"Enhancing Material Efficiency in Construction through BIM-Based Circular Economy Approaches: A Framework for Sustainable Building Design"

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Abstract

The research assesses the efficiency of circular economy building materials in construction. This research created a Building Information Modelling (BIM)-based Whole-life Performance Estimator (BWPE) to assess the salvage performance of building structural components, commencing from the design phase. The research utilized mathematical modeling and Building Information Modelling (BIM) to design a system for assessing the reusability and recycling capacity of building materials. The BIM-based estimator (BWPE) was verified via case studies and integrates lifecycle performance data. The study examines the use of circular economy concepts throughout the design process, emphasizing the extension of building material lifespans and the enhancement of resource efficiency. The findings indicate that using BWPE during the initial design phase can enhance material reutilization and diminish environmental impact, along with circular economy goals.

Introduction

In recent years, the notion of a circular economy has arisen as a transformational paradigm for attaining sustainability. The fundamental concept of the circular economy is to reduce waste and optimize resource use by recycling, reusing, and repurposing materials in a closed loop. This contrasts with the conventional linear economic paradigm of "take, make, and dispose," in which items are discarded post-consumption. The construction sector's adoption of circular economy concepts is particularly pertinent due to its substantial consumption of raw materials and large contribution to trash production. This study examines the function of building materials in the circular economy, emphasizing the assessment of material utilization efficiency throughout the construction process. The thesis examines the significant impact of the design process, frequently neglected, on the long-term sustainability of building materials. The use of Building Information Modelling (BIM) in the building process facilitates more accurate decision-making about the reuse and recycling possibilities of materials. Life Cycle Assessment (LCA) is a fundamental tool employed in this thesis to evaluate the environmental implications of building projects from inception to completion. The research illustrates the utilization of BIM in conjunction with LCA to enhance the precision of material performance assessments and to assure the efficient application of circular economy concepts. The project seeks to establish a pragmatic framework for architects and engineers to make educated decisions on material utilization that emphasize sustainability from the first design phases. The paper provides significant insights into the implementation of a circular economy in construction through case studies and mathematical models.

Research Methodology and Results

A circular economy in construction necessitates significant alterations in building methodologies. This methodology appraises structures to maximize their longevity and promote repurposing or recycling. This strategy reduces construction and demolition waste and resource consumption. Life Cycle Assessment (LCA) and Life Cycle Costing evaluate building sustainability using environmental and economic metrics. Decision-making in challenging areas such as construction need extensive knowledge and expertise. Lifecycle tools assess circular options at every construction phase to enhance decision-making. Nonetheless, Life Cycle Assessment (LCA) has not been thoroughly examined for decision-making purposes. Coordinating and reconciling several design objectives necessitates multi-criteria decision-making (MCDM). Techniques for decision-making in construction differ. Rezai et al.'s 2015 Best Worst Multicriteria (BWM) method surpasses the Analytic Hierarchy Process. The BWM methodology is superior to AHP due to its reduced necessity for pairwise comparisons. The BWM method necessitates 2n-3 comparisons, whereas AHP demands n(n-1)/2 comparisons. Secondly, BWM demonstrates greater consistency than AHP, hence augmenting trust in decision-making. Thirdly, BWM's association with other MCDM methodologies, such as AHP, provides decision-makers with supplementary alternatives. Fourth, integers facilitate the utilization of BWM and reduce subjectivity, particularly for decision-makers unacquainted with fractional scales.

This thorough analysis employs BWM and TOPSIS methodologies. The objective was to identify key credit areas for LCA design. The alternatives for wood, concrete, and steel structures were evaluated and graded utilizing the Best-Worst Method (BWM). This method identified the structural material that had the greatest impact on the building's life cycle assessment (LCA). Revit used as the design and construction computer model throughout phase 3. This technique enabled a one-click life cycle assessment (LCA) to identify the most pertinent impact categories during the design phase. The BWM methodology was employed once more to identify the most pertinent categories, considering diverse situations and highlighting the essential function of scenario selection in decision-making. The TOPSIS method was employed to select the optimal design from wood, concrete, or steel. This technique evaluated criteria, scenarios, and impact categories to identify the most suitable structural material for the building's life cycle assessment (LCA) design in a knowledgeable and environmentally sustainable manner. The extensive literature review indicates that BIM predominates in studies of building life cycles and the circular economy. The majority of experts and students concur that BIM improves architectural design, particularly over time. BIM enhances circularity and sustainability in building and design. Researchers believe that

BIM enhances building design over its whole life cycle. Advantages of design and decision-making: BIM facilitates the integration of data sources for construction, operation, maintenance, and deconstruction/recycling. This integrated data approach evaluates the long-term effects of design decisions. Secondly, BIM performance simulations evaluate energy-efficient materials and designs. Analytical abilities enable designers to create circular, sustainable decisions. BIM may be effectively linked with LCA technologies to evaluate the environmental impacts of design alternatives throughout a building's lifecycle. Strategic alignment discovers enhancements and design solutions that effectively minimize resource consumption and waste. BIM facilitates collaboration and communication among architects, engineers, contractors, and facilities managers. Collaboration discovers designs for a circular economy. Maintenance and end-of-life considerations are integrated early in BIM design, reducing costs. This comprehensive approach maximizes construction expenses across its life cycle, including cost-effective, sustainable materials. The versatility and flexibility of BIM facilitate the reuse and repurposing within the circular economy. All researchers endorse BIM, illustrating its efficacy in sustainable and circular building design. It assists designers in prioritizing life cycles by integrating data, modeling processes, conducting life cycle assessments, fostering collaboration, minimizing costs, and enhancing flexibility.

This research presents a Revit model for the case study of the Riga office building. Models constructed from steel, concrete, and wood are available. OneClick LCA computes the life cycle assessment (LCA) of the building utilizing the model. The models' total energy usage was assessed utilizing Autodesk Green Building Studio. OneClick LCA study assesses the environmental implications of Steel Frame, Wood Structure, and Concrete Frame construction materials over a structure's life cycle. During the A1-A3 Materials phase, the Steel Frame has the most significant environmental effect owing to the energy-intensive processes of steel manufacture and extraction. Nevertheless, the Wood Structure has a reduced environmental effect throughout this phase, highlighting the advantages of sustainable sourcing and manufacturing of wood components. The concrete manufacturing process is energy-intensive, resulting in a moderate environmental impact for the Concrete Frame. A4 Transport and A5 Construction illustrate that the transportation and construction operations of steel exert a greater environmental impact. Wood structures exert diminished impacts during these phases, rendering them a more ecologically sustainable option. Steel has a reduced environmental effect compared to wood during the B4-B5 Replacement, potentially attributable to maintenance and replacement factors. All materials derive advantages from the operational phases of B6 Energy and B7 Water. Steel exhibits greater environmental consequences during C2 trash Transport, C3 Waste Processing, and C4 Waste Disposal owing to trash disposal and energy-intensive recycling processes. Wood exhibits diminished impacts in waste-related areas, indicating its sustainability in waste management. Concrete has challenges in recycling and disposal, constituting a moderate waste problem. This study shows that selecting appropriate materials is essential for evaluating a structure's environmental impact. The research emphasizes the ecological advantages of wood in material production and waste management. This extensive life cycle analysis underscores the need of evaluating a structure's whole life cycle when choosing environmentally sustainable design choices. In the forthcoming session, the Best Worst

Decision-making approach will ascertain the weight of design specifications and the significance of the building life cycle for each effect. This study evaluated the performance and sustainability of wood, concrete, and steel as building frame materials. This study was motivated by the Recipe Matrix, a widely utilized method for organizing and evaluating culinary elements. The aim is to create a scenario that comprehensively assessed these chemicals, taking into account many sustainable building factors. Initially, criteria weights for the model were established for this situation. Phase three of the study endeavor included modeling to compute weights. Shannon Entropy weights indicated the relative significance of environmental, social, and design factors. The sustainability assurance, extensive construction protocols, and standard performance metrics were assessed. This phase was crucial for the equitable and unbiased evaluation of resources within a comprehensive assessment framework. Wood, concrete, and steel frames were evaluated using the TOPSIS method. This research evaluates materials based on performance and importance through several criteria and design attributes. Following the establishment of BWM weights, it is essential to select the optimal alternative and evaluate the outcomes. The results were evaluated utilizing the TOPSIS method. The overview analyzes the environmental, social, and design impacts of wood, concrete, and steel in projects and products. Wood, being the primary energy source, exerts the most significant adverse impact on transportation and overall consumption, succeeded by Steel and Concrete. Steel produced from non-renewable energy sources poses significant risks. Ozone depletion and global warming are most pronounced in concrete. Steel has the greatest detrimental effect on Photochemical Ozone Creation Potential. Steel influences the consumption of sanitary water. Wood poses significant societal damage. Design analyses indicate that steel and concrete are sustainable owing to their reusability and recyclability. The aforementioned studies examine the environmental, social, and design trade-offs associated with project or product material choices. Prioritization and limitation facilitate decision-making.

The investigation revealed that "Total use as primary energy" exhibited the highest Shannon Weight of 0.401. This figure illustrates significant fluctuations in subcategory data. This sub-category influences the energy consumption of projects or products. “Social Impact,” “Reusability,” and “Recyclability” possess the lowest Shannon Weights, signifying a reduced range of values or diversity. Certain aspects may exhibit reduced variability and facilitate evaluation. Atrophy Weights quantify the disparity between each sub-category's Shannon Weight and the maximum Shannon Weight, highlighting its significance in relation to the category with the highest values. The subcategory "Total use as primary energy" has the lowest Atrophy Weight (0.046) while demonstrating the highest evaluation impact. Atrophy weights allocate values to subcategories. The metric "total use as primary energy" is the highest (1), influencing the assessment. “Net fresh water use” and “Social Impact” are ranked second and third, indicating their significance. Nonetheless, "Transportation to the site" occupies the 13th position, indicating a diminished impact of judgment. The subcategories of Wood, Steel, and Concrete frames in building design are evaluated and prioritized with Shannon Entropy. It underscores design considerations that may have been overlooked. “Total use as primary energy” scores highest among all three materials, underscoring its significance in the sustainability of construction projects. Commencing with energy-efficient design is crucial. The elevated score of "Utilization of net freshwater" emphasizes water use across the whole life cycle of a structure. This fosters innovative, sustainable water management in architectural design and construction. Advocates of the circular economy, "Reusability" and "Recyclability," emphasize the need of recycling. This study emphasizes the importance of life-cycle-oriented building materials and design. These procedures are essential for sustainability and environmental protection. These insights can aid architects and builders in making superior design decisions and fostering ecologically and socially responsible growth. Prior research indicates that building design and utilization are the primary contributors to carbon emissions. The research revealed that timber structures produce lower carbon emissions compared to reinforced concrete or steel, establishing them as optimal low-carbon structural materials. Structures such as frames, frame shear walls, brick concrete, and shear walls exhibit diverse distributions of steel, concrete, blocks, and mortar.

Conclusion

The research conducted in this thesis concludes that integrating circular economy principles into the design phase of construction projects can significantly enhance material reuse and recycling potential. By adopting the BIM-based Whole-life Performance Estimator (BWPE), construction professionals can more accurately predict the performance of building materials and make informed decisions that extend the life of these materials. The study underscores the importance of early design decisions in determining the overall sustainability of construction projects. It highlights the effectiveness of the BWPE model in providing a comprehensive analysis of a building's end-of-life phase, identifying which materials can be salvaged, reused, or recycled. By considering the long-term environmental impacts during the design stage, construction professionals can align their projects with the goals of the circular economy, reducing waste and promoting resource efficiency. Moreover, the practical application of decision-making frameworks such as the Best Worst Method (BWM) and Life Cycle Assessment (LCA) enhances the ability of stakeholders to prioritize sustainability goals. The study concludes with a call for the widespread adoption of circular economy practices in the construction industry, emphasizing that the use of digital tools like BIM can greatly facilitate this transition. By embracing these methodologies, the industry can move towards a more sustainable future.