technical control during spring/autumn season	Twice a year	0.5 day
Gradual vegetation loss	Passive system degradation (replanting), 10-15% loss of plantings per year	Once a year	1 day
Vegetative module failure	Mechanical damage, replacement of damaged planter/ module	Once every 3-5 years	1 day
Facade water infiltration (insulation/irrigation failure)	Mechanical failure, repair of waterproofing or piping	Once every 7-10 years	1-2 day
Complete renewal of the vegetative layer	General maintenance, substrate replacement and replanting	Once every 10-12 years	2-3 day

AI was subsequently deployed to create a predictive timeline for the life cycle of the vegetation element, including an estimate of the overall system lifetime. This design served as a basis for visualization and implementation into the BEXEL Manager environment, where a simulation of the expected development of the vegetation system during its operational phase was created. The timeline, shown in Figure 2, captures the anticipated interventions over the 14-year life cycle of the green facade, such as annual plant maintenance and seasonal irrigation checks. Mechanical failures of the planters or modules appear in the 5th, 8th, and 11th year, while insulation or irrigation failures are predicted for the 7th and 10th year. In the 13th and 14th year, AI predicts the need for complete substrate and vegetation renewal, including replacing the entire system. The timeline generated with the help of AI thus provides a clear overview of intervention dynamics over time and forms the basis for strategic maintenance planning, as well as assessing the operational efficiency and cost-effectiveness of the green element.

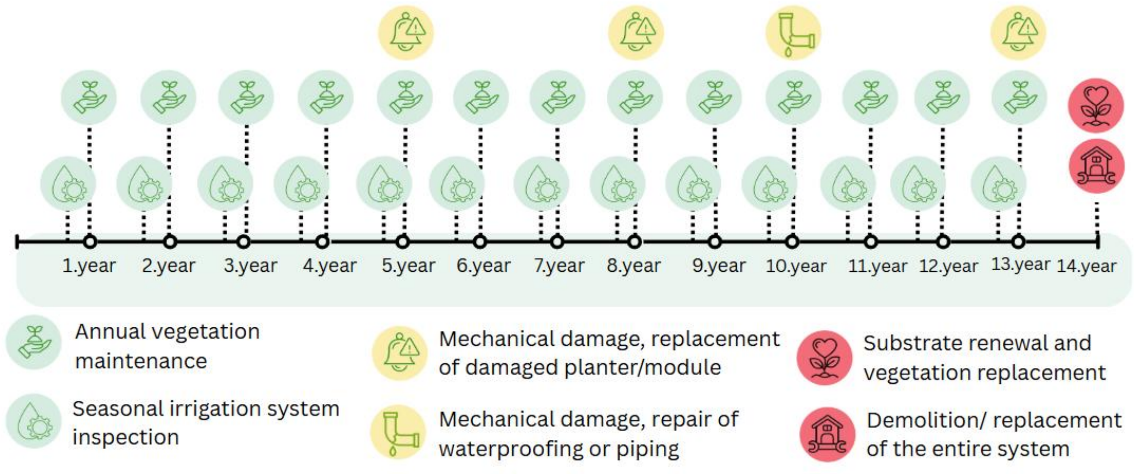

Figure 2: Predictive maintenance cycle of the green facade during its operational phase, developed using AI-based data (Source: Authors)

The simulation carried out in the BEXEL Manager software environment was based on outputs generated by artificial intelligence, enabling a comprehensive and realistic visualization as well as analytical evaluation of the vegetation system's behavior during its operational phase. In addition to regularly recurring maintenance interventions, the simulation also accounted for the probability of random mechanical failures, technical component malfunctions, and the need for vegetation layer renewal. The integration of such unpredictable events into the simulation model is a key prerequisite for effective operation planning, cost optimization, and reliable assessment of long-term sustainability within the entire life cycle of the green element.

The simulation provided a basis for identifying critical moments that may impact the functionality and sustainability of the vegetative system, thereby allowing the suitability of the proposed solution to be verified from a long-term operational perspective.

An additional advantage of the proposed approach lies in its interoperability. The workflow developed between ArchiCAD, SketchUp, and BEXEL Manager demonstrated that AI-generated parameters can be seamlessly transferred across different software environments through standardized IFC formats and custom property sets. This compatibility helps overcome the limitations of existing BIM libraries of vegetative elements, which often lack unified data structures or metadata for maintenance and life-cycle modeling. The integration therefore contributes not only new datasets but also a more flexible framework for cross-platform application.

To enhance the credibility of the AI-generated outcomes, a comparative check was carried out against empirical data available from documented green façade projects reported in previous studies [1-10]. The comparison revealed that the AI-derived predictions correspond well with observed maintenance cycles and vegetation replacement rates reported in real implementations. This alignment suggests that the proposed simulation model provides a realistic approximation of actual facade performance, though further validation using long-term monitoring datasets would be beneficial.

The simulation results thus form the foundation for maintenance optimization, cost planning, and decision-making support in the management and operation of green architectural elements.

4 Conclusion

The integration of artificial intelligence (AI) into the simulation process of vegetative elements in digital construction represents a significant contribution in line with the principles of Construction 4.0. The research demonstrated that AI can effectively generate relevant inputs for various categories of digital technologies, contributing to a deeper understanding of green systems that integrate living vegetation, with the ability to predict their behavior throughout the life cycle of green elements.

In the case of the green facade system, AI enabled not only the identification of typical interventions during its life cycle but also the creation of a predictive timeline that accounts for both regular maintenance and less predictable events, such as mechanical failures or the need for vegetation layer renewal. These outputs were successfully implemented into the BEXEL Manager simulation environment, resulting in a digital model reflecting the realistic behavior of the vegetative system over 14 years of operation.

The findings suggest that the use of AI in the context of BIM modeling of green elements significantly enhances the accuracy of planning, optimizes operational costs, and improves the environmental sustainability of architectural solutions. The approach confirms AI's potential as both an analytical tool and a strategic driver of digital transformation in construction.

Nevertheless, several limitations should be acknowledged. The accuracy of AI-generated predictions largely depends on the quality, representativeness, and availability of input data. Incomplete or inconsistent datasets may lead to biased or unrealistic simulations. Another challenge lies in the interoperability between BIM software, AI frameworks, and simulation tools, which can complicate data exchange and workflow automation. Furthermore, the implementation of AI-based modeling and simulation requires computational resources and financial investment that may limit its adoption, especially in small- to medium-scale projects. Addressing these constraints through standardized data formats, open-source integration frameworks, and cost–benefit analyses should therefore be a focus of future research.

Beyond these constraints, the proposed methodology shows strong potential for scalability and broader application. Because the AI framework operates on data-driven parameters rather than fixed system specifications, it can be adapted to different façade typologies, materials, and climatic contexts by updating the underlying dataset. Moreover, its integration with BIM and simulation platforms allows expansion toward large-scale building portfolios and urban-level analyses, supporting predictive maintenance and sustainability planning across multiple assets. Future research will continue exploring these directions, strengthening the role of AI as a catalyst for innovation in digital and sustainable construction.

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[11] Online. In: ChatGPT, GPT-4o. Available at: https://chatgpt.com/?model=gpt-4o. [Accessed: 4.6.2025]. Prompt: „Propose anticipated interventions and maintenance processes for the vegetative system of a green façade during the post-construction phase of its life cycle. Consider possible influences or phenomena that could affect the system's maintenance phase. For each intervention, specify its nature, expected frequency of occurrence, and estimated duration."