COMPARATIVE ANALYSIS OF MATERIAL USE IN URBAN AND RURAL AREAS OF LATVIA: FINANCIAL AND ENVIRONMENTAL EFFECTS OF BIM-DRIVEN CONSTRUCTION

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Abstract. The digital transformation of the construction industry has the potential to significantly impact both financial and environmental aspects, particularly through the implementation of Building Information Modelling (BIM). This study examines how BIM adoption influences cost efficiency, resource optimization, and sustainability in Latvia's construction sector, with a specific focus on rural growth initiatives. In rural areas, where infrastructure development faces financial constraints and environmental challenges, BIM can enhance project planning, reduce material waste, and improve lifecycle cost management. By integrating BIM with circular economy principles, construction projects can minimize resource depletion and lower carbon emissions. The study utilizes both qualitative and quantitative methods, incorporating primary data from industry stakeholders and secondary data from academic sources. The findings aim to provide insights into the financial benefits and environmental improvements driven by digital transformation in construction, offering a framework for more efficient and sustainable rural development in Latvia.

Keywords: BIM, circular economy, digital transformation, sustainable construction, rural development.

Introduction

The circular economy (CE) is commonly understood as an environmentally friendly economic framework that aims to divorce economic growth from resource consumption by emphasizing the reduction and recycling of natural resources. The quantification of product and service circularity, as well as their contribution to the circular economy (CE), plays a pivotal role in the development of laws and business strategies, as well as the prioritization of evidence-based sustainable solutions [1]. The implementation of the Circular Economy (CE) concept has the potential to greatly enhance the sustainability of this particular sector [2]. The design phase of the building construction process emerges as the most crucial stage when viewed within the framework of life cycle assessment (LCA). At this point in the process, important decisions concerning the building's form, materials, and systems are being deliberated over. These choices have the potential to greatly impact on the environmental performance of the building over the course of its entire existence. During a life cycle assessment (LCA), there are a variety of environmental, economic, and social issues that need to be evaluated. These are referred to as the impact categories. Consumption of energy, emissions of greenhouse gases, use of water, sources of materials, generation of waste, and other factors are included here. Because the design phase lasts for such a short amount of time and involves such a sophisticated amount of data, decision-making methods have become very necessary tools [3]. An organized way for analyzing the many design options is provided by decision-making approaches such as multi-criteria decision analysis (MCDA) and life cycle costing (LCC). The Multiple Criteria Decision Analysis (MCDA) tool gives designers the ability to evaluate different impact categories based on the priority they attach to them and then make decisions that are in line with the principles of the circular economy. For instance, a designer can evaluate the pros and drawbacks of utilizing recycled materials (which helps reduce the depletion of resources) and selecting energy-efficient systems (which helps reduce the amount of energy that is consumed). LCC, on the other hand, is a tool that assists in the evaluation of the economic consequences of design choices by taking into consideration the total cost of ownership throughout the lifecycle of the building. This study aims to analyze the selection of building materials for construction projects in Latvia, considering both financial and environmental aspects. The research contrasts material choices in rural and urban settings, evaluating which materials are most suitable for different environments. The study also investigates the potential benefits of combining materials and how digital tools like BIM can optimize their use.

Materials and methods

According to EN 15804, a European standard for evaluating the environmental impact of buildings, a building's life cycle consists of several stages. The Product Stage (A1-A3) covers raw material

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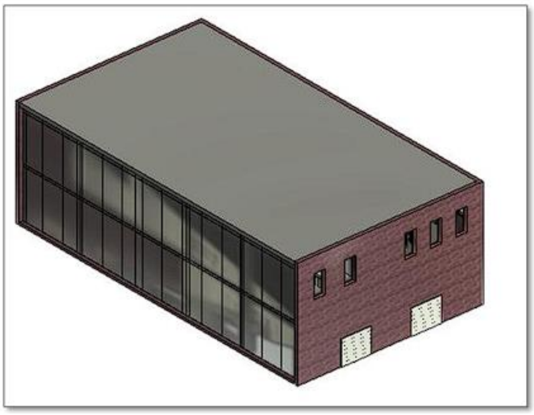
extraction, processing, and production, as well as the transportation of finished goods to the construction site. The Construction Stage (A4-A5) involves on-site activities such as assembly and installation. The Use Stage (B1-B7) represents the building's operational phase, including energy consumption, maintenance, and repairs. Finally, the End-of-Life Stage (C1-C4) includes deconstruction, demolition, and the disposal or recycling of materials [4]. To promote sustainable development, the building sector must significantly minimize its environmental impact. Existing life cycle assessment (LCA) methodology quantifies environmental consequences and is increasingly used to evaluate building environmental performance. Combining LCAs with digital design technologies, such as BIM, enables the detection and mitigation of environmental hotspots during design [5]. In order to conduct a life cycle assessment (LCA) of a structure, it is necessary to collect a substantial amount of data pertaining to the building materials, construction procedures, operational phase, and end-of-life considerations. This particular procedure requires a significant amount of effort and consumes a substantial amount of time [5]. The "Best-Worst Method (BWM)", introduced by Rezaei in 2015, is a multi-criteria decision-making (MCDM) method that improves upon the "Analytic Hierarchy Process (AHP)" by requiring fewer comparisons and ensuring greater consistency. In BWM, the decision-maker identifies the most and least important criteria (best and worst) and then conducts pairwise comparisons between them and the remaining criteria. A mathematical model is then used to determine the optimal weights for the criteria. Compared to AHP, BWM is more efficient, requiring less calculations. It also produces more "consistent and reliable" weight assignments and is easier to interpret due to its use of integer values rather than fractional scales. BWM can be used independently or in combination with other MCDM methods, offering a "simpler and less subjective" approach to decision-making while maintaining computational efficiency [6]. A case study is presented in this section. A two-story rural building is modeled in Revit 2024. The ground floor area (GFA) is equal to 362 m^2 and three different scenarios have been considered for structural, steel, concrete, and timber. The second floor is 363 m^2, and the roof is 371 m^2. On the first floor, 283 m^2 is the office area and 34 m^2 is dedicated to the WC and 29 m^2 as the staircase and entrance part. The second floor has 130 m^2 as open offices and 85 m^2 as management rooms, 71 m^2 as meeting room, 35 m^2 as WC and 29 m^2 as entrance and staircase. Fig. 1 shows the description of the model.



Category	Count	Material: Area (m²)	Material: Volume (m³)
Casework	61	288	5.11
Doors	42	128	2.45
Floors	3	1074	124.93
Specialty Equipment	15	80	1.90
Stairs	1	32	2.58
Stairs: Landings	2	8	0.74
Stairs: Runs	3	24	1.85
Structural Columns	18	162	11.90
Walls	66	2117	235.50
Windows	34	126	1.25

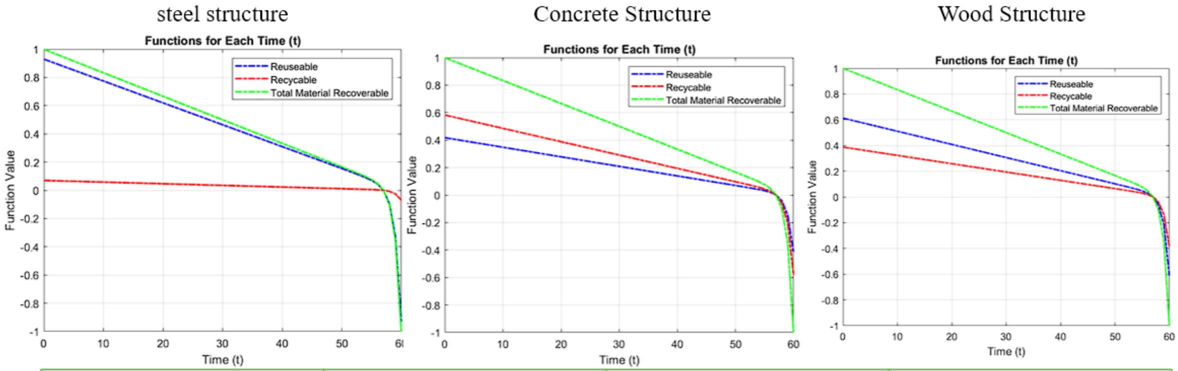
Fig. 1. **Revit 2024 BIM model and table used for the study**

The model has LCA inventory, Social Cost Analysis, and Design Specification. The LCA inventory was created using the OneClick LCA platform, based on the British Standard Institute (BSI, 2015), with a ground floor area (GFA) of 362 m² and a computation time of 60 years. The reference building, "International Reference Building V2022.1", illustrates market circumstances. Ventilation, heat, electrical, water, wastewater drainage, and elevators are prohibited. Everything from raw material extraction to disposal is analyzed using cradle-to-grave LCA. Calculations include annual lighting, HVAC, and water use. Weibull distribution hazard functions must be rising, decreasing, or constant. It cannot model lifetime data like human mortality and machine life cycles with a bathtub-shaped hazard function. It is now possible to depict the role of design specification over the building life cycle by using the Weibull distribution function over time and considering equations 1 is how salvaging effect has been entered into the model [7].

$$S_{ru}=\left(\beta\frac{ndc}{nc}+\gamma\frac{nf\,b}{ne}+\mu\frac{\nu\,\overline{S}_f}{\nu m}+\rho\frac{\nu\,\overline{h}_t}{\nu m}\right)*\left(1-e^{t-\alpha}-\frac{t}{10*\alpha}\right)$$
$$S_{rc}=\left(1-\left(\beta\frac{ndc}{nc}+\gamma\frac{nf\,b}{ne}+\mu\frac{\nu\,\overline{S}_f}{\nu m}+\rho\frac{\nu\,\overline{h}_t}{\nu m}\right)\right)*\left(1-e^{t-\alpha}-\frac{t}{10*\alpha}\right). \quad (1)$$

where S – set of design specifications;
$D(t)$ – time-dependent building deterioration
t – the building's age in years.

The *ndc* indicates the number of demountable connections, while *nc* represents the total number of connections, with *dc* and *fb* both expressing the ratio of demountable connections to total connections. The *nfb* refers to the number of prefabricated assemblies, and ne denotes the possible building elements. The $\overline{s}_f$ indicates the volume ratio without secondary finishes, while $v\overline{s}_f$ represents the non-finished material volume. The *vm* signifies the total volume of building materials, whereas $v\overline{h}_t$ denotes the non-hazardous volume, and $\overline{h}_t$ is the ratio of toxic-free materials to total materials. The *SP* defines the salvage performance of the building within the range $\{0 \leq SP \leq 1\}$, where SP_{ru} refers to the reusable building part and SP_{rc} denotes the reused building component. The γ represents landfilled building materials, and α indicates the life expectancy of the building. Wood structures exemplify sustainability with high renewable and recycled content and a strong capacity for bio-carbon dioxide sequestration. Steel frames serve as an intermediate option, excelling in acidification potential and downcycling. This study, conducted by the Sustainable Construction Knowledge Network (SCKN), provides insights for sustainable material selection based on circular economy principles. Evaluating reusability (*Sru*) and recyclability (S_{rc}) across steel, concrete, and wood frames reveals key trade-offs. Steel frames show the highest reusability (0.9313) and recyclability (0.7121), extending material lifespan and reducing resource demand. Concrete frames have lower reusability (0.4176) but good recyclability (0.5824), making them viable for aggregate reuse. Wood frames offer a balanced approach, with reusability at 0.6125 and recyclability at 0.3875, promoting waste reduction. These findings underscore the importance of selecting materials based on project needs, existing recycling infrastructure, and sustainability goals (See Fig. 2).



	Steel Frame	Concrete Frame	Wood Frame
Sru	0.9313	0.4176	0.6125
Src	0.7121	0.5824	0.3875

Fig. 2. **Salvage performance of case study building by age for three different structures** (developed by the authors)

Fig. 2 presents a comprehensive framework for ranking building material options – Wood Frame, Concrete Frame, and Steel Frame – based on sustainability factors. These factors are categorized into five main impact areas: Energy Consumption, Environmental Aspects, Water Impact, Social Impact, and Design Impact. Each category consists of specific indicators that influence the material selection process in sustainable construction. Energy consumption is evaluated through Operational Energy, which accounts for heating, cooling, and lighting demands; Embodied Energy, which measures the energy required for material extraction, processing, and installation; and Transport Energy, which considers the fuel consumption for delivering materials to the construction site.

Environmental aspects focus on the material's ecological footprint, including Global Warming Potential (GWP), which quantifies CO_2 emissions; Smog Formation (POCP), measuring the release of pollutants contributing to urban smog; and Ozone Depletion Potential (ODP), which assesses the impact on the ozone layer. Water impact is assessed through Sanitary Water Usage, representing the amount of potable water consumed; Acidification Potential (AP), which measures the release of acidic compounds leading to acid rain; and Eutrophication Potential (EP), which evaluates nutrient accumulation in water bodies, contributing to algal blooms and ecosystem degradation. The social impact category considers Social Costs, which encompass the broader economic and labor-related consequences of material sourcing and construction. Lastly, the design impact includes Reusability, assessing the potential for materials to be repurposed in future constructions, and Recyclability, measuring the efficiency of material reintegration into the supply chain. Life-cycle assessment tool One Click LCA calculates all elements except design influence to assess building materials' environmental performance. Design impact factors Weibull distribution function predicts reuse and recycling based on material degradation. This comprehensive approach evaluates construction sustainability for circular economy and environmental responsibility decision-making. After BWM calculates weights, sorting the results and choosing the best option is critical. Results were ranked using TOPSIS. Results are in Table 1. The overview examines the environmental, social, and design effects of wood, concrete, and steel in projects and products. Wood has the biggest negative influence on site transportation and energy use, followed by steel and concrete. Non-renewable primary energy use is negatively impacted by steel. Ozone depletion and global warming are highest in concrete. Steel is the worst for photochemical ozone production. Steel utilization considerably impacts sanitary water use. Wood is the most socially harmful. Design impacts show that steel and concrete are sustainable due to their reusability and recyclability. The preceding conclusions explain the environmental, social, and design tradeoffs of project or product material selection. It informs priority and constraint decisions.

Table 1

Summary of the results and the impact type (developed by the authors)

Category	Sub-Category	Wood	Concrete	Steel	Impact
Energy Aspects	Transportation to the site	0.629	0.143	0.229	Negative
	Total use as primary energy	0.625	0.083	0.292	Negative
	Total use of non-renewable primary energy	0.250	0.250	0.500	Negative
	Use of fresh water	0.563	0.125	0.313	Negative
Environmental Aspects	GWP	0.231	0.454	0.315	Negative
	ODP	0.167	0.542	0.292	Negative
	POCP	0.067	0.158	0.775	Negative
Sanitary Water Impact	Sanitary Water Use	0.241	0.056	0.704	Negative
	Acidification Potential	0.056	0.667	0.278	Negative
	Eutrophication Potential	0.713	0.231	0.056	Negative
Social Impacts	Social Impact	0.563	0.125	0.313	Negative
Design Impacts	Reusability	0.154	0.077	0.769	**Positive**
	Recyclability	0.091	0.197	0.712	**Positive**

As it can be seen in Table 1, the results are difficult to interpretate. That is why TOPSIS technique is applied to rank the results. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a widely used approach in the field of multi-criteria decision analysis [8]. It involves evaluating a group of alternatives by determining their proximity to both the positive ideal alternative (which represents the best performance in each criterion) and the negative ideal alternative (which represents the worst performance) across various dimensions. This is achieved by employing different distance measures, such as the Euclidean distance, to quantify the dissimilarity between each alternative and the ideal solutions [8]. In 1981, Hwang and Yoon introduced TOPSIS with shanon antrophy weighting method in their work "Multiple Attribute Decision Making: Methods and Applications" [9].

The utilization of the Shannon Entropy approach has been employed to determine the weights assigned to the sub-categories. These weights are afterwards used to rank the impacts that are related to the assessment of the project or product. Shannon Weights are a measure that quantifies the level of diversity or dispersion within individual sub-categories. Higher values of Shannon Weights indicate a higher degree of diversity. In contrast, lower numbers indicate a reduced level of diversity within the sample. Table 2 shows the TOPSIS ranking results by category.

Table 2

TOPSIS Results by ranking, comparing the impact categories (developed by the authors)

Category	**TOPSIS**	**Rank**
Total use as primary energy	0.52709	1
Use of net fresh water	0.51066	2
ODP	0.50776	3
Acidification Potential	0.47311	4
Eutrophication Potential	0.45303	5
Social Impact	0.3845	6
Sanitary Water Use	0.3678	7
Recyclability	0.3655	8
Reusability	0.36469	9
POCP	0.35558	10
GWP	0.31123	11
Transportation to the site	0.23617	12
Total use of non-renewable primary energy	0.22716	13

Material	**Wood**	**Concrete**	**Steel**
TOPSIS	0.554	0.397	0.539
Rank	1	3	2

Results and discussion

The results reveal that wood structure has a little better impact than steel structure. TopSIS evaluated Wood, Concrete, and Steel frames using multiple parameters, yielding performance scores of 0.554, 0.397, and 0.539. From the scores, the wood frame performs slightly better than the steel frame, while the concrete frame performs intermediately. A thorough review of design parameters showed that wood was preferred over steel due to its environmental, social, and design impacts. The performance scores between wood and steel are insignificant, but these evaluations involve complex trade-offs across numerous areas. Design specifications, which include reusability, recyclability, and other sustainability considerations, greatly impact the review process. Therefore, including these factors in decision-making is consistent with a holistic and ecologically friendly construction approach. In conclusion, this scientific study shows how complex construction material selection is. Although wood has a little advantage over steel, the careful study of design criteria shows a commitment to conscientious and sustainable building methods, promoting environmentally and socially responsible construction. While single-material solutions provide certain advantages, hybrid materials, such as timber-concrete composites, offer improved structural performance while maintaining sustainability benefits. By integrating BIM with life cycle analysis, optimal combinations can be selected based on location-specific factors such as climate, availability, and cost efficiency.

Conclusions

1. Material Impact Comparison: Concrete has the highest Global Warming Potential (GWP) and environmental impact, while wood excels in carbon sequestration and lower water usage. Steel offers high recyclability.
2. Decision-Making Efficiency: The Best Worst Method (BWM) is a more efficient decision-making tool compared to AHP, reducing computational complexity while maintaining accuracy.
3. Importance of Primary Energy Use: “Total use as primary energy” is the most critical factor in material selection, followed by water consumption and social impact considerations.
4. Social and Environmental Trade-offs: Steel has a greater social impact, while wood and concrete perform better in various environmental categories, highlighting the need for a balanced approach.
5. Circular Economy Considerations: Reusability and recyclability are essential for sustainable construction, with steel leading in reusability and concrete and steel performing well in

recyclability. Research indicates that timber-based building is ideal for rural Latvia because of its sustainability, cost-efficiency, and flexibility to local environmental circumstances. However, reinforced concrete and hybrid constructions are ideal for urban areas because of their structural durability and high-density development compatibility. Timber-concrete composites may also balance cost, durability, and sustainability in various circumstances.

Author contributions

Conceptualization, S.S.; methodology, S.S. and I.G.; software, J.Z.; validation, I.G. and A.K.; formal analysis, S.S. and J.Z.; investigation, S.S., I.G., A.K., and J.Z.; data curation, S.S. and J.Z.; writing – original draft preparation, S.S.; writing – review and editing, I.G. and A.K.; visualization, J.Z. and S.S.; project administration, I.G.; funding acquisition, I.G. and A.K. All authors have read and agreed to the published version of the manuscript.

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