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LCA-TOPSIS Integration for Minimizing Material Waste in the Construction Sector: A BIM-Based Decision-Making

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Abstract: The construction sector is one of the industries with the highest environmental impact due to resource consumption and waste generation. Material waste exacerbates these impacts by increasing carbon emissions and energy consumption. This study introduces an innovative approach by integrating Life Cycle Assessment (LCA) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to evaluate material waste and environmental impacts simultaneously. By analyzing scenarios of material use in the design and construction phases, this study explores their effects on material efficiency and environmental performance while addressing a notable research gap. Existing studies on the integration of LCA and TOPSIS in evaluating material waste and its environmental impacts remain limited. This research not only demonstrates the applicability of these methods but also contributes to filling this gap. Material waste and efficiency were assessed through Building Information Modeling (BIM), while BIM-LCA integration was used to evaluate environmental impacts. The findings were examined in two stages: LCA and TOPSIS. The TOPSIS analysis considered two scenarios—material waste and environmental impacts. In the first scenario, cast-in-place concrete (5000 psi) and stone and ceramic tiles emerged as priorities. In the second scenario, where carbon emissions and environmental impacts were emphasized, cast-in-place concrete (5000 psi), laminated timber, and stone tiles were identified as critical materials. The results reveal that reducing material waste significantly enhances environmental performance, lowers costs, and promotes sustainability. These findings provide practical insights for developing sustainable strategies in diverse cultural and geographical contexts, particularly for residential projects. The integration of LCA and TOPSIS offers a robust decision-making framework, enabling targeted actions to minimize environmental footprints across all life cycle stages. This study contributes to the literature by providing actionable recommendations for optimizing resource use and improving sustainability in construction practices.

Keywords: life cycle assessment; building information modelling; TOPSIS; multi-criteria decision-making; material waste; construction industry; residential building

Citation: Yardimci, Y.; Kurucay, E. LCA-TOPSIS Integration for Minimizing Material Waste in the Construction Sector: A BIM-Based Decision-Making. *Buildings* **2024**, *14*, 3919. https://doi.org/10.3390/buildings14123919

Academic Editor: Yun Gao

Received: 6 October 2024
Revised: 26 November 2024
Accepted: 5 December 2024
Published: 7 December 2024

1. Introduction

The construction sector is one of the world's largest and most influential industries, with significant environmental, economic, and social impacts [1,2]. The growth of the world's population, coupled with rapid urbanization, has increased the environmental impacts and the demand for construction-related natural resources [3]. This phenomenon has not fostered the requisite conditions for ecological balance; indeed, it imposes significant constraints on the ecosystem [4,5]. The achievement of sustainable construction practices is contingent upon the environmental impact of each stage of the process, from the production and distribution of building materials through to their utilization during construction and, finally, their disposal [6]. In these processes, Life Cycle Assessment (LCA) is employed as a principal instrument for the implementation of sustainable management practices [7–9]. By

assessing the environmental impacts of materials throughout their entire life cycle, LCA contributes to the more environmentally friendly and efficient management of projects [10–12]. This analysis method not only helps reduce the carbon footprint but also enhances the economic sustainability of construction projects [13]. Therefore, LCA has become a critical tool for ensuring environmental, economic, and social sustainability at every stage of a project [14,15]. LCA provides a systematic analysis of the impacts that occur at every stage of a material's life cycle, from production to use, reuse, and disposal [16,17]. This method supports data-driven decision-making for environmental sustainability [18,19]. In order to minimize the environmental impact of construction projects and facilitate the creation of a sustainable built environment, it is necessary to utilize recyclable and low-carbon emission materials [20,21]. It is well established that life cycle assessment (LCA) is an important method for supporting the realization of environmental sustainability objectives [22,23].

Material waste in construction has long been a sustainability challenge. Material waste primarily results from poor planning, insufficient material management, and ineffective implementation mechanisms [24–26]. Material waste leads not only to environmental impacts but also to economic losses [27,28]. Unnecessary material usage and the resulting waste contribute to the depletion of natural resources and increase waste management costs [29]. LCA provides an effective roadmap for reducing waste by identifying the stages where material waste occurs most frequently [30]. The implementation of sustainable material management strategies throughout the process is critical to reducing the environmental footprint of projects, as evidenced in the literature. [31–33].

LCA is a crucial element in ensuring the sustainability of construction projects, identifying the stage of a material's life cycle where it has the greatest environmental impact [34,35]. This approach facilitates the development of improvement strategies to minimize waste throughout the entire lifecycle of materials, from production and transportation to use and disposal [36,37]. Proper material selection and efficient usage contribute to reducing waste and improving the environmental and economic performance of projects [38,39]. Especially the use of recyclable and low-environmental-impact materials plays a significant role in preventing material waste and enhancing resource efficiency [40,41].

Integrating Building Information Modeling (BIM) with LCA provides enhanced capabilities for sustainable construction, automating material selection, and improving data flow between project phases to increase accuracy [42]. BIM tools, such as Revit and Tally, used in early design stages, facilitate real-time environmental assessments and support optimal material selection to reduce embodied carbon [43]. Moreover, automated multi-criteria selection based on environmental and economic performance ensures efficient resource use throughout the life cycle [44]. Studies also emphasize that LCA-based BIM applications provide critical insights into material efficiency and sustainability [45]. Other applications highlight how modular data structures, such as IFC-based interfaces, streamline sustainability assessments in complex projects [46].

BIM-enhanced LCA tools help stakeholders make more informed decisions during the design phase. For example, the use of environmental product declarations (EPDs) within BIM tools improves data consistency and reduces errors, thereby enhancing decision-making [47]; however, certain challenges remain, such as system boundary management and ensuring data accuracy [48]. In addition, BIM-integrated sustainability tools offer multi-dimensional analyses, aligning environmental, economic, and social objectives within construction projects [49]. This holistic approach ensures that sustainable decisions are made early in the design phase, facilitating better resource management throughout the project lifecycle [45].

Multi-criteria decision-making (MCDM) methods offer effective tools that ensure a balanced consideration of economic, environmental, and technical criteria throughout this process [50–52]. Material and technology selection in construction projects is not only about environmental impact. It is also about performance and feasibility [53,54]. MCDM methodologies facilitate a more comprehensive, objective, and sustainable evaluation process by considering all identified criteria [55]. The Technique for Order Pref-

erence by Similarity to Ideal Solution (TOPSIS) is one of the most widely used MCDM methods [56,57]. This method measures the distance of alternatives from the ideal solution, helping to determine the optimal choice in each case [58]. It offers significant advantages, particularly in evaluating environmental impacts in sustainable material selection [59,60]. By streamlining complex material and technology selection processes, TOPSIS facilitates more strategic and informed decisions, supporting sustainability goals in construction projects [61,62]

The integration of LCA with MCDM methods provides an effective approach to prevent material waste and enhance resource efficiency [63,64]. While the former evaluates materials over their entire life cycle, MCDM addresses multiple criteria to reduce waste, improving sustainable material management and overall project performance [65,66]. In conclusion, these methods serve as essential tools in sustainable material selection for construction projects, effectively minimizing environmental impacts and achieving sustainability goals [67,68].

LCA and TOPSIS are powerful and complementary tools for material selection in construction projects [69]. LCA provides a comprehensive assessment of a material's environmental performance throughout its life cycle, while TOPSIS identifies the optimal solution by considering environmental, economic, and technical criteria [70,71]. When LCA is used alone, materials with high environmental impacts can be identified, but it may be unclear which materials should be prioritized for intervention. At this stage, TOPSIS facilitates strategic decision-making by balancing environmental sustainability with cost-effectiveness [72]. This integration is particularly valuable in complex construction projects, providing a critical tool for optimizing resource use, costs, and environmental performance. Ranking data obtained from LCA using TOPSIS not only highlights materials with significant environmental impacts but also helps prioritize these materials for effective intervention to reduce the project's environmental footprint [72]. This approach accelerates the achievement of sustainability goals while minimizing resource waste. In conclusion, integrating these methods makes decision-making processes in construction projects more strategic and effective, enhancing environmental, economic, and operational performance through more informed and balanced approaches to material selection and intervention decisions [73].

A review of the literature reveals that previous studies have indeed investigated the integration of these methodologies in the construction field, primarily focusing on areas such as sustainable material selection, building energy performance, and infrastructure project assessments. For example, Bhuiyan and Hammad (2023) explored this approach to optimize sustainable material selection in high-rise building projects [74]. Similarly, Fazeli et al. (2022) integrated these methods with BIM to evaluate sustainable building components and improve efficiency [60]. Additionally, AbouHamad and Abu-Hamd (2019) applied this integration to assess sustainability and life cycle costs in medium-scale residential buildings [75]; however, this research addresses a specific gap by focusing on the evaluation of alternative scenarios involving different levels of material usage during the design and construction phases. While earlier studies have typically been limited to examining the general applications of LCA and TOPSIS, this study provides a detailed analysis of how various material management strategies employed at these stages influence material efficiency and sustainability outcomes. This approach offers new insights into waste reduction and resource optimization, thereby enhancing the understanding of sustainable construction practices and making a unique contribution to the existing body of literature.

This paper explores the environmental effects of building materials wastage during construction and provides a way forward. The goal is to optimize the material efficiency in construction projects by utilizing LCA and TOPSIS. The objective of this study is to assess the impact of material waste on construction efficiency and to propose effective methods for achieving sustainability goals. In this context, reducing material waste is targeted to develop more environmentally friendly and efficient construction processes.

This study focuses on minimizing material waste during the construction process and improving efficiency. Within this scope, the environmental impacts of materials used in projects have been observed throughout their life cycle, and the relationship between material waste and construction efficiency has been assessed. Each construction material was evaluated from the production stage to the maintenance, operation, and disposal stages, and then the ranking of necessary interventions for construction materials was based on the technique for order preference by similarity to the ideal solution (TOPSIS). The research questions are as follows:

- How can the waste rates of materials used in the construction process be evaluated and reduced using LCA-TOPSIS integration?
- Which specific material types in the construction project have the potential to minimize material waste through these methods?
- How can the materials prioritized by TOPSIS based on the "material waste" criterion be assessed in terms of environmental sustainability?
- How can the materials prioritized by TOPSIS according to environmental impact criteria be evaluated in terms of material waste and efficiency?

2. Materials and Methods

The construction industry is one of the most resourc × 10-intensive and wast × 10-generating sectors globally [76,77]. Building materials have significant environmental impacts throughout their life cycle stages (production, transportation, use, and disposal), and material waste further exacerbates these effects [6]. Material waste generated during construction projects leads to increased energy consumption during the production phase and higher carbon emissions, causing both economic and environmental sustainability issues [78,79]. The inability to balance environmental sustainability and efficiency in construction processes results in major environmental damage throughout the life cycle [80]; therefore, developing sustainable material selection strategies and minimizing material waste have emerged as critical challenges in the sector.

In this context, the principles of circular economy and BIM-based technologies are of great importance for optimizing material use and enhancing sustainability [81]. In this study by Talla and McIlwaine (2022), it was demonstrated that digital twin technologies and material passports contribute to waste reduction during the design phase [82]. Tokede (2022) proposed strategies aimed at improving the environmental performance of structural systems by promoting the sustainable use of materials such as wood and concrete [83]. In line with the principles of the circular economy, strategies for reuse, recycling, and reduction are being adopted in the construction process [84]. Additionally, BIM-based waste management frameworks facilitate more effective management of construction waste [85]. In the design of green building materials, BIM increases sustainability by optimizing maintenance processes [86]. In addition, various optimization techniques are gaining popularity to minimize the use of materials in construction projects. In their study, Sadeghi et al. (2021) investigated the effectiveness of advanced optimization strategies in reducing material use while maintaining structural integrity under static and dynamic loads [87]. Szigeti et al. (2023) emphasize the importance of sustainable material selection by standardizing the environmental impact of materials such as concrete and steel [88].

It is equally important to ensure the accuracy and reliability of environmental data used in decision-making. These uncertainties can affect the environmental impact assessments of specific materials and lead to possible errors in TOPSIS rankings. To improve data reliability, cross-checks with on-site data and project information were carried out throughout this study. Fluctuations in GWP values can push carbon-intensive materials to lower positions in the ranking or elevate sustainable alternatives; therefore, regularly reviewing the environmental performance of materials and updating analyses based on evolving databases is essential to maintain the accuracy of rankings. As a result, a flexi-

ble decision-making approach in accordance with international LCA standards has been adopted, taking into account data uncertainties.

2.1. Information About the Field Study

The field study was conducted on a residential building located in Turkey and monitored throughout its construction from May 2022 to April 2024. The building, situated on a 710-squar × 10-meter plot with a construction area of 355 square meters, consists of two floors: a basement and a ground floor. Designed with modern architectural features, the basement includes essential utility spaces such as a plumbing room, hydrophore room, generator room, storage area, and parking space, while the ground floor comprises common living areas, including an entrance hall, kitchen, living room, bedrooms, and bathrooms (see Figure 1). The building's layout and construction phases reflect universally applicable principles frequently observed in contemporary residential architecture. Modern residential designs prioritize open and functional plans, spacious living areas, and dedicated utility rooms, all of which enhance both functionality and user comfort. This architectural approach aligns with design trends adopted in numerous countries and remains applicable across varied cultural and geographical contexts. Collectively, these elements suggest that the structure analyzed in this study exemplifies widely accepted principles in contemporary housing projects, ensuring its adaptability and relevance to residential construction standards in diverse regions.

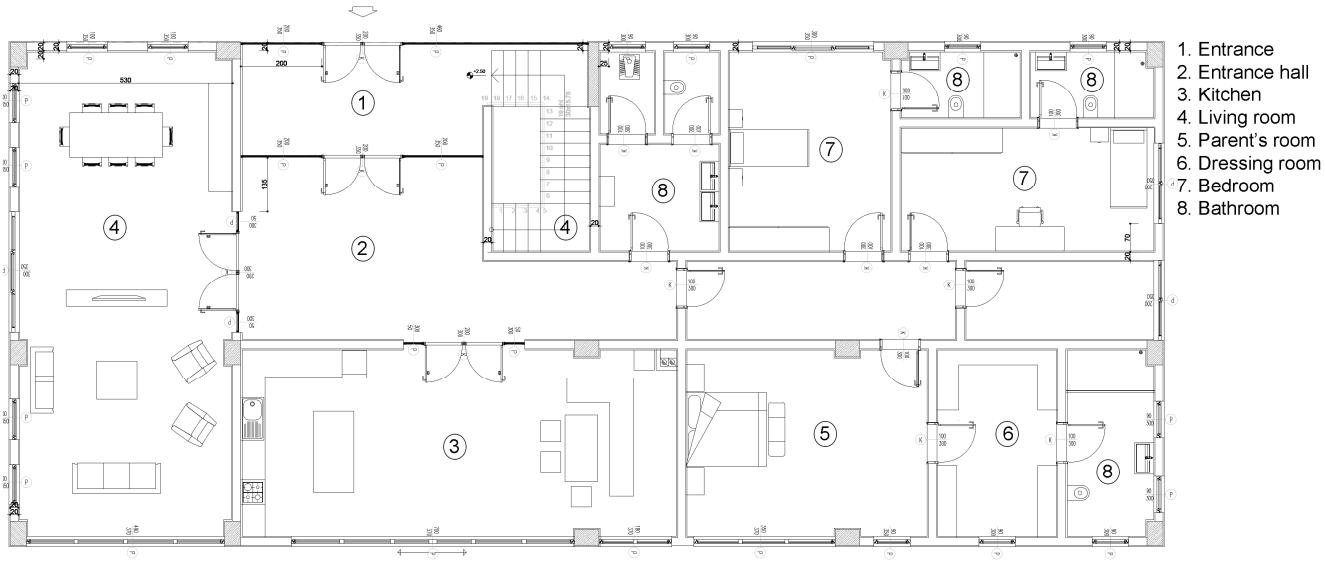

Figure 1. Ground floor plan of residential building.

The efficiency problems encountered during the construction process can arise because of inaccurate material calculations, poor planning, and insufficient labor. This situation can result in more negative impacts on the ecosystem balance than initially estimated, increasing the environmental footprint of projects. For this reason, the efficiency of materials was monitored throughout the construction phase of the residential project in monthly intervals, and the types and quantities of materials used were recorded. Subsequently, in order to verify the predetermined material quantities before the construction phase, the building's CAD (Computer Aided Design) drawings were modeled in a BIM environment using Autodesk Revit 2024. Information regarding the construction phases, sections, areas, and materials used, obtained from the BIM model, is presented in Table 1.

Table 1. Data obtained from the BIM model regarding the building.

Construction Phases	Building Layers	Area (m^2)	Materials Used
	Gross floor area	710	
	Net internal area	355	
Foundation phase	Foundation	391	Concrete, lean concrete, gravel, water proofing
Basement floor	Stairs	17.82	Concrete, masonry, plaster, marble, aluminum
	Plumbing room	9.90	Concrete, masonry, plaster, paint, screed
	Hydrophore room	10.37	Concrete, masonry, plaster, paint, screed
	Generator room	10.51	Concrete, masonry, plaster, paint, screed
	Storage	8.14	Concrete, masonry, plaster, paint, screed
	Parking	102.30	Concrete, masonry, plaster, paint, screed
Ground floor	Windbreak	16.78	Concrete, masonry, plaster, marble, paint, screed
	Entrance hall	36.91	Concrete, masonry, plaster, marble, paint, screed
	Kitchen	49.97	Concrete, masonry, plaster, marble, paint, screed
	Living room	63.30	Concrete, masonry, plaster, laminated wood, marble, paint, screed
	Room 1	27.65	Concrete, masonry, plaster, laminated wood, paint, screed
	Room 2	20.20	Concrete, masonry, plaster, laminated wood, paint, screed
	Room 3	19.53	Concrete, masonry, plaster, laminated wood, paint, screed
	Bathroom (all)	26.18	Concrete, masonry, ceramic tile, paint, screed
	Night hallway	13.60	Concrete, masonry, ceramic tile, paint, screed
	Storage	9.39	Concrete, masonry, ceramic tile, paint, screed
	Stairs	12.12	Concrete, masonry, marble, paint, screed
Roof		371	Wood structure, clay tile

Information Regarding the Construction Process of the Building

The construction phases of the selected building were monitored over a period of two years, and the materials used were recorded. The foundation construction took fifteen days, the basement column and ground floor slab construction took fifteen days, and the ground floor column and ceiling slab construction took fifteen days, resulting in a total of two months. After the basement column construction, wall masonry work began, and the overall rough construction, including masonry activities, took a total of three months. Alongside the masonry activities, electrical, plumbing, and ventilation system installations commenced, and once the masonry work was completed, plastering and painting processes began. Following the completion of plastering, marble, ceramic, and parquet flooring installations were initiated in parallel with the exterior cladding work.

Due to the user-specific designs of both movable and immovable elements within the residence, the subsequent phases after the rough construction became more complex. As a result, tracking the process became difficult, and only the materials used were monitored. Since the production of windows and doors was carried out in factories, and the installation of items such as aluminum stair railings, roof construction, and other components was performed after being pr $\times$ 10-fabricated in workshops, information regarding material losses could not be obtained; therefore, synthetic data generated by computer-supported systems were used in three components, and material waste calculations were excluded. Table 2 presents the construction materials and their usage quantities, analyzed in two sections: Revit and the construction process.

Table 2. Construction Materials and Usage Quantities.

Revit Building Layer	Material	Material Quantity m^2 (Autodesk Revit)	Material Quantity m^3 (Autodesk Revit)	Amount of Material Used m^2 or m^3 (During Construction)	Material Waste %
Wall and floor	Concrete C30		591.26	618	4.522545073
Floor	Lean concrete	-	39.21	41	4.565161948
Floor	Gravel	-	78.42	90	14.76664116
Floor	Water-proofing material	392	-	394	0.510204082
Wall and floor	Water-proofing material	385	-	387	0.519480519
Floor	Screed	-	44.76	47	5.004468275
Wall	Masonry	593	-	621.16	4.748735245
Wall and floor	Plaster	2248	-	2360	4.982206406
Wall	Paint	548	-	583	6.386861313
Wall and floor	Ceramic tile	147	-	169.49	15.29931973
Floor	Marble	159	-	162	1.886792453
Assembled Stair	Stone tile	38	-	44	15.78947368
Floor	Laminated wood	98	-	121	23.46938776
Wall	Mineral wool	881	-	885	0.454029512
Roof	Roofing, tile	371	-	386.85	4.272237197

During the concrete pouring phase of construction, due to calculation errors and formwork issues caused by workers, 4.52% more material was used than anticipated. Since a shortage of concrete during pouring would prolong the construction process, this risk was avoided by requesting slightly more than the calculated amount from the concrete production companies. Additionally, due to the fast pace of the construction, occasional errors by workers were observed. The same issue occurred with the lean concrete, resulting in 4.56% more material being used.

Crushed stone, which was used to stabilize the ground before the foundation was laid, was overused by 14.76% because the soil was looser than initially expected. The waterproofing materials used in the foundation and basement (below-ground sections) were applied 0.51% more than estimated to ensure waterproofing and prevent condensation. Screed, a lightweight concret $\times$ 10-based material used to level the floor before applying parquet, marble, and ceramic tiles, was overused by 5% because of similar issues encountered during the concrete pouring phase.

Aerated concrete, used for wall construction, is not an easily modifiable material because of its composition. Excess usage of aerated concrete blocks occurred either during shaping or because of damage during transportation, leading to 4.74% more material being used. Although the technical drawings specified a plaster thickness between 2 to 3 cm, maintaining this exact thickness during the plastering process proved difficult, resulting in 4.98% more plaster material being used.

Ceramic tiles were overused by 15.30% because of breakage during transportation and installation, as well as measurement discrepancies. On the other hand, marble, which is a more durable and costlier material, experienced less waste, with only 1.88% excess usage. This was partly because marble was used in areas that did not require extensive labor; however, the natural stone used for the staircase saw a 15.78% excess usage because of the need for intricate craftsmanship and the material's use in smaller dimensions.

For laminate parquet used in the flooring of rooms, significant material loss was observed, with 23.46% more material used than expected. This was due to discrepancies

between the parquet dimensions and room sizes, as well as the custom design requested by the user for the living room. During the application of stone wool, minimal excess material was used, although 0.45% more material was ordered to avoid shortages. Finally, 4.27% more roofing tiles were used due to breakage caused by transportation and labor.

2.2. Methodology

The field study project was observed throughout the construction period to identify the environmental impacts caused by material waste, with relevant data collected and analyzed regularly. This process integrated Life Cycle Assessment (LCA) and the TOPSIS multi-criteria decision-making method to address the environmental effects associated with material waste. The LCA analysis was conducted using Autodesk Tally 2023 integrated with the BIM model, following the four fundamental stages of LCA. The first stage, "Goal and Scope Definition", aimed to assess the environmental impacts related to material waste and to develop strategies for minimizing these impacts throughout the entire life cycle, including production, maintenance, replacement, and end-of-life stages, with a projected building lifespan of 50 years. During the "Inventory Analysis" stage, data on material types, quantities, and construction processes were collected using the BIM model, and Autodesk Tally was used to quantify inputs and outputs. Modeling was conducted with GaBi 8.5 software, using GaBi 2018 databases to assess various factors such as material consumption, energy use, and emissions. The "Impact Assessment" stage involved the calculation of environmental impacts identified during the inventory analysis using the Tally methodology in strict compliance with the relevant LCA standards. The Tally methodology adheres to the principles and practices established for conducting life cycle assessment (LCA) of construction works and construction products. It aligns with internationally recognized standards, including ISO 14040-14044 [89,90], ISO 21930:2017 [91], ISO 21931:2010 [92], EN 15804:2012 [93], and EN 15978:2011 [94]. Within this framework, environmental impacts such as global warming potential (GWP), acidification potential, and energy demand were quantified utilizing the TRACI 2.1 impact assessment method [95]. In the final "Interpretation" stage, the materials contributing most significantly to environmental impacts were identified, guiding targeted interventions aimed at minimizing these effects.

Following LCA calculations and construction-phase data collection, the TOPSIS method was applied to identify materials most in need of intervention based on environmental impact and material waste scenarios, calculating the distance of each alternative from the ideal solution to facilitate material selection. The stages of the TOPSIS application are shown below.

2.2.1. Creation of the Decision Matrix

In the construction of the decision matrix, the LCA parameters and the percentage of excess material usage were employed as criteria. The matrix comprised the following criteria: acidification potential (kg SO_2eq), eutrophication potential (kg Neq), global warming potential (kg CO_2eq), ozone depletion (CFC-11eq), smog formation potential (kg O_3eq), primary energy demand (MJ), non-renewable energy demand (MJ), renewable energy demand (MJ), and material waste (%).

2.2.2. Normalization of Values in the Decision Matrix

To streamline the calculations in the decision matrix, normalization was applied to each criterion. During the normalization process, each value in the column was normalized by dividing it by the square root of the sum of the squares of all values in the column. For reference, the normalization formula and an example of the normalization process are presented in Table 3. The full results of the normalization process can be found in Appendix A.

Table 3. Normalization equation and an example.

Equation:	$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$
r_{ij}: normalized value; x_{ij}: value in the original decision matrix; m: number of alternatives	
Normalization of the "material waste" criteria for "cast-in-place concrete 5000 psi" material:	$r_{ij} = \frac{4.522545}{\sqrt{4.522545^2 + 4.565162^2 + 5.004468^2 + \ldots}}$

2.2.3. Weighted Normalization of the Values in the Decision Matrix

In order to ascertain the relative weights, two distinct scenarios were devised for the purpose of evaluating the environmental impact and efficiency of the materials in question. In the initial scenario, the weights were determined in accordance with the principles of material efficiency. The criteria were distributed as follows: The percentage of "material waste" was set at 50%, the Global Warming Potential (GWP) at 26%, and the remaining parameters at 3% each. In the second scenario, the weights were determined by focusing on the environmental impacts of the materials. The criteria were distributed as follows: "GWP" at 40%, percentage of "material waste" at 25%, and the other parameters at 5% each. Table 4 presents the equation and an example of the weighted normalization process. The complete results of the weighted normalization process can be found in Appendix A.

Table 4. Weighted normalization equation and an example.

Equation:	$v_{ij}=r_{ij} \cdot w_j$
v_{ij}: weighted normalized value; w_j: criterion weight	
Weighted normalization of the "material wastage" criteria for "cast-in-place concrete 5000 psi" according to Scenario 1:	$v_{ij} = 0.127572 \cdot 0.5 = 0.063786$

2.2.4. Determination of Ideal and Negative Ideal Solutions

In the TOPSIS method, the ideal solution represents the alternatives with the best values for each criterion, while the negative ideal solution represents the alternatives with the worst values. Accordingly, the highest and lowest weighted normalized values are determined for each criterion. The equations and examples for the ideal and negative ideal solutions are presented in Table 5.

Table 5. Ideal solution and negative ideal solution equations and an example.

Ideal solution (A^+) Equation:	$A^+ = \left(\max v_{ij} \,\middle|\, j \in J_1, \min v_{ij} \,\middle|\, j \in J_2 \right)$
Negative ideal solution (A^-) Equation:	$A^- = \left(\min v_{ij} \,\middle|\, j \in J_1, \max v_{ij} \,\middle|\, j \in J_2 \right)$
Normalized weights for the material wastage criteria (Scenario 1):	**An example:** Cast-in-place concrete, 5000 psi: 0.063785858 Ceramic tile: 0.215781206 Aluminum, angle: 0 Using three data sets, we can determine that the ideal solution would be "ceramic tile", while the a negative ideal solution would be "aluminum angel":

2.2.5. Calculation of Distances

This phase in the TOPSIS method determines the distances to the ideal and negative ideal solutions and is used to measure the performance of each material. The equations and examples related to the calculation are presented in Table 6.

Table 6. Equations and examples for "ideal distance" and "negative ideal distance" calculations.

Distance to the ideal solution D^+ Equation:	$D^+ = \sqrt{\sum_{j=1}^{n}\left(v_{ij}-v_j^+\right)^2}$	
Distance to negative ideal solution D^- Equation:	$D^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij}-v_j^-\right)^2}$	
An Example: Ideal distance calculations for "Cast-in-place concrete, 5000 psi"	Acidification potential: Ozone depletion potential: Global warming potential: Material waste:	$(0.0)^2 = 0.000$ $(0.0389 - 0.0777)^2 = 0.001514$ $(0.0)^2 = 0.000$ $(0.426 - 0.700)^2 = 0.071410$
	The square root of the sum of their squares:	$D^+ = \sqrt{0.000 + 0.001514 + 0.071410} = 0.2700$
An Example: Negative ideal distance calculations for "Cast-in-place concrete, 5000 psi"	Global warming potential: Acidification potential: Material waste:	$(0.0389 - 0.245)^2 = 0.065746$ $(0.0268 - 0.0)^2 = 0.000723$ $(0.426 - 0.300)^2 = 0.004069$
	The square root of the sum of their squares:	$D^- = \sqrt{0.065746 + 0.000723 + 0.004069} = 0.2728$

2.2.6. Calculation of Relative Closeness

At this stage of the TOPSIS method, the goal is to determine how close each alternative is to the ideal solution. Relative closeness is calculated using the distances to both the ideal and negative ideal solutions. Table 7 presents the equation for calculating relative closeness and an example. The value of Ci ranges between 0 and 1, where a value close to 1 indicates materials requiring intervention, and a value close to 0 indicates materials that do not require immediate attention.

Table 7. Equation and examples for calculating "relative closeness".

Equation:	$C_i^* = \frac{D_i^-}{D_i^+ + D_i^-}$
C_i: Relative closeness value of the alternative; D^+: Distance to the ideal solution; D^-: Distance to the negative ideal solution	
Relative closeness value for "Cast-in-place concrete 5000 psi":	$C_i = \frac{D^-}{D^+ + D^-} = \frac{0.2728}{0.2700 + 2728} = \frac{0.2728}{0.5428} \approx 0.5026$

3. Results and Discussion

3.1. LCA Analysis

The LCA analysis of the BIM model, which was modeled using Autodesk Revit 2024, was conducted through the Autodesk Tally 2023. The LCA analyses were examined in three sections: life cycle stages, material categories, and materials used. Figure 2 presents the environmental impacts of the building throughout its life cycle stages.

A review of the Global Warming Potential (GWP) data revealed the following distribution: The "Product" (A1–A3) stages accounted for 88.97% of the total, while the "Transportation" (A4) stage constituted 1.19%. The "Maintenance and Replacement" (B2–B5) stage accounted for 2.84%, the "End of Life" stage for 9.84%, and the "Module D" stage for −2.82%. The distribution of acidification data was as follows: The "Product" (A1–A3) stages accounted for 89.52%, "Transportation" (A4) for 1.34%, "Maintenance and Replacement" (B2–B5) for 4.34%, "End of Life" for 6.46%, and "Module D" for −1.65%. With regard to the potential for eutrophication, these data indicated the "Product" (A1–A3) stages contributed 82.80% to the total, while the "Transportation" (A4) stage contributed 2.14%, the "Maintenance and Replacement" (B2–B5) stage contributed 7.10%, the "End of Life" stage contributed 8.88%, and the "Module D" stage contributed −0.93%. With regard to the smog formation, the distribution was as follows: Data indicated that the "Product" (A1–A3) stages exhibited an 86.90% rating, while the "Transportation" (A4) stage demonstrated a 2.60% rating. The "Maintenance and Replacement" (B2–B5) stage and the "End of Life" stage were rated at 4.02% and 7.05%,

respectively. The "Module D" stage exhibited a rating of −0.56%. Concerning data pertaining to "Ozone Depletion Potential", the following was observed: The "Product" (A1–A3) stage exhibited a value of 48.02%, while the "Maintenance and Replacement" (B2–B5) stage demonstrated a value of 20.90%. The "Module D" stage exhibited a value of 31.08%. With regard to the category of "Non-renewable Energy Demand", the distribution was as follows: The "Product" (A1–A3) stages exhibited an 87% prevalence, while the "Transportation" (A4) stage demonstrated a 1.77% occurrence. The "Maintenance and Replacement" (B2–B5) stage exhibited a 5.34% prevalence, the "End of Life" stage exhibited an 8.91% prevalence, and the "Module D" stage exhibited a −3.02% prevalence. With regard to the category of "Renewable Energy Demand", data revealed the following distribution: "Product" (A1–A3) stages at 81.75%, "Transportation" (A4) at 0.45%, "Maintenance and Replacement" (B2–B5) at 14.48%, "End of Life" at 6.39%, and "Module D" at −3.06%.

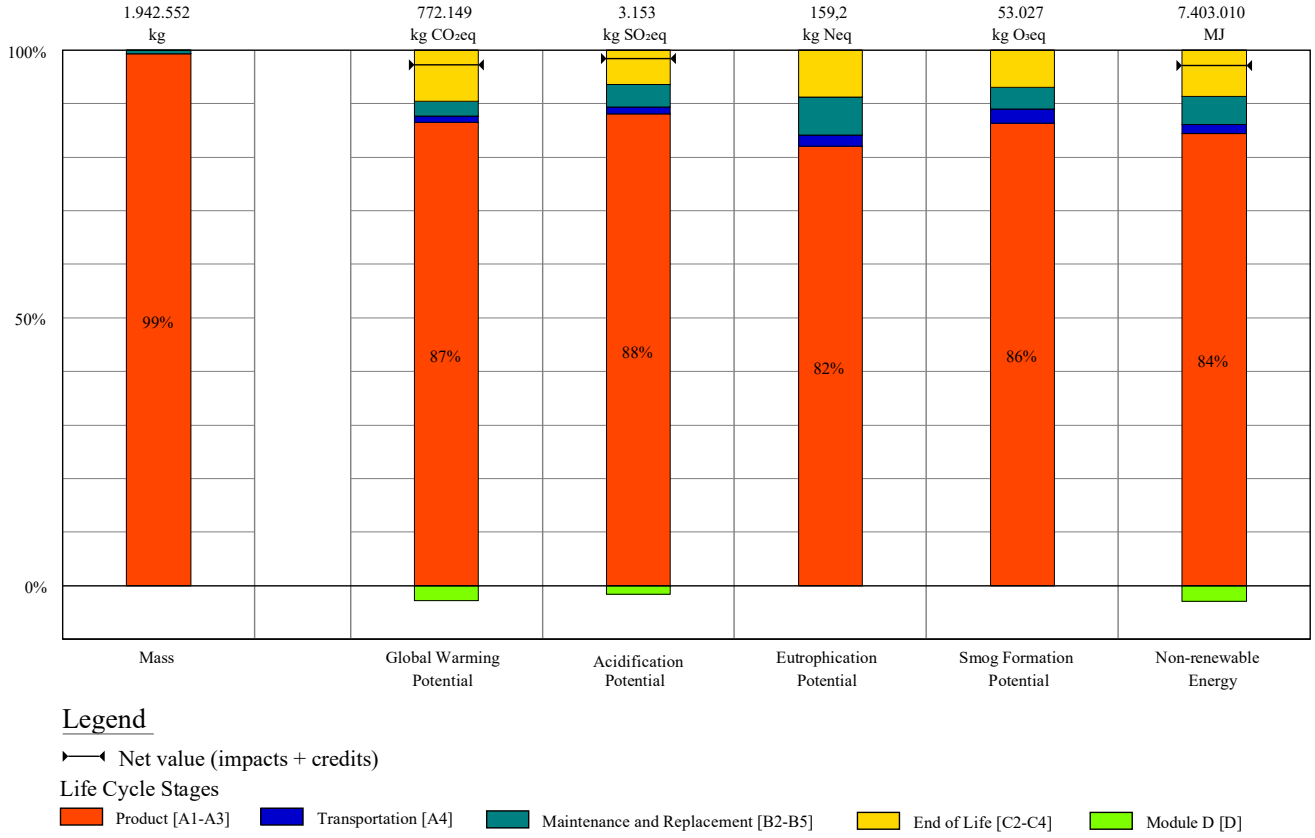

Figure 2. Environmental impact assessments by life cycle stages.

Following an in-depth analysis of the various material categories employed, it was established that the environmental impact of concrete materials accounted for a significant portion of the overall environmental impact, ranging from 58% to 80%. Following concrete materials, finishes accounted for 13% to 33% of the environmental impact. The finishes category includes materials such as plaster, paint, ceramic tile, and stone tile. These material categories were followed by the openings and glazing categories in all parameters except for the GWP environmental impact assessment. In terms of GWP, the masonry category stood out. Figure 3 presents the distribution of environmental impacts according to material categories.

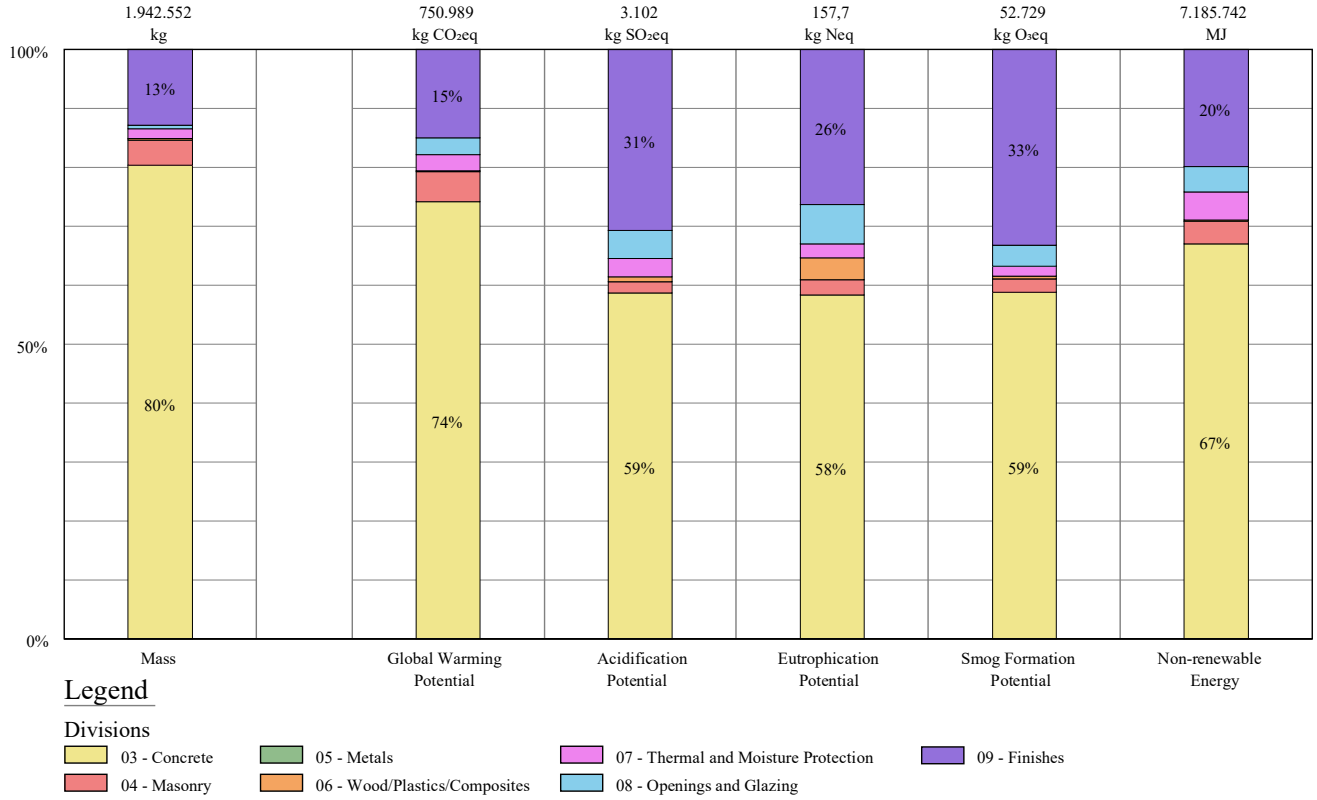

Figure 3. Environmental impact assessments by material categories.

The distribution of the LCA analysis by material categories is presented in Table 8. When examining the environmental impact value for "Global Warming Potential (GWP)", the distribution is as follows: 74.12% "concrete", 15.05% "finishes", 5.20% "masonry", 2.77% "openings and glazing", 2.77% "thermal and moisture protection", and 0.09% "woods". For the "Acidification Potential (AP)" environmental impact value, the distribution is 58.68% "concrete", 30.74% "finishes", 4.75% "openings and glazing", 3.12% "thermal and moisture protection", 1.89% "masonry", and 0.81% "woods". For the "Smog Formation Potential" environmental impact value, the distribution is 58.85% "concrete", 33.26% "finishes", 3.56% "openings and glazing", 2.22% "masonry", 1.65% "thermal and moisture protection", and 0.46% "woods". For the "Primary Energy Demand" environmental impact value, the distribution is 65.15% "concrete", 20.23% "finishes", 4.78% "openings and glazing", 4.64% "thermal and moisture protection", 4.10% "masonry", and 1.10% "woods". For the "Non-renewable Energy Demand" environmental impact value, the distribution is 67.01% "concrete", 19.87% "finishes", 4.78% "thermal and moisture protection", 4.24% "openings and glazing", 3.82% "masonry", and 0.28% "woods". For the "Renewable Energy Demand" environmental impact value, the distribution is 46.02% "concrete", 23.94% "finishes", 10.34% "openings and glazing", 9.42% "woods", 7.08% "masonry", and 3.20% "thermal and moisture protection".

When examining the environmental impact distributions of the materials, it was observed that the "cast in place concrete, 5000 psi" material stands out in the "concrete" category. Among other prominent materials, "stone tile" was identified in the "finishes" category. The negative environmental contribution of concrete material is evident from these material distributions. The environmental impact distributions of the materials are presented in Figure 4.

Table 8. Distribution of environmental impact values by material categories.

	Global Warming Potential ($kgCO_2eq$)	Acidification Potential ($kgSO_2eq$)	Eutrophication Potential (kgNeq)	Ozone Depletion Potential (CFC-11eq)	Smog Formation Potential (kgO_3eq)	Primary Energy Demand (MJ)	Non-Renewable Energy Demand (MJ)	Renewable Energy Demand (MJ)
03—Concrete	5.57×10^5	1.82×10^3	9.21×10^1	-4.39×10^{-4}	3.10×10^4	5.14×10^6	4.82×10^6	3.25×10^5
04—Masonry	3.90×10^4	5.87×10^1	4.02×10^0	-2.34×10^{-6}	1.17×10^3	3.24×10^5	2.74×10^5	5.01×10^4
05—Metals	5.80×10^0	9.23×10^{-2}	2.35×10^{-3}	3.36×10^{-12}	5.17×10^{-1}	1.14×10^2	9.62×10^1	1.75×10^1
06—Woods	6.62×10^2	2.50×10^1	5.83×10^0	-4.05×10^{-9}	2.43×10^2	8.69×10^4	2.04×10^4	6.66×10^4
07—Thermal and Moisture Protection	2.08×10^4	9.67×10^1	3.72×10^0	3.79×10^{-4}	8.70×10^2	3.66×10^5	3.43×10^5	2.26×10^4
08—Openings and Glazing	2.08×10^4	1.47×10^2	1.06×10^1	2.85×10^{-5}	1.88×10^3	3.77×10^5	3.05×10^5	7.31×10^4
09—Finishes	1.13×10^5	9.54×10^2	4.14×10^1	4.99×10^{-4}	1.75×10^4	1.60×10^6	1.43×10^6	1.69×10^5
Grand Total	7.51×10^5	3.10×10^3	1.58×10^2	4.66×10^{-4}	5.27×10^4	7.89×10^6	7.19×10^6	7.07×10^5

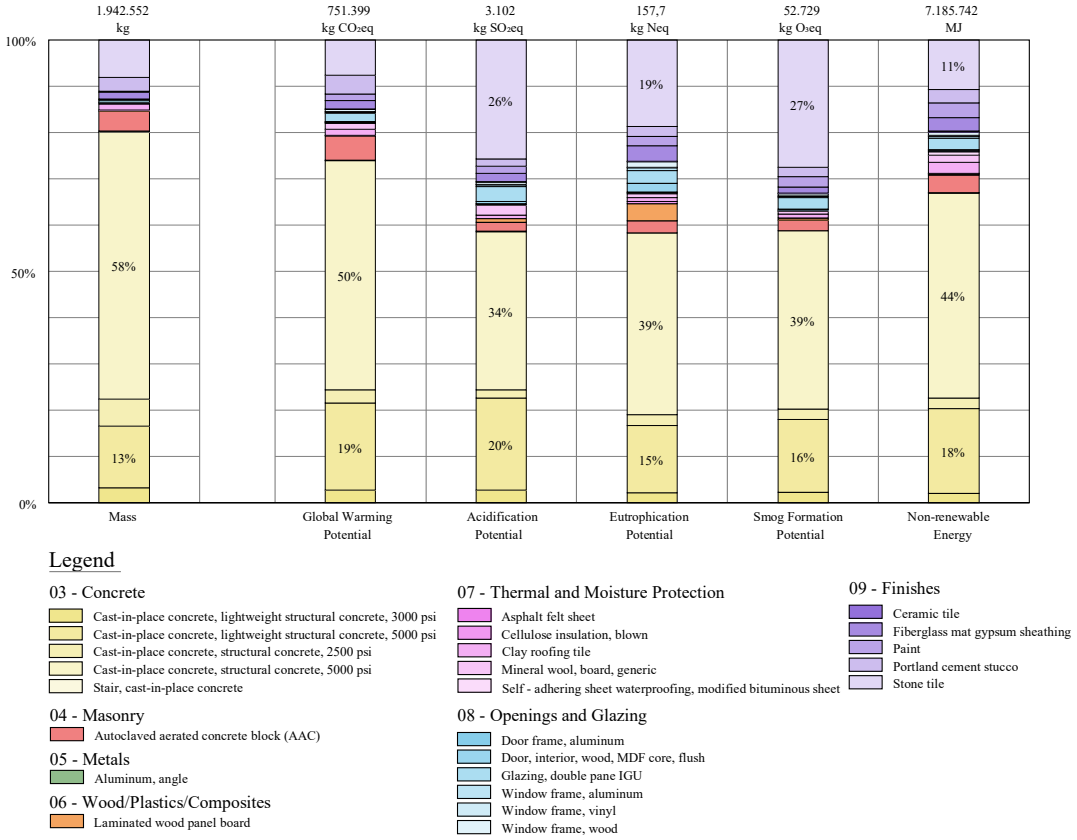

Figure 4. Detailed environmental impact distributions of materials.

Data regarding the environmental impacts of materials are analyzed in detail in Table 9. When examining the "Global Warming Potential (GWP)" data, the materials with the highest impact are as follows: 68.54% from "cast-in place concrete 5000 psi", 7.58% from "stone tile", 4.10% from "portland cement stucco", 5.20% from "AAC", 1.74% from "glazing, double pane IGU", and 1.73% from "gypsum plasterboard". In the "Acidification Potential" data, the distribution shows 54.12% from "cast-in place concrete 5000 psi", 25.75% from "stone tile", 3.27% from "glazing, double pane IGU", 2.18% from "mineral wool", and 1.89% from "AAC". When analyzing the "Eutrophication Potential" data, the materials with the highest impact are: 53.86% from "cast-in place concrete 5000 psi", 18.72% from "stone tile", 3.70% from "laminated wood", 3.28% from "gypsum plasterboard", 2.78% from "glazing, double pane IGU", 2.09% from "paint", and 2.07% from "portland cement stucco".

In the "Smog Formation Potential" data, the distribution includes 54.23% from "cast-in place concrete 5000 psi", 27.49% from "stone tile", 2.45% from "glazing, double pane IGU", 2.22% from "AAC", 2.23% from "paint", and 2.02% from "portland cement stucco". When examining the "Primary Energy Demand", "Non-renewable Energy Demand", and "Renewable Energy Demand" data, the materials with the highest impacts are "cast-in-place concrete 5000 psi", "stone tile", "AAC", "paint", and "gypsum plasterboard". Additionally, in the "Renewable Energy Demand" data, "laminated wood" also shows a significant environmental impact.

Table 9. Distribution of environmental impact values by material details.

	Global Warming Potential Total ($kgCO_2eq$)	Acidification Potential Total ($kgSO_2eq$)	Eutrophication Potential Total (kgNeq)	Ozone Depletion Potential Total (CFC-11eq)	Smog Formation Potential Total (kgO_3eq)	Primary Energy Demand Total (MJ)	Non-Renewable Energy Demand Total (MJ)	Renewable Energy Demand Total (MJ)
03—Concrete	5.57×10^5	1.82×10^3	9.21×10^1	-4.39×10^{-4}	3.10×10^4	5.14×10^6	4.82×10^6	3.25×10^5
Cast-in-place concrete, lightweight structural concrete, 3000 psi	2.04×10^4	8.59×10^1	3.37×10^0	3.24×10^{-9}	1.19×10^3	1.59×10^5	1.47×10^5	1.19×10^4
Cast-in-place concrete, lightweight structural concrete, 5000 psi	1.42×10^5	6.16×10^2	2.30×10^1	-1.80×10^{-4}	8.28×10^3	1.41×10^6	1.31×10^6	9.72×10^4
Cast-in-place concrete, structural concrete, 2500 psi	2.07×10^4	5.37×10^1	3.63×10^0	3.21×10^{-9}	1.20×10^3	1.77×10^5	1.66×10^5	1.14×10^4
Cast-in-place concrete, structural concrete, 5000 psi	3.73×10^5	1.06×10^3	6.20×10^1	-2.58×10^{-4}	2.03×10^4	3.39×10^6	3.18×10^6	2.05×10^5
Stair, cast-in-place concrete	7.88×10^2	2.01×10^0	1.32×10^{-1}	-2.77×10^{-7}	4.21×10^1	6.66×10^3	6.27×10^3	3.96×10^2
04—Masonry	3.90×10^4	5.87×10^1	4.02×10^0	-2.34×10^{-6}	1.17×10^3	3.24×10^5	2.74×10^5	5.01×10^4
Autoclaved aerated concrete block (AAC)	3.90×10^4	5.87×10^1	4.02×10^0	-2.34×10^{-6}	1.17×10^3	3.24×10^5	2.74×10^5	5.01×10^4
05—Metals	5.80×10^0	9.23×10^{-2}	2.35×10^{-3}	3.36×10^{-12}	5.17×10^{-1}	1.14×10^2	9.62×10^1	1.75×10^1
Aluminum, angle	5.80×10^0	9.23×10^{-2}	2.35×10^{-3}	3.36×10^{-12}	5.17×10^{-1}	1.14×10^2	9.62×10^1	1.75×10^1
06—Wood/Plastics/Composites	6.62×10^2	2.50×10^1	5.83×10^0	-4.05×10^{-9}	2.43×10^2	8.69×10^4	2.04×10^4	6.66×10^4
Laminated wood panel board	6.62×10^2	2.50×10^1	5.83×10^0	-4.05×10^{-9}	2.43×10^2	8.69×10^4	2.04×10^4	6.66×10^4
07—Thermal and Moisture Protection	2.08×10^4	9.67×10^1	3.72×10^0	3.79×10^{-4}	8.70×10^2	3.66×10^5	3.43×10^5	2.26×10^4
Asphalt felt sheet	1.71×10^2	6.21×10^{-1}	9.88×10^{-2}	6.30×10^{-9}	1.15×10^1	7.36×10^3	6.50×10^3	8.49×10^2
Cellulose insulation, blown	-4.10×10^2	1.61×10^0	6.67×10^{-1}	1.70×10^{-10}	1.14×10^1	6.44×10^3	9.52×10^2	5.51×10^3
Clay roofing tile	1.00×10^4	2.11×10^1	1.38×10^0	1.25×10^{-4}	4.26×10^2	1.75×10^5	1.66×10^5	9.13×10^3
Mineral wool, board, generic	9.58×10^3	6.78×10^1	1.21×10^0	2.54×10^{-4}	3.29×10^2	1.19×10^5	1.14×10^5	5.46×10^3
Self-adhering sheet waterproofing, modified bituminous sheet	1.50×10^3	5.59×10^0	3.67×10^{-1}	1.24×10^{-7}	9.17×10^1	5.73×10^4	5.56×10^4	1.68×10^3
08—Openings and Glazing	2.08×10^4	1.47×10^2	1.06×10^1	2.85×10^{-5}	1.88×10^3	3.77×10^5	3.05×10^5	7.31×10^4
Door frame, aluminum	6.97×10^2	3.81×10^0	2.87×10^{-1}	1.12×10^{-7}	4.36×10^1	1.08×10^4	9.46×10^3	1.32×10^3
Door, interior, wood, MDF core, flush	6.31×10^2	1.44×10^1	2.93×10^0	2.80×10^{-5}	1.24×10^2	4.42×10^4	2.03×10^4	2.40×10^4
Glazing, double pane IGU	1.31×10^4	1.01×10^2	4.38×10^0	5.22×10^{-9}	1.29×10^3	1.88×10^5	1.79×10^5	9.39×10^3
Window frame, aluminum	2.15×10^3	1.15×10^1	8.40×10^{-1}	3.28×10^{-7}	1.31×10^2	3.36×10^4	2.92×10^4	4.27×10^3
Window frame, vinyl	1.08×10^3	2.76×10^0	3.22×10^{-1}	2.96×10^{-8}	4.32×10^1	1.97×10^4	1.80×10^4	1.76×10^3
Window frame, wood	3.19×10^3	1.36×10^1	1.87×10^0	7.40×10^{-9}	2.45×10^2	8.07×10^4	4.85×10^4	3.24×10^4
09—Finishes	1.13×10^5	9.54×10^2	4.14×10^1	4.99×10^{-4}	1.75×10^4	1.60×10^6	1.43×10^6	1.69×10^5
Ceramic tile	1.24×103	3.64×10^0	1.79×10^{-1}	8.74×10^{-7}	6.79×10^1	1.84×10^4	1.73×10^4	1.13×10^3
Gypsum plaster board	1.30×100^4	5.60×10^1	5.17×10^0	4.97×10^{-4}	7.37×10^2	2.37×10^5	2.06×10^5	3.13×10^4
Paint	1.11×10^4	4.79×10^1	3.29×10^0	5.90×10^{-9}	1.17×10^3	2.50×10^5	2.25×10^5	2.49×10^4
Portland cement stucco	3.08×10^4	4.73×10^1	3.27×10^0	3.23×10^{-9}	1.06×10^3	2.24×10^5	2.13×10^5	1.12×10^4
Stone tile	5.69×10^4	7.99×10^2	2.95×10^1	9.90×10^{-7}	1.45×10^4	8.65×10^5	7.66×10^5	1.01×10^5
Grand Total	7.51×10^5	3.10×10^3	1.58×10^2	4.66×10^{-4}	5.27×10^4	7.89×10^6	7.19×10^6	7.07×10^5

3.2. Determining Material Performance Based on Scenarios

The scenarios were shaped in line with the sustainability goals of construction projects, with the aim of optimizing both environmental impacts and material waste. In the first scenario, a weight of 50% was assigned to material waste, targeting the reduction in project costs and environmental impacts through waste management [96,97]. This approach highlights that waste in material usage directly contributes to the carbon footprint of construction projects and emphasizes the critical importance of reducing waste to minimize environmental impacts. The TOPSIS decision-making method facilitated a flexible and balanced optimization of sustainability criteria based on project priorities. In the second scenario, a 40% weight was assigned to GWP (Global Warming Potential) to align with global climate targets, such as the Paris Agreement [98]. GWP is considered a priority criterion in construction projects, especially due to the use of carbon-intensive materials. This weighting reflects strategies aimed at promoting the use of low-carbon materials in construction projects and minimizing emissions throughout the life cycle of buildings. The literature indicates that prioritizing GWP over other parameters is appropriate in projects that emphasize sustainable material choices [48]. In the same scenario, assigning a 25% weight to material waste aims to draw attention to its contribution to carbon emissions and environmental impacts while encouraging efficient resource use [99]. The TOPSIS method was used to optimize the prioritization of these criteria according to project-specific goals, resulting in a flexible and balanced decision-making model that considers both environmental impacts and material waste.

3.2.1. Scenario 1 (Material Waste 50%, Global Warming 26%, Other 3%)

In the first scenario, where material waste was weighted at 50%, the aim was to determine which material caused the greatest environmental impact due to material waste. In this scenario, the TOPSIS analysis revealed that the highest score was achieved by "laminated wood" (0.5559), highlighting the critical importance of material waste on environmental impact. Other materials, such as "cast-in-place concrete, 5000 psi" (0.5026), "stone tile" (0.4679), and "ceramic tile" (0.4280), also received high scores, indicating that reducing material waste would similarly reduce environmental impacts. These data show that intervening in such materials could significantly reduce natural resource usage and energy consumption resulting from the production process. Reducing the usage of materials with high waste rates or increasing their efficiency would contribute to a more sustainable future by decreasing the carbon footprint and resource consumption.

On the other hand, materials with low scores included "aluminum, angle" (0.0411), "asphalt felt sheet" (0.0447), "self-adhering sheet waterproofing" (0.0448), and "mineral wool" (0.0534). Since no information on material waste related to aluminum angle was available, it was excluded from the scope. For the remaining insulation materials, it was observed that material waste is minimal and poses few usage problems. The environmental impact caused by material waste is relatively low, and adopting sustainable strategies in the production of these materials would ensure more efficient material management in the future. Table 10 presents the TOPSIS scores for the materials based on Scenario 1 (ranked from 1, least efficient, to 17, most efficient).

Table 10. TOPSIS Scores of Materials Based on Scenario 1.

Material	Ideal Distance S1	Negative Ideal Distance S1	Relative Closeness S1	Ranking Scenario 1
Laminated wood panel board	0.264922809	0.331571334	0.555866873	1
Cast-in-place concrete, 5000 psi	0.270043032	0.272846812	0.502582274	2
Stone tile	0.257605109	0.226497619	0.467870983	3
Ceramic tile	0.289375757	0.216553539	0.428031231	4
Paint	0.355001648	0.091297701	0.204566064	5

Table 10. *Cont.*

Material	Ideal Distance S1	Negative Ideal Distance S1	Relative Closeness S1	Ranking Scenario 1
Fiberglass mat gypsum sheathing	0.366897821	0.080677367	0.180254334	6
Portland cement stucco	0.361669081	0.074245598	0.170321399	7
Cast-in-place concrete, structural concrete, 2500 psi	0.364835193	0.07366824	0.167999231	8
Autoclaved aerated concrete block (AAC)	0.361022531	0.072261336	0.166775967	9
Stair, cast-in-place concrete	0.372042888	0.0728961	0.163833923	10
Cast-in-place concrete, 3000 psi	0.369368667	0.067736533	0.154966202	11
Clay roofing tile	0.375724389	0.064866856	0.147226838	12
Mineral wool, board, generic	0.416199568	0.029926014	0.067079797	13
Openings and Glazing	0.417357168	0.023566969	0.053449033	14
Self-adhering sheet waterproofing, modified bituminous sheet	0.418485571	0.019669326	0.044891262	15
Asphalt felt sheet	0.419055096	0.019595009	0.044671161	16
Aluminum, angle	0.424703564	0.018225169	0.041146956	17

3.2.2. Scenario 2 (Material Usage 25%, Global Warming 40%, Other 5%)

In the second scenario, environmental sustainability and global warming potential were prioritized, and the percentage distributions were determined accordingly. In this scenario, "cast-in-place concrete 5000 psi" (0.7349) received the highest score, identifying it as the most critical material in terms of global warming potential and carbon emissions. Considering the high carbon emissions and energy consumption during the production process of this material, replacing it with alternative materials or making concrete more sustainable could significantly reduce environmental impacts and lower carbon emissions, promoting sustainable construction strategies.

Although there is a significant numerical difference between the first and subsequent scores, materials such as "laminated wood" (0.2914) and "stone tile" (0.2620) also stand out as important materials in environmental impact assessments. The environmental impacts of "laminated wood" could be mitigated by using renewable forest products and adopting eco-friendly technologies during the production and transportation processes.

Among the materials with lower scores, besides insulation materials and "openings and glazing", materials such as "clay roofing tile" (0.1052) and "cast-in-place concrete 3000 psi" (0.1015) are also included. Although these materials are less critical in terms of environmental impact, strategies for improvement should still be developed. Table 11 presents the TOPSIS scores for the materials based on Scenario 2.

Table 11. TOPSIS Scores of Materials Based on Scenario 2.

Material	Ideal Distance S2	Negative Ideal Distance S2	Relative Closeness S2	Ranking Scenario 2
Cast-in-place concrete, 5000 psi	0.148515709	0.411694322	0.734892806	1
Laminated wood panel board	0.409888658	0.168589044	0.291435683	2
Stone tile	0.365103373	0.129668992	0.262078081	3
Ceramic tile	0.414916775	0.112105954	0.212715596	4
Fiberglass mat gypsum sheathing	0.420003067	0.074709083	0.151015259	5
Autoclaved aerated concrete block	0.403416445	0.054870372	0.119729327	6

Table 11. *Cont.*

Material	Ideal Distance S2	Negative Ideal Distance S2	Relative Closeness S2	Ranking Scenario 2
Paint	0.420032677	0.05494465	0.115678468	7
Portland cement stucco	0.409400538	0.052289523	0.113256765	8
Cast-in-place concrete, structural concrete, 2500 psi	0.416419471	0.049377683	0.106006837	9
Clay roofing tile	0.425264091	0.050002327	0.105209046	10
Cast-in-place concrete, 3000 psi	0.417571611	0.047152839	0.10146408	11
Mineral wool, board, generic	0.434509885	0.048730811	0.100841695	12
Stair, cast-in-place concrete	0.431408083	0.046554914	0.097402757	13
Openings and Glazing	0.426625344	0.038713539	0.083194292	14
Self-adhering sheet waterproofing (basement)	0.441331201	0.03063906	0.064917352	15
Asphalt felt sheet (foundation)	0.442430648	0.030588789	0.064667086	16
Aluminum, angle	0.443909	0.030375282	0.064044462	17

3.3. Discussions

The findings of this study are largely consistent with recent research addressing sustainable material selection in the construction sector and the integration of LCA with multi-criteria decision-making methods. Alam Bhuiyan and Hammad (2023) developed a hybrid multi-criteria decision support system for sustainable material selection in high-rise building construction, identifying the most suitable materials in terms of sustainability, resource usage, and efficiency [74]. Fazeli et al. (2022) optimized the selection of sustainable building components by integrating the TOPSIS–Fuzzy framework with BIM, highlighting the impact of systems incorporating LCA on efficiency [60]. The findings of this study align with other studies in the literature, which aim to increase efficiency and reduce material waste. In a 2019 study, AbouHamad and Abu-Hamd examined the sustainability and life cycle cost assessments of building systems, exploring the potential for applying these methods to medium-scale and local buildings [75]. Minhas and Potdar (2020) examined how multi-criteria decision support systems can be aligned with local market dynamics for material selection in sustainable housing production processes in Western Australia [100]. Data obtained in this study corroborates the findings of previous research, which underscores the significance of multi-criteria decision-making techniques in attaining sustainability objectives and curbing energy consumption throughout the life cycle of construction projects. Mousavi-Nasab and Sotoudeh-Anvari (2018) demonstrated the applicability of methods such as TOPSIS and COPRAS in material selection and illustrated how these methods can be used to reduce environmental impacts [101].

However, while integrating LCA and TOPSIS within BIM provides a valuable decision-making framework, these methods also carry potential challenges and biases [102]. For instance, the weighting process in TOPSIS can introduce subjectivity, as the assignment of weights is often influenced by user preferences or project-specific regional priorities [103]. This may lead to a potential bias that could affect the objectivity of sustainability assessments and limit the generalizability of results across different application areas. Future studies that incorporate diverse expert opinions or algorithms to mitigate this subjectivity could enhance the reliability of this method in decision-making processes. Additionally, the accuracy and detail level of BIM data used in LCA analyses can vary depending on the quality of the input information and the modeling detail within BIM [104,105]. In particular, data gaps or insufficient detail in BIM can limit the accuracy of lifecycle impact assessments. To address these challenges, improvements

focused on reducing data limitations or providing higher levels of detail could enhance the precision of LCA analyses in specific projects [106].

While this study provides a foundation for sustainable material selection through LCA and multi-criteria decision-making, further research is warranted to explore how technological advancements can be integrated to improve data transparency and accountability. For instance, Morteza (2021) proposed a Blockchain-based framework to manage construction safety data, highlighting the potential of Blockchain technology for enhancing data traceability and trust among project stakeholders [107]. Future studies could investigate how Blockchain can be incorporated into BIM-based decision-making frameworks to ensure reliable tracking of materials, lifecycle impacts, and safety records. Additionally, as noted by Rajabi et al. (2022), regional variations in BIM capabilities indicate that strategies adapted to local conditions can enhance the effectiveness of BIM for sustainability [108]. In this regard, future research could expand multi-criteria decision-making frameworks by incorporating regional factors such as local regulations, resource accessibility, and cultural aspects. The combined application of technological innovations and region-specific strategies could support the unique construction dynamics of each region, enabling the development of sustainable practices that are tailored to diverse geographic and economic conditions.

Such efforts could improve the applicability of this integrated approach across different construction contexts, facilitating more objective project comparisons and decision-making processes. Research focused on overcoming these limitations may contribute to the formulation of more comprehensive and effective sustainability strategies aimed at minimizing environmental impacts throughout the lifecycle of construction projects.

4. Conclusions

This study investigates the impact of excessive material usage due to waste during the construction process on life cycle assessment (LCA) and evaluates the role of the TOPSIS multi-criteria decision-making method in improving resource efficiency. Dissimilar to previous studies, this research provides a detailed comparison of material usage scenarios during the design and construction phases, analyzing how strategies at these stages affect material efficiency and sustainability. This approach highlights the interconnected effects of material waste on environmental impact and construction efficiency, offering new insights into optimizing resource use in residential projects.

The findings demonstrate that reducing material waste improves environmental performance and enables more efficient resource utilization. The integration of LCA and TOPSIS shows that targeted interventions for materials prone to waste can significantly reduce the environmental footprint across the life cycle stages of production, use, and disposal. Moreover, TOPSIS proves to be an effective tool for identifying and prioritizing materials requiring intervention, thereby enhancing resource efficiency and operational performance. Although this study focuses on specific material categories and scenarios, the proposed methodology provides a flexible and adaptable framework applicable to various construction contexts. This framework can effectively be used to reduce material waste and improve environmental performance across different settings. Future studies are recommended to extend the integrated LCA-TOPSIS approach to various building types, incorporating additional environmental indicators such as water consumption and biodiversity loss.

In conclusion, this study emphasizes the importance of exploring innovative materials and construction methods to minimize waste further and promote circular economy principles. Additionally, broader implementation of decision support systems such as TOPSIS across the construction industry could significantly enhance environmental outcomes. These findings underline the necessity of embedding such systems into construction processes to achieve sustainability goals and proactively address global environmental challenges.

Author Contributions: Conceptualization, Y.Y. and E.K.; methodology, Y.Y. and E.K.; software, Y.Y.; validation, Y.Y., and E.K.; formal analysis, E.K. and Y.Y.; investigation, Y.Y.; resources, Y.Y. and E.K.; data curation, Y.Y. and E.K.; writing—original draft preparation, Y.Y.; writing—review and editing, Y.Y. and E.K.; visualization, Y.Y. and E.K.; supervision, Y.Y. and E.K.; project administration, Y.Y. and E.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article; further inquiries can be directed to the corresponding author.

Acknowledgments: We would like to thank the architectural office 'Senfoni Architects' in Turkey for drawing and implementing the project that we observed the construction project.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Normalized Matrix.

	Material	Acidification Potential ($kgSO_2eq$)	Eutrophication Potential (kgNeq)	Global Warming Potential ($kgCO_2eq$)	Ozone Depletion Potential (CFC-11eq)	Smog Formation Potential (kgO_3eq)	Primary Energy Demand (MJ)	Non-Renewable Energy Demand (MJ)	Renewable Energy Demand (MJ)	Material Waste %
Normalized Matrix	Cast-in-place concrete, 5000 psi	0.896362059	0.931085439	0.986202121	−0.607505631	0.886985357	0.973391707	0.976387108	0.887558065	0.127571715
	Cast-in-place concrete, 3000 psi	0.04594123	0.036914799	0.039065094	4.49388×10^{-6}	0.036931861	0.0322436	0.031966349	0.034950169	0.12877385
	Cast-in-place concrete, structural concrete, 2500 psi	0.028719954	0.039762825	0.03963958	4.45227×10^{-6}	0.037242212	0.035893819	0.036098053	0.033481674	0.14116578
	Stair, cast-in-place concrete	0.001074993	0.001445921	0.001508985	−0.000384199	0.001306581	0.001350581	0.001363463	0.001163048	0.14116578
	Autoclaved aerated concrete block (AAC)	0.031394065	0.044034864	0.074683267	−0.003245578	0.036311157	0.06570394	0.059583534	0.147143147	0.133952076
	Aluminum, angle	4.93641×10^{-5}	2.57418×10^{-5}	1.11067×10^{-5}	4.66032×10^{-9}	1.60452×10^{-5}	2.31181×10^{-5}	2.09195×10^{-5}	5.13973×10^{-5}	0
	Laminated wood panel board	0.013370556	0.063861507	0.001267701	-5.61735×10^{-6}	0.007541548	0.017622446	0.004436146	0.195603465	0.662023265
	Asphalt felt sheet	0.000332125	0.00108225	0.000327457	8.73809×10^{-6}	0.000356905	0.001492534	0.001413478	0.002493504	0.01439181
	Self-adhering sheet waterproofing, modified bituminous sheet	0.002989656	0.004020098	0.002872433	0.000171988	0.002845926	0.011619864	0.012090673	0.004934141	0.014653479
	Clay roofing tile	0.011284749	0.015116446	0.019149556	0.173374895	0.013220985	0.035488239	0.036098053	0.026814709	0.120511044
	Mineral wool, board, generic	0.036260947	0.013254275	0.018345274	0.352297786	0.010210573	0.024132003	0.024790229	0.01603596	0.012807241
	Openings and Glazing	0.078618868	0.116111831	0.039831076	0.039529476	0.058346133	0.076451807	0.066324737	0.214693893	0
	Ceramic tile	0.001946753	0.001960756	0.002374545	0.001212237	0.002107289	0.003731335	0.003762026	0.003318798	0.431562413
	Fiberglass mat gypsum sheathing	0.029950045	0.056631903	0.024894422	0.689338581	0.022872925	0.048061216	0.04479638	0.091927755	0.140537818
	Portland cement stucco	0.025297092	0.035819405	0.058980632	4.48001×10^{-6}	0.032897288	0.045424946	0.046318587	0.032894276	0.140537818
	Paint	0.025617985	0.036038483	0.021256007	8.1833×10^{-6}	0.036311157	0.050697485	0.048928084	0.073131025	0.178441946
	Stone tile	0.427322962	0.323141417	0.108960972	0.001373129	0.450010065	0.175413297	0.166572945	0.296635886	0.44538865

Table A2. Weighted Matrix S1.

	Material	Acidification Potential ($kgSO_2eq$)	Eutrophication Potential (kgNeq)	Global Warming Potential ($kgCO_2eq$)	Ozone Depletion Potential (CFC-11eq)	Smog Formation Potential (kgO_3eq)	Primary Energy Demand (MJ)	Non-Renewable Energy Demand (MJ)	Renewable Energy Demand (MJ)	Material Waste %
Weighted Matrix S1	Cast-in-place concrete, 5000 psi	0.026890862	0.027932563	0.256412551	−0.018225169	0.026609561	0.029201751	0.029291613	0.026626742	0.063785858
	Cast-in-place concrete, 3000 psi	0.001378237	0.001107444	0.010156924	1.34816×10^{-7}	0.001107956	0.000967308	0.00095899	0.001048505	0.064386925
	Cast-in-place concrete, structural concrete, 2500 psi	0.000861599	0.001192885	0.010306291	1.33568×10^{-7}	0.001117266	0.001076815	0.001082942	0.00100445	0.07058289
	Stair, cast-in-place concrete	3.22498×10^{-5}	4.33776×10^{-5}	0.000392336	-1.1526×10^{-5}	3.91974×10^{-5}	4.05174×10^{-5}	4.09039×10^{-5}	3.48914×10^{-5}	0.07058289
	Autoclaved aerated concrete block (AAC)	0.000941822	0.001321046	0.01941765	-9.73673×10^{-5}	0.001089335	0.001971118	0.001787506	0.004414294	0.066976038
	Aluminum, angle	1.48092×10^{-6}	7.72253×10^{-7}	2.88775×10^{-6}	1.3981×10^{-10}	4.81356×10^{-7}	6.93542×10^{-7}	6.27584×10^{-7}	1.54192×10^{-6}	0
	Laminated wood panel board	0.000401117	0.001915845	0.000329602	-1.6852×10^{-7}	0.000226246	0.000528673	0.000133084	0.005868104	0.331011633
	Asphalt felt sheet	9.96374×10^{-6}	3.24675×10^{-5}	8.51389×10^{-5}	2.62143×10^{-7}	1.07071×10^{-5}	4.4776×10^{-5}	4.24043×10^{-5}	7.48051×10^{-5}	0.007195905
	Self-adhering sheet waterproofing,	8.96897×10^{-5}	0.000120603	0.000746833	5.15964×10^{-6}	8.53778 × 10-05	0.000348596	0.00036272	0.000148024	0.00732674
	Clay roofing tile	0.000338542	0.000453493	0.004978884	0.005201247	0.00039663	0.001064647	0.001082942	0.000804441	0.060255522
	Mineral wool, board, generic	0.001087828	0.000397628	0.004769771	0.010568934	0.000306317	0.00072396	0.000743707	0.000481079	0.00640362
	Openings and Glazing	0.002358566	0.003483355	0.01035608	0.001185884	0.001750384	0.002293554	0.001989742	0.006440817	0
	Ceramic tile	5.84026×10^{-5}	5.88227×10^{-5}	0.000617382	3.63671×10^{-5}	6.32187×10^{-5}	0.00011194	0.000112861	9.95639×10^{-5}	0.215781206
	Fiberglass mat gypsum sheathing	0.000898501	0.001698957	0.00647255	0.020680157	0.000686188	0.001441836	0.001343891	0.002757833	0.070268909
	Portland cement stucco	0.000758913	0.001074582	0.015334964	1.344×10^{-7}	0.000986919	0.001362748	0.001389558	0.000986828	0.070268909
	Paint	0.00076854	0.001081155	0.005526562	2.45499×10^{-7}	0.001089335	0.001520925	0.001467843	0.002193931	0.089220973
	Stone tile	0.012819689	0.009694243	0.028329853	4.11939×10^{-5}	0.013500302	0.005262399	0.004997188	0.008899077	0.222694325

Table A3. Weighted Matrix S2.

	Material	Acidification Potential ($kgSO_2eq$)	Eutrophication Potential (kgNeq)	Global Warming Potential ($kgCO_2eq$)	Ozone Depletion Potential (CFC-11eq)	Smog Formation Potential (kgO_3eq)	Primary Energy Demand (MJ)	Non-Renewable Energy Demand (MJ)	Renewable Energy Demand (MJ)	Material Waste %
Weighted Matrix S2	Cast-in-place concrete, 5000 psi	0.044818103	0.046554272	0.394480848	−0.030375282	0.044349268	0.048669585	0.048819355	0.044377903	0.031892929
	Cast-in-place concrete, 3000 psi	0.002297061	0.00184574	0.015626037	2.24694×10^{-7}	0.001846593	0.00161218	0.001598317	0.001747508	0.032193463
	Cast-in-place concrete, 2500 psi	0.001435998	0.001988141	0.015855832	2.22613×10^{-7}	0.001862111	0.001794691	0.001804903	0.001674084	0.035291445
	Stair, cast-in-place concrete	5.37496×10^{-5}	7.2296×10^{-5}	0.000603594	-1.92099×10^{-5}	6.5329×10^{-5}	6.7529×10^{-5}	6.81731×10^{-5}	5.81524×10^{-5}	0.035291445
	Autoclaved aerated concrete block (AAC)	0.001569703	0.002201743	0.029873307	−0.000162279	0.001815558	0.003285197	0.002979177	0.007357157	0.033488019
	Aluminum, angle	2.4682×10^{-6}	1.28709×10^{-6}	4.4427×10^{-6}	2.33016×10^{-10}	8.02259×10^{-7}	1.1559×10^{-6}	1.04597×10^{-6}	2.56987×10^{-6}	0

Table A3. *Cont.*

	Material	Acidification Potential ($kgSO_2eq$)	Eutrophication Potential (kgNeq)	Global Warming Potential ($kgCO_2eq$)	Ozone Depletion Potential (CFC-11eq)	Smog Formation Potential (kgO_3eq)	Primary Energy Demand (MJ)	Non-Renewable Energy Demand (MJ)	Renewable Energy Demand (MJ)	Material Waste %
Weighted Matrix S2	Laminated wood panel board	0.000668528	0.003193075	0.00050708	-2.80867×10^{-7}	0.000377077	0.000881122	0.000221807	0.009780173	0.165505816
	Asphalt felt sheet	1.66062×10^{-5}	5.41125×10^{-5}	0.000130983	4.36905×10^{-7}	1.78452×10^{-5}	7.46267×10^{-5}	7.06739×10^{-5}	0.000124675	0.003597953
	Self-adhering sheet waterproofing,	0.000149483	0.000201005	0.001148973	8.59939×10^{-6}	0.000142296	0.000580993	0.000604534	0.000246707	0.00366337
	Clay roofing tile	0.000564237	0.000755822	0.007659822	0.008668745	0.000661049	0.001774412	0.001804903	0.001340735	0.030127761
	Mineral wool, board, generic	0.001813047	0.000662714	0.00733811	0.017614889	0.000510529	0.0012066	0.001239511	0.000801798	0.00320181
	Openings and Glazing	0.003930943	0.005805592	0.01593243	0.001976474	0.002917307	0.00382259	0.003316237	0.010734695	0
	Ceramic tile	9.73376×10^{-5}	9.80378×10^{-5}	0.000949818	6.06119×10^{-5}	0.000105364	0.000186567	0.000188101	0.00016594	0.107890603
	Fiberglass mat gypsum sheathing	0.001497502	0.002831595	0.009957769	0.034466929	0.001143646	0.002403061	0.002239819	0.004596388	0.035134455
	Portland cement stucco	0.001264855	0.00179097	0.023592253	2.24×10^{-7}	0.001644864	0.002271247	0.002315929	0.001644714	0.035134455
	Paint	0.001280899	0.001801924	0.008502403	4.09165×10^{-7}	0.001815558	0.002534874	0.002446404	0.003656551	0.044610486
	Stone tile	0.021366148	0.016157071	0.043584389	6.86565×10^{-5}	0.022500503	0.008770665	0.008328647	0.014831794	0.111347162

Table A4. TOPSIS Scenario 1.

	Material	Ideal Distance S1	Negative Ideal Distance S1	Relative Closeness S1	TOPSIS Score S1
Scenario 1	Cast-in-place concrete, 5000 psi	0.270043032	0.272846812	0.502582274	0.502582274
	Cast-in-place concrete, 3000 psi	0.369368667	0.067736533	0.154966202	0.154966202
	Cast-in-place concrete, structural concrete, 2500 psi	0.364835193	0.07366824	0.167999231	0.167999231
	Stair, cast-in-place concrete	0.372042888	0.0728961	0.163833923	0.163833923
	Autoclaved aerated concrete block (AAC)	0.361022531	0.072261336	0.166775967	0.166775967
	Aluminum, angle	0.424703564	0.018225169	0.041146956	0.041146956
	Laminated wood panel board	0.264922809	0.331571334	0.555866873	0.555866873
	Asphalt felt sheet	0.419055096	0.019595009	0.044671161	0.044671161
	Self-adhering sheet waterproofing, modified bituminous sheet	0.418485571	0.019669326	0.044891262	0.044891262
	Clay roofing tile	0.375724389	0.064866856	0.147226838	0.147226838
	Mineral wool, board, generic	0.416199568	0.029926014	0.067079797	0.067079797
	Openings and Glazing	0.417357168	0.023566969	0.053449033	0.053449033
	Ceramic tile	0.289375757	0.216553539	0.428031231	0.428031231
	Fiberglass mat gypsum sheathing	0.366897821	0.080677367	0.180254334	0.180254334
	Portland cement stucco	0.361669081	0.074245598	0.170321399	0.170321399
	Paint	0.355001648	0.091297701	0.204566064	0.204566064
	Stone tile	0.257605109	0.226497619	0.467870983	0.467870983

Table A5. TOPSIS Scenario 2.

	Material	Ideal Distance	Negative Ideal Distance	Relative Closeness	TOPSIS Score S2
Scenario 2	Cast-in-place concrete, 5000 psi	0.148515709	0.411694322	0.734892806	0.734892806
	Laminated wood panel board	0.409888658	0.168589044	0.291435683	0.291435683
	Stone tile	0.365103373	0.129668992	0.262078081	0.262078081
	Ceramic tile	0.414916775	0.112105954	0.212715596	0.212715596
	Fiberglass mat gypsum sheathing	0.420003067	0.074709083	0.151015259	0.151015259
	Autoclaved aerated concrete block (AAC)	0.403416445	0.054870372	0.119729327	0.119729327
	Paint	0.420032677	0.05494465	0.115678468	0.115678468
	Portland cement stucco	0.409400538	0.052289523	0.113256765	0.113256765
	Cast-in-place concrete, structural concrete, 2500 psi	0.416419471	0.049377683	0.106006837	0.106006837
	Clay roofing tile	0.425264091	0.050002327	0.105209046	0.105209046
	Cast-in-place concrete, 3000 psi	0.417571611	0.047152839	0.10146408	0.10146408
	Mineral wool, board, generic	0.434509885	0.048730811	0.100841695	0.100841695
	Stair, cast-in-place concrete	0.431408083	0.046554914	0.097402757	0.097402757
	Openings and Glazing	0.426625344	0.038713539	0.083194292	0.083194292
	Self-adhering sheet waterproofing, modified bituminous sheet	0.441331201	0.03063906	0.064917352	0.064917352
	Asphalt felt sheet	0.442430648	0.030588789	0.064667086	0.064667086
	Aluminum, angle	0.443909	0.030375282	0.064044462	0.064044462

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