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Farzad Pour Rahimian, Nashwan Dawood,
Alessandro Bruttini, Tommaso Sorbi

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INTEGRATING GREEN ROOFS INTO BUILDING INFORMATION MODELING (BIM): A COMPUTATIONAL APPROACH FOR SUSTAINABLE BUILDING DESIGN

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ABSTRACT: *The construction industry is currently witnessing a transformative period characterized by the convergence of the green and digital transitions. The green transition seeks to address environmental challenges such as climate change and resource depletion, while the digital transition leverages advanced technologies to enhance construction processes. This paper specifically explores the integration of green roofs, as component of sustainable buildings, into the Building Information Modeling (BIM) framework, a key enabler of the digital transition. Green roofs, known for their environmental benefits, consist of layers that contribute to energy efficiency, stormwater management, and biodiversity enhancement. To optimize their design and performance, this research employs Dynamo Visual Programming Language (VPL) within Autodesk Revit to create parametric models of green roofs. These models facilitate the evaluation of thermal and structural characteristics under varying water content conditions (dry and saturated). Results reveal that the choice of substrate and drainage materials significantly impacts thermal resistance, particularly in dry conditions. However, in saturated conditions, the influence on thermal performance converges, emphasizing the importance of structural considerations in both scenarios. The research also highlights various limitations and outlines avenues for future studies, including expanding the range of materials, exploring additional performance metrics, and incorporating AI and machine learning techniques. By addressing these aspects, this research contributes to a comprehensive understanding of the integration of green roofs and BIM. It provides designers and researchers with a practical tool for optimizing green roof designs, aligning with contemporary sustainable construction practices, and promoting the holistic development of green buildings.*

KEYWORDS: *Sustainability integration; Parametric modeling; Digital Transformation*

1. INTRODUCTION

The construction sector is currently undergoing significant transformations driven by the green and digital transitions. The green transition refers to the shift towards sustainable practices and environmentally friendly solutions within the industry (Mina et al., 2021). This transition is motivated by the urgent need to address climate change, resource depletion, and environmental degradation (Bherwani et al., 2022). As a result, the construction sector is increasingly adopting strategies and technologies that reduce the environmental impact of buildings and infrastructure. Simultaneously, the digital transition has brought about a profound change in the construction industry, fueled by the rapid advancements in digital technologies (Huang et al., 2021). This transition involves the integration of digital tools, processes, and data management systems to improve efficiency, productivity, and collaboration across all stages of the building life cycle (Giovanardi et al., 2023). Building Information Modeling (BIM) has emerged as a key component of the digital transition, revolutionizing the way information is shared, analyzed, and utilized within the construction industry.

Among the various components employed in green buildings, green roofs have gained recognition as an effective technological solution for improving sustainability and the life cycle performance of buildings (S. Cascone, 2022). A green roof, also known as a living roof or vegetated roof, refers to a roofing system that incorporates vegetation, growing medium, and waterproofing layers (Vijayaraghavan, 2016). It offers numerous environmental, social, and economic benefits, making it an integral part of green building practices (Shafique et al., 2020). Each layer of the green roof system works in tandem to provide a range of benefits. The waterproofing layer ensures the building's protection, while the root barrier prevents potential damage. The drainage layer manages stormwater, preventing flooding and alleviating pressure on drainage infrastructure. The growing medium layer supports plant growth by providing adequate nutrients and moisture retention. Finally, the vegetation layer enhances biodiversity, improves air quality, reduces energy consumption, and mitigates the environmental impact of the building.

The digital transition has ushered in a new era of possibilities and advancements in the construction industry, necessitating the adoption of digital tools and processes to optimize project outcomes (Mehrbod et al., 2019). At the forefront of this transition is Building Information Modeling (BIM), a powerful technology that revolutionizes the way information is managed, shared, and utilized throughout the building life cycle (Wang et al., 2019). BIM

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is a collaborative process that involves creating and managing digital representations of physical and functional characteristics of a building. It enables stakeholders, including architects, engineers, contractors, and facility managers, to work together in a coordinated manner, streamlining communication and enhancing decision-making. BIM serves as a digital repository of information, encompassing 3D models, 2D drawings, specifications, schedules, and other pertinent data related to the building (Gimenez et al., 2015).

One of the key advantages of BIM lies in its ability to support the supply, integration, and management of information throughout the entire life cycle of a building (Alireza et al., 2017). During the design phase, BIM facilitates the creation of detailed 3D models that allow for visualization, clash detection, and simulation of various design scenarios. Therefore, to fully capitalize on the advantages of green roofs, the integration of these systems with BIM is of utmost importance. Previous research (Korol et al., 2019) discussed the integration between green roof and BIM technologies used in the engineering design of such systems. This previous research explained that to create a BIM object of an extensive green roof system, complex programs such as AECOsim, ARCHICAD, IFC, Revit, and Vectorworks are needed. The authors also mentioned that the NBS National BIM Library in the UK sets an industry standard for quality, efficient generic and manufacturers' objects, including green roof systems. However, they did not provide detailed information on the integration process between green roof and BIM. Other authors (Yu et al., 2017) discussed the application of BIM in the case study of green roof innovation. Specifically, the authors incorporated BIM and energy consumption analysis software to demonstrate the benefits of the proposed eco-innovative green roof alternative. Finally, in a further study (Kasmion et al., 2000) reported on a simulation study using Autodesk Revit BIM software to investigate how types of roof design and green roof application may reflect on container's heat absorption. This study found that a curved roof surface with green roof produces a better heat absorption quality.

While there is a growing recognition of the benefits of green roofs and the potential of BIM in the construction industry, there is a notable gap in research that specifically explores the integration of these two domains. The gap in scientific knowledge lies in the lack of established frameworks, guidelines, and best practices for effectively integrating green roofs within the BIM environment. There is limited research that examines the specific workflows, data management strategies, and computational automation techniques required to successfully incorporate green roofs into the BIM framework. Furthermore, the understanding of how green roof components, materials, and performance characteristics can be accurately represented and analyzed within the BIM environment is also lacking.

In this paper, the focus lies in studying the integration methods between green buildings and BIM, specifically emphasizing the incorporation of green roofs. Green roofs, also comprising innovative components and products, such as recycled polyethylene, offer unique opportunities to enhance the sustainability of buildings. To achieve this integration, the Dynamo Visual Programming Language (VPL) workflow within Autodesk Revit, the most widely used BIM authoring software, was employed. Dynamo enabled computational automation, allowing for the development of parametric and informative models of green roofs. These models provided computational automation for determining the thermal and structural characteristics of the different green roof technologies in different water content conditions (dry and saturated) that can be used for controlling and coordinating the entire life cycle of a green roof, especially during the initial design stage.

This research aims to contribute to a deeper understanding of how the combined power of green building practices and BIM technology can foster sustainable development in the construction sector.

2. MATERIALS AND METHODS

The research is focused on investigating the integration methods between green buildings and Building Information Modeling (BIM), with a specific emphasis on the incorporation of green roofs, and it involves the computational modelling using the Dynamo Visual Programming Language (VPL) workflow within Autodesk Revit. The parametric models enable the manipulation of design parameters, such as green roof technologies and water content conditions (dry and saturated), to assess their impact on thermal and structural characteristics.

2.1. Green roof technologies

The material characteristics of the drainage layer and substrate in green roofs were evaluated through previous experimental studies. Three types of drainage layers and substrates were considered in this study. In terms of the drainage layers, commercially available granular products such as perlite and expanded clay were examined. Additionally, previous research proposed recycled polyethylene as a potential drainage layer for green roofs, aiming to enhance sustainability while reducing environmental and economic impacts associated with production and transportation.

Regarding the substrates, three different compositions were investigated. Substrate S1 consisted of lapilli, pumice, zeolites, peat, and slow-release fertilizers. Substrate S2 comprised a mixture of mineral volcanic materials combined with organic substances, while Substrate S3 was formulated with a higher percentage of organic matter compared to the other substrates to increase water retention. It was also composed of locally available materials.

Following laboratory tests conducted in previous research, the thermal and physical characteristics of the materials used for both the drainage layer and substrate were considered under dry and saturated conditions. In a green roof system, saturated conditions are reached after a rain or irrigation event, while dry conditions are obtained when the water has completely evaporated during prolonged droughts. As evidenced by Table 1 and Table 2, altering the water content in the materials resulted in changes to their thermal and physical properties.

These evaluations provide valuable insights into the performance of drainage layer and substrate materials, offering a comprehensive understanding of their behavior under different water content conditions. This knowledge is essential for optimizing the design and performance of green roofs, enabling informed decision-making and promoting sustainable practices within the construction industry.

Table 1: Thermal and physical properties for drainage layer materials (Cascone & Gagliano, 2022).

	Dry conditions		**Saturated conditions**	
	Thermal conductivity [W/mK]	Density [kg/m3]	Thermal conductivity [W/mK]	Density [kg/m3]
Perlite	0.076	164.2	0.312	510.5
Expanded clay	0.124	410.4	0.234	579.3
Recycled polyethylene	0.098	329.4	0.144	411.7

Table 2: Thermal and physical properties for substrate materials (S. Cascone & Gagliano, 2023).

	Dry conditions		**Saturated conditions**	
	Thermal conductivity [W/mK]	Density [kg/m3]	Thermal conductivity [W/mK]	Density [kg/m3]
Substrate S1	0.113	1000.2	0.463	1355.5
Substrate S2	0.134	919.4	0.458	1358.4
Substrate S3	0.084	605.4	0.418	1183.9

2.2. Computational modelling with Dynamo Visual Programming Language (VPL)

To achieve the integration of green buildings and Building Information Modeling (BIM), the research employs the Dynamo Visual Programming Language (VPL) as a key tool within Autodesk Revit. Dynamo VPL enables computational automation and facilitates the development of parametric and informative models specifically tailored to green roofs.

The initial step involved modeling the materials utilized for green roof layers within the Dynamo environment. This was accomplished by duplicating existing materials from the Revit Material's Asset and renaming them using custom nodes based on Python scripts previously developed within Dynamo. This approach was necessary as standard nodes do not directly manipulate the Revit Material's Asset.

The "Thermal conductivity" and "Density" nodes provide the property values under both dry and saturated conditions, as indicated in Table 1 and Table 2 (Fig. 1 depicts the Dynamo workflow for creating the perlite drainage material). The "If" node automatically switches the thermal conductivity and density values between dry and saturated conditions. In this research, "true" represents dry conditions and "false" represents saturated conditions. For example, in the case of perlite, when the water condition is set to dry, the thermal conductivity is

0.076 W/mK and the density is 164.2 kg/m^3. Conversely, when the water condition is set to saturated, the thermal conductivity becomes 0.312 W/mK and the density changes to 510.5 kg/m^3.

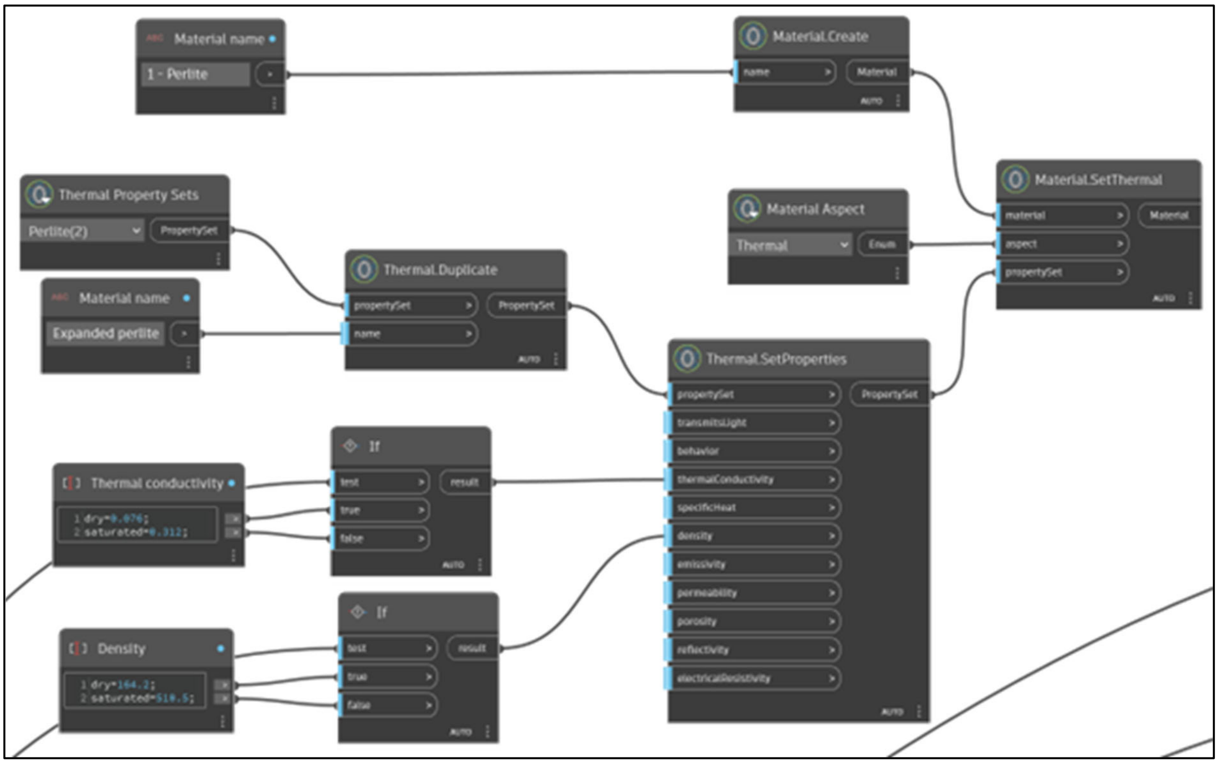
This aspect of the workflow is particularly noteworthy as it enables the computational automation of thermal and physical properties for green roofs during the design stage, depending on the water content. With just a single click, users can assess the thermal and physical performance of green roofs under dry or saturated conditions, as described later in the research.

The "Material.SetThermal" node is responsible for creating new materials, such as "Perlite" in Fig. 1, with properties defined in "Thermal.SetProperties" that vary based on the input from the "True/False" node positioned at the beginning of the workflow.

The workflow illustrated in Fig. 1 for creating perlite serves as the basis for generating the other drainage and substrate materials. Fig. 2 showcases the workflow with all the materials created. All the "Thermal conductivity" and "Density" nodes are connected to the same "True/False" (dry/saturated) node, ensuring the water content condition is automatically considered.

2.3. Thermal and structural characteristics

The first step involves assigning the green roof materials to the "Green roof" type, which consists of two layers: one for the substrate and another for the drainage layer. The impact of waterproof and anti-root membranes, as well as the filter layer, on the thermal and structural characteristics of the green roof is negligible and, therefore, not considered.



```
dry=0.076;
saturated=0.312;
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dry=164.2;
saturated=510.5;
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Fig. 1: Material creation in Revit by using Dynamo workflow.

To facilitate the evaluation of the thermal and structural characteristics of the green roof, custom nodes were developed (Fig. 3). The "Index" parameter indicates the layer position, with "0" representing the substrate (upper layer) and "1" representing the drainage layer (lower layer). Since the thickness of the materials plays a crucial role in determining the performance of the green roof, the workflow incorporates a component that automatically adjusts the material thicknesses.

Given the focus on extensive green roofs in this research, the substrate thickness varies between 10 cm and 20 cm, while the drainage layer thickness ranges from 4 cm to 6 cm. As an average value, a substrate thickness of 15 cm and a drainage layer thickness of 5 cm were adopted.

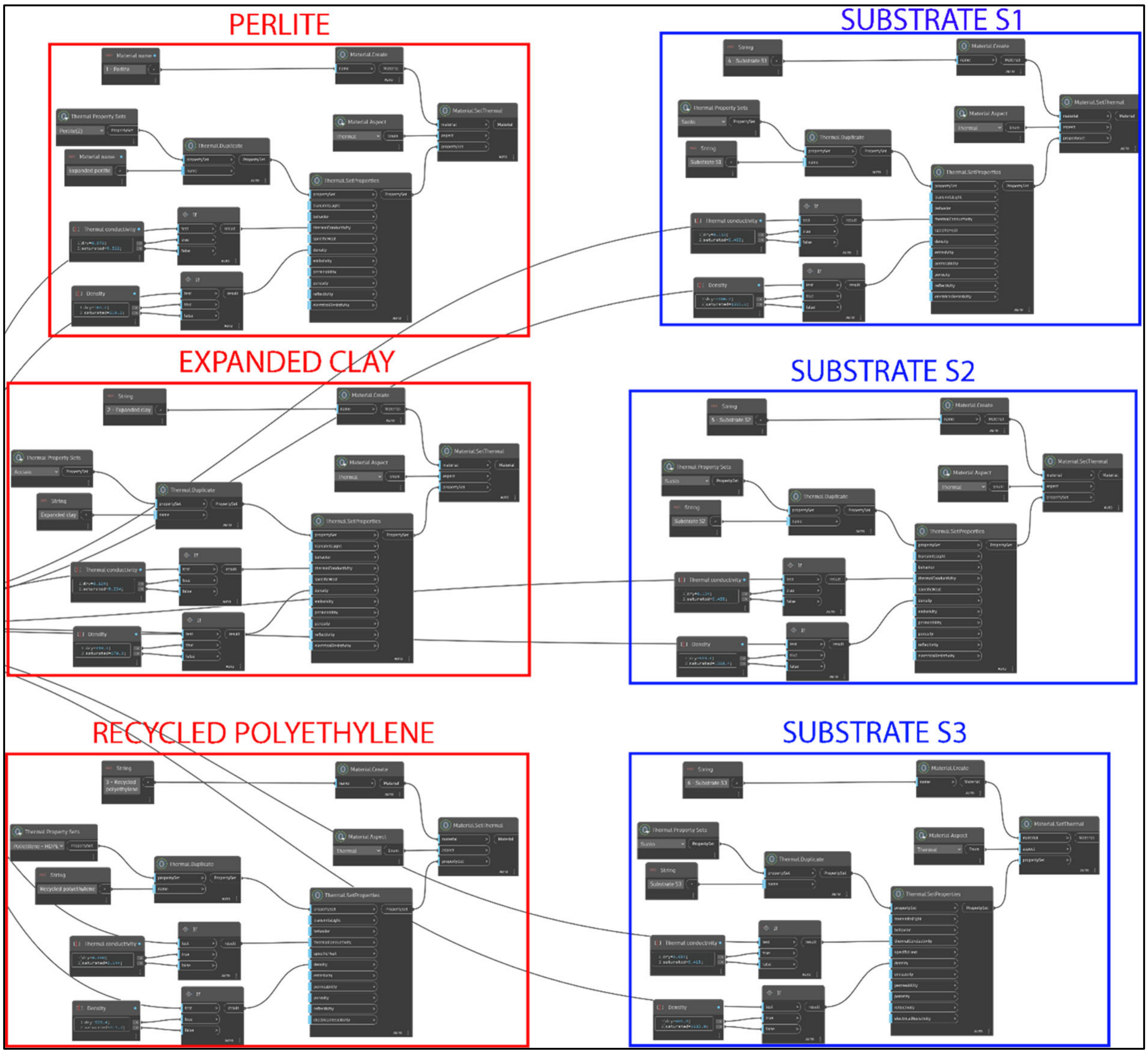

Fig. 2: Material creation for drainage layers (in red) and substrates (in blue).

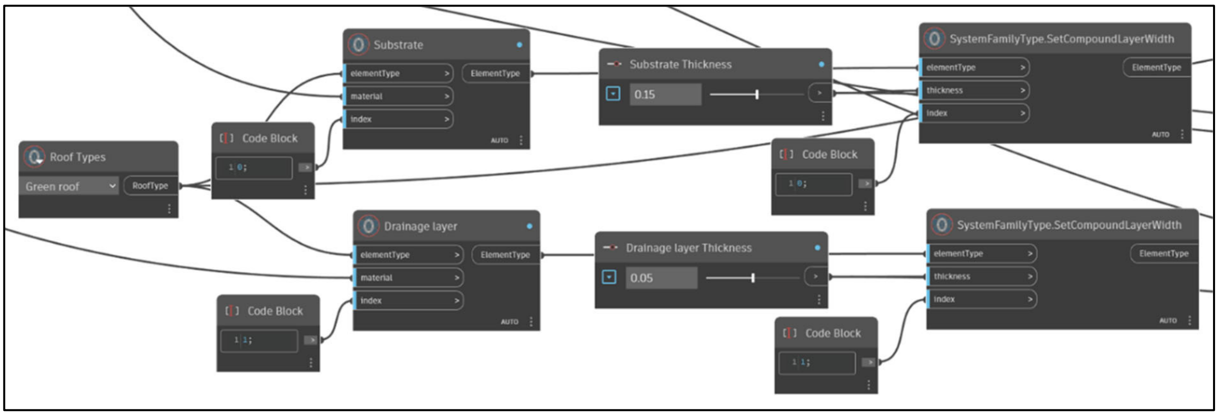

Fig. 3: Layer creation into the green roof type and parametric thickness modelling.

By selecting the appropriate materials within the "Substrate" and "Drainage layer" nodes, the new materials are automatically assigned to the Revit model, ensuring seamless integration and representation of the green roof components.

Finally, Fig. 4 illustrates the workflow employed to evaluate the thermal and structural characteristics of green roofs. In terms of thermal performance, the thermal resistance was a key factor considered. This property was automatically measured by Revit and imported into Dynamo, considering the thermal conductivities of the various substrate and drainage materials, which are influenced by the water content conditions (dry or saturated), as well as the material thicknesses.

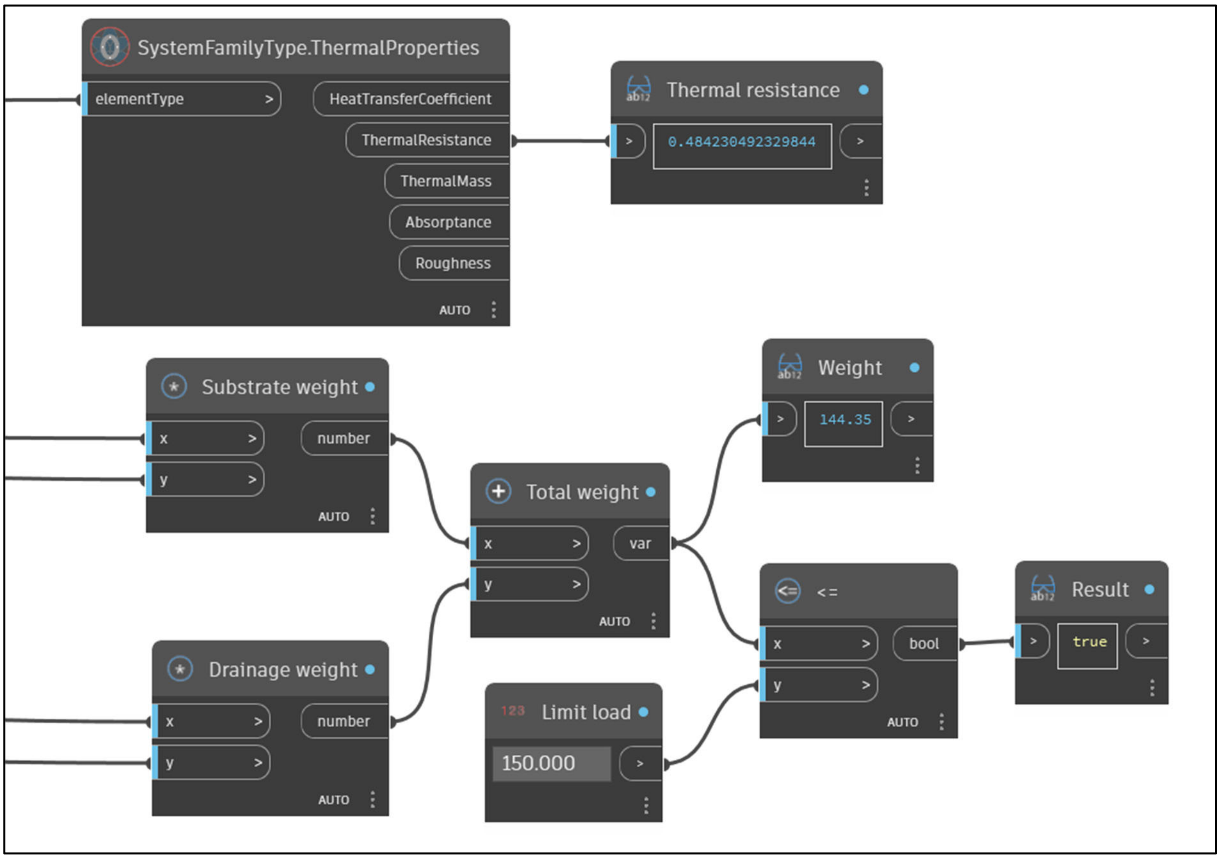

Fig. 4: Thermal and structural characteristics of green roof evaluation.

Regarding the structural performance, the weight of the different green roof configurations was determined. The total weight depends on the density of the substrate and drainage layers, which are also influenced by the water content conditions and the material thicknesses. By multiplying the density of the materials by their respective thicknesses, the total weight of each green roof configuration was calculated.

According to the European standard, if a roof is intended to be walkable during the design stage, it should be able to withstand a maximum load of 200 kg/m^2. The total weight of the different green roof solutions was compared to this limit to assess their compatibility with existing buildings, aiming to avoid costly structural modifications.

By considering both the thermal and structural characteristics aspects, this workflow provides valuable insights into the suitability of different green roof options, facilitating informed decision-making during the design stage. It enables designers and researchers to assess the thermal efficiency and structural integrity of green roofs, ensuring their compatibility with existing building structures and meeting the required standards.

3. RESULTS AND DISCUSSION

Table 3 and Table 4 present the results for green roofs in dry and saturated conditions, respectively. In terms of thermal resistance in dry conditions, the highest performance was observed when combining Substrate S3 with perlite (2.44 m2K/W), while the lowest performance was measured when Substrate S2 was coupled with expanded clay (1.52 m2K/W). These results highlight the significant impact of substrate and drainage material combinations on the thermal performance of green roofs in dry conditions. Therefore, in dry conditions, the materials tested have similar thermal performance of 3-cm insulation materials.

Table 3: Thermal and structural characteristics in dry condition.

	Perlite		Expanded clay		Recycled polyethylene	
	Thermal Resistance [m^2K/W]	Weight [kg/m^2]	Thermal Resistance [m^2K/W]	Weight [kg/m^2]	Thermal Resistance [m^2K/W]	Weight [kg/m^2]
Substrate S1	1.99	158.2	1.73	170.5	1.84	166.5
Substrate S2	1.78	146.1	1.52	158.4	1.63	154.4
Substrate S3	2.44	99.0	2.19	111.3	2.30	107.3

Table 4: Thermal and structural characteristics in saturated condition.

	Perlite		Expanded clay		Recycled polyethylene	
	Thermal Resistance [m2K/W]	Weight [kg/m2]	Thermal Resistance [m2K/W]	Weight [kg/m2]	Thermal Resistance [m2K/W]	Weight [kg/m2]
Substrate S1	0.48	228.8	0.54	232.3	0.67	223.9
Substrate S2	0.49	229.3	0.54	232.7	0.67	224.3
Substrate S3	0.52	203.1	0.57	206.6	0.71	198.2

In saturated conditions, the thermal resistance decreased due to the higher thermal conductivity of water. As a result, the thermal performance of different green roofs became similar, with an average value of 0.55 m2K/W. These findings indicate that under saturated conditions, the thermal performance of green roofs is less influenced by the specific substrate and drainage material combinations and tends to converge to a similar performance level across the tested variants. This resistance value is close to the one measured for natural materials, such as wood, straw, etc. Designers can consider these average values during the design stage to estimate the energy performance of green roofs in terms of energy consumption.

Regarding the structural performance, all green roof configurations exhibited weights lower than the imposed limit overload of 200 kg/m2 in dry conditions, with the lighter solution being the Substrate S3, due to its composition, when coupled with perlite as drainage layer. The heaviest solution is the Substrate S1 in combination with expanded clay. However, in saturated conditions, only when Substrate S3 was coupled with recycled polyethylene as drainage materials, the weight remained below the limit overload due to hygroscopic structure of the granular materials used for the green roof. In fact, the recycled plastic does not absorb water differently from perlite and expanded clay. This finding is significant, particularly for the retrofitting of existing buildings, as it highlights the importance of considering the structural performance of green roofs not only in dry conditions, as is often the case, but also in saturated conditions.

The workflow created using Dynamo within Revit proved to be effective in automating the determination of thermal and structural characteristics of green roofs during the design stage. This automation allowed for seamless transition between dry and saturated conditions by adjusting the material properties accordingly. The ability to rapidly assess these characteristics enables designers to make informed decisions during the early design stage.

Designers can employ the algorithm to explore various green roof configurations and materials, considering both thermal resistance and structural weight. By inputting different parameters into the Dynamo workflow, such as substrate types and drainage materials, designers can optimize green roof designs for specific project requirements. For instance, if the primary goal is to maximize thermal resistance while keeping structural weight within a certain limit, the algorithm can assist in identifying the most suitable combinations of materials.

Furthermore, the algorithm's flexibility extends to various climate conditions and building types. Designers can use it to assess the performance of green roofs in different regions, taking into account variations in temperature, precipitation, and structural load requirements. This adaptability empowers architects and engineers to tailor green roof designs to meet energy efficiency goals and structural integrity standards in diverse contexts.

Overall, the results demonstrate the importance of considering both thermal and structural characteristics of green roofs, not only in dry conditions but also in saturated conditions. The integration of the developed workflow using Dynamo and Revit provides a practical and efficient means to assess and compare the performance of green roof options, facilitating informed decision-making during the design stage. These findings contribute to the understanding and optimization of green roof designs in terms of energy consumption and structural integrity.

By incorporating this algorithm into the design process, architects and engineers can enhance the sustainability of buildings by leveraging green roofs as energy-efficient and structurally viable components. This technology-driven approach aligns with contemporary design practices that prioritize eco-friendly solutions while maintaining building performance standards.

4. LIMITATIONS AND FUTURE DEVELOPMENTS

This section outlines the limitations of the current study and presents directions for future research to address these limitations.

Future research should include real-world case studies to provide a more concrete understanding of the algorithm's practical use and effectiveness. These case studies can demonstrate how the Dynamo Visual Programming Language (VPL) workflow within Autodesk Revit can be effectively applied to model green roofs in various construction projects, thus contextualizing the algorithm within practical design scenarios.

The analysis in the current study primarily focused on thermal resistance and structural weight as key performance metrics. However, a broader range of performance indicators, including water retention, stormwater management, biodiversity enhancement, and acoustics, should be explored in future research. This will enable a more comprehensive evaluation of green roof performance, considering their contributions to sustainable construction from multiple angles.

While the current research addressed the design phase of green roofs and their integration with BIM, it did not extensively explore the construction and maintenance phases. Future research should encompass these phases to gain a holistic understanding of green roofs' performance, durability, and maintenance requirements throughout the entire building lifecycle.

To ensure the robustness and adaptability of the methodology, future research should consider alternative methodologies and tools. This diversification will accommodate different research questions and potential variations in results. Additionally, exploring interoperability with other BIM software platforms will enhance the methodology's relevance and applicability.

Integration of artificial intelligence (AI) and machine learning techniques within the BIM environment should be explored in future research. This will enable the optimization of green roof designs, prediction of performance outcomes, and data-driven recommendations for materials and configurations, aligning the work with emerging trends in construction technology.

Future research should involve the development of standardized guidelines and protocols for integrating green roofs within the BIM framework. These guidelines can streamline data exchange, model interoperability, and collaboration among stakeholders, promoting efficient and consistent implementation of green roof projects. Additionally, analyzing the economic aspects, including life cycle costs, return on investment, and financial incentives, should be a focus. Assessing the economic benefits of green roofs in terms of energy savings, improved building performance, and increased property value will provide valuable insights for decision-makers.

To promote holistic and integrated sustainable building solutions, collaborative research efforts should be initiated to explore potential synergies between green roofs and other sustainable building strategies, such as renewable energy systems, water conservation measures, and smart technologies. Integrating these strategies within the BIM framework will contribute to a more comprehensive approach to sustainable construction, thereby addressing the de-contextualization issue raised by the reviewer.

Incorporating these considerations into future research agendas will provide a more comprehensive and contextualized view of the integration of green roofs and BIM, addressing the reviewer's concerns and enhancing the practicality and relevance of the work.

5. CONCLUSIONS

In conclusion, this research contributes to a deeper understanding of the integration methods between green buildings and Building Information Modeling (BIM), with a specific focus on the incorporation of green roofs. By employing the Dynamo Visual Programming Language (VPL) workflow within Autodesk Revit, computational automation was achieved, enabling the development of parametric and informative models of green roofs.

The analysis in dry and saturated conditions provided valuable insights into the thermal and structural characteristics of different green roof technologies. The findings highlight the importance of substrate and drainage material combinations in influencing thermal resistance in dry conditions, as well as the significance of considering structural performance in both dry and saturated conditions.

However, it is important to acknowledge the limitations of this research, including the specific focus on certain green roof technologies, the limited scope of performance metrics, and the emphasis on the design stage. Future developments can address these limitations and further advance the integration of green buildings and BIM:

- Exploring a wider range of green roof technologies and materials.
- Investigating additional performance metrics related to water retention, stormwater management, biodiversity enhancement, and acoustics.
- Extending the research to include the construction and maintenance phases.
- Considering alternative methodologies and software tools.
- Integrating artificial intelligence and machine learning techniques, developing standardized guidelines, assessing the economic aspects, and exploring synergies with other sustainable building strategies.

By addressing these limitations and pursuing future developments, the integration of green buildings and BIM can be further optimized, contributing to the advancement of sustainable development in the construction sector.

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