Mansoura Engineering Journal

Volume 48 | Issue 1 Article 1

April 2023

System Dynamics and TOPSIS Models for Sustainable Building Materials Selection Considering Life Cycle Assessment

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ORIGINAL STUDY

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Abstract

Construction industry is the most contributor to the environmental impacts. Achieving sustainability in construction is complicated, but one of the most optimal strategies is selecting sustainable building materials. The major goal of this study is to present a new idea for choosing sustainable building materials (SBMs) by simulating sustainability parameters' behaviour. This research proposes a System Dynamics (SD) model along with the TOPSIS method based on the dynamic interactions among a number of sustainable criteria to help decision makers in sustainable building materials selection. The sustainable criteria that form system boundary are determined from previous studies and experts' opinions. The SD model started with creating the Causal Loop Diagram (CLD) of the sustainable criteria to illustrate the interrelation between these criteria. Then, stock and flow (SF) diagram is generated to simulate these criteria and evaluate the performance of building material alternatives. Furthermore, The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is applied to select the most sustainable building material depending on the evaluation criteria. Finally, a case study of some common building materials is presented. The results show that wood, (cast-in-situ) concrete, marble tiles, cement bricks are the best SBMs. The development model will assist decision-makers to select SBMs.

Keywords: Sustainability, Sustainable building materials, System dynamics, TOPSIS method

1. Introduction

Construction industry has direct impact on the environment, ranging from the use of raw materials through construction, maintenance, and renovation to emission of harmful substances throughout the whole life cycle of a building (Balaras et al., 2005). The construction sector is responsible for a huge amount of energy consumption and natural resource depletion. According to statistics, building industry is responsible for 40% of the world's annual consumption of resources, 36% of the world's total CO2 emissions, and 40% of the total world waste generation annually (Hussin et al., 2013).

To minimize buildings' environmental impacts, the use of sustainable building materials (SBMs) is one way to protect the environment (Du Plessis, 2007). To achieve the goal of sustainable construction, greater attention should be paid to the design and selection of SBMs rather than reducing the overall amount of resources utilized in construction. Selection of SBMs helps in reducing the environmental impacts associated with using building materials throughout the whole life cycle. The whole life cycle of building materials includes extraction of raw materials, manufacturing, transportation, operation, and end of life cycle (disposal or recycling).

Received 13 September 2022; revised 7 December 2022; accepted 20 December 2022.
Available online 10 April 2023

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https://doi.org/10.58491/2735-4202.3026

Selection of building materials plays an important role in achieving the goal of sustainable construction development (Franzoni, 2011). SBMs are usually considered as natural materials. These materials characterized with inexpensive maintenance requirements, low energy consumption, and an improvement in occupant comfort and health. However, Franzoni (2011) argued that natural materials are not always green materials. There are a number of green materials, which are harmful to the environment. Therefore, SBMs indicate environmentally friendly materials (Franzoni, 2011). Consequently, SBMs are those materials that are derived from renewable sources as opposed to nonrenewable ones. They must use less energy during production and be sustainable for the period of their entire life cycle. Also, these materials must reduce the harmful environmental impacts.

Sustainable building development considers the whole life cycle of buildings in the early design stages to minimize the overall environmental impacts through an appropriate design and material selection. Selection of construction materials has an impact on the environment throughout a building's entire life cycle. Different techniques are used to improve material selection according to their physical and mechanical properties to help designers to make an appropriate decision about material selection.

Materials' selection is considered a multicriteria subject. Some studies have pointed out the significance of choosing environmentally friendly materials in the construction industry. Li et al. (2012) investigated how using green building materials could contribute to the sustainable development of local architecture. The findings of this study demonstrated the significance of using green building materials in the construction of societies due to their positive effects on resource conservation (such as water and energy), material protection, and pollution prevention. Franzoni (2011) stated that SBMs are related to energy and resource efficiency, and these materials have no adverse impacts on the environment or on human health.

In addition to regarding the environmental issues in material selection process, Abeysundara et al. (2009) studied a life cycle assessment approach for the selection of SBMs taking social and economic factors into account. They devised an evaluation matrix to help decision-makers to select sustainable materials according to social, economic, and environmental factors. Florez and Castro-Lacouture (2013) suggested that other subjective factors such as cultural and metaphysical aspects should be taken into account in addition to environmental, economic, and social aspects when choosing sustainable materials. Marzouk et al. (2013) developed an system dynamics (SD) model to assist project stakeholders in choosing the best option among construction materials. They use the LEED rating system and building process expenses as two performance indicators for choosing SBMs. Chakraborty and Chatterjee (2013) used three common multicriteria decision-making (MCDM) techniques (VIKOR, TOPSIS, and PROMETHEE) to demonstrate the effect of number of criteria on the final rankings of material alternatives. Chan and Tong (2007) presented a weighted average method using the gray relational analysis methodology for creating a multiobjective optimization model of material selection. To enhance the decision-making process in material selection, the study combined technical and economic aspects for the choice of material with end-of-life product strategy. Rao and Patal (Rao and Patel, 2010) used a multiple attribute decision-making method that took both qualitative and quantitative qualities into account for choosing the best material for an engineering design. The approach used fuzzy logic to translate the decision-maker's experience and judgment into numerical qualities. Marzouk et al. (2014) used building information modeling for selecting building materials. This paper presented the integration of building information modeling with Saudi Arabia Green Buildings Rating System (SAGRS), life cycle cost (LCC) analysis, and genetic algorithm optimization technique to select the SBMs.

Selecting building material is an important decision in construction industry. The decision of selecting building materials is become more difficult in recent years as various building material alternatives are available. Also, this decision is permanently associated with significant environmental, economic, and social influences. This research presented an SD model to simulate the behavior of sustainable criteria for selecting SBMs. Then, the TOPSIS method is used to select the most SBMs based on the performance evaluation of building materials.

2. Research methodology

This research presents a dynamic model to evaluate the performance of building material alternatives. This research can help designers for selecting SBMs. The procedures of this research can be summarized as follows:

(1) Collect all related criteria that affect SBM selection from previous studies.
(2) Performing a questionnaire survey on the whole collected criteria. The aim of this step is to measure the importance of these criteria in SBM selection.
(3) Creating a simulation model of criteria interaction. The aim of this model focuses on developing a way of studying the performance of building materials over time.
(4) Applying the TOPSIS method using MATLAB software to select the most SBMs.

3. Sustainable criteria collected from previous studies

Selecting SBMs has gained the attention of researchers. During the past decades, many researchers presented some criteria that affect SBM selection. Reviewing previous studies shows different criteria that covers the principles of sustainability. This study collects pool of criteria from previous studies. Then, a questionnaire survey is performed on the whole collected criteria to measure the importance of these criteria in SBMs selection. The survey includes local experts such as academics, site engineers, consultants, designers, and architects. Experts were asked about the collected criteria to determine the most important criteria in SBMs selection dependent on their experience. Table 1 shows the most influencing criteria affecting SBMs selection.

4. System dynamics model for evaluation of sustainable building materials

SD is considered as a holistic approach for determining interactions between linked components over a long term (Forrester, 1987). It aims to analyze complex dynamic systems to explore the intercorrelation and changes over time. It is also used to encompass relevant cause and effect relationships, delays and feedback loops in complex systems to simulate their unexpected behavior (Grobbelaar, 2007). In the construction industry, SD is used to analyze a variety of aspects such as resource management, labor productivity, sustainability performance, risk analysis, and project management. Also, it has been applied extensively for many areas including socioeconomic systems, ecological systems, transport systems, environmental management, and policy assessment.

Table 1. The most influencing criteria affecting sustainable building material selection.

No	Criteria
1	Embodied energy within materials
2	Effects on occupants of building or handlers
3	Recycled potential
4	Thermal conductivity
5	CO_2 emissions
6	Waste generation
7	Quantities of raw materials used
8	Life cycle cost
9	Recycled content/recycled materials
10	Durability of materials

Motawa et al. (2007) developed an integrated change management system using SD to evaluate the adverse impacts of changes of construction performance. Nasirzadeh et al. (2008) presents an approach to construction risk analysis. SD was used to model and simulate the dynamic nature of risks overall the whole life cycle of the construction project. Yuan and Wang (2014) used SD to evaluate an appropriate waste disposal charging fee in the construction industry. The model can be applied to minimize waste generation and maximize waste recycling.

Zhang et al. (2014) developed an SD model for assessing the sustainability of the construction projects. The model assesses construction projects in terms of their sustainable development values and sustainable development ability for implementation in the project life cycle. Maryani et al. (2015) used the SD approach for modeling work accidents of construction projects. The results of the model describe the process of occupational accidents and the cost incurred. Ojugbele and Bodhanya (2015) used SD to investigate the puzzling performance problems that plagued the project outsourcing in the public sector in South Africa. Their study investigates outsourcing problems in terms of poor quality and delivery delay.

SD starts with the identification of the problem being modeled, which in turn determines the system boundary and elements of the system (Forrester and Senge, 1980). The system boundary is significantly affected by problem specification. This in turn influences the variables and essential components of the system. The model structure is mainly derived from previous studies and experts' opinion in which variables, interactions, and relationships are determined.

4.1. Causal loop diagram

Causal loop diagrams (CLDs) have long been used in standard SD practice. CLD is a tool that illustrates the relationships between the various model variables and simulates system feedback.

CLD consists of variables connected by arrows denoting the causal relationships among the variables. Each link is a line with an arrowhead that connects variables. Links can be classified as either 'positive' or 'negative' depending on their polarity. A positive link donates that the two variables are changed in the same direction, while the negative link means that the two variables are changed in the opposite direction. The feedback loops are closed chains of cause-and-effect links that the result of actions is fed back to create further action. The idea of modeling of SD is to identify the feedback from solutions and within the system. There are only two sorts of feedback recognized as reinforcing and balancing feedback. A reinforcing loop is a cycle in which the impact of a change in any one variable is replicated throughout the loop and then goes back to the variable that reinforced the initial deviation. A balanced loop, however, is a cycle in which the impact of a change in any variable is reproduced through the loop and returns to the variable with a deviation that is the polar opposite of the initial one (Sterman, 2000). In this study, the sustainable criteria represent the key variables affecting the behavior of the system. Fig. 1 shows the CLD of the current study.

The CLD (Fig. 1) consists mainly of four balancing loops. The first loop 'B1' (Fig. 2) draws attention to the waste generation, which is influenced by quantities of the raw material used. The loop advises that the amount of waste generation increases when quantities of raw material increases (Petkar, 2014). The recycled potential, as well, increases as a result of increase in waste generation (Petkar, 2014). Also, the recycled content increases as the recycled potential increases (Pavlu et al., 2019). Finally, the increase in recycled content of building materials decreases the quantities of raw materials used and closes the loop (Bolden et al., 2013). However, the increase of raw material quantities used increases CO_2 emissions (Sagheb et al., 2011), which subsequently have a negative impact on buildings' occupants (Mohmmed et al., 2019).

The second balanced loop 'B2' (Fig. 3) shows the effect materials' recycled content on the durability of building materials. Durability of material decreases due to the increase in recycled content of materials (Carlisle and Friedlander, 2016). The increase in durability decreases the recycled potential (Lassandro, 2003) and duly the recycled potential increase draws the recycled content of material to increase to close the loop. The out-of-loop parameter 'LCC' is

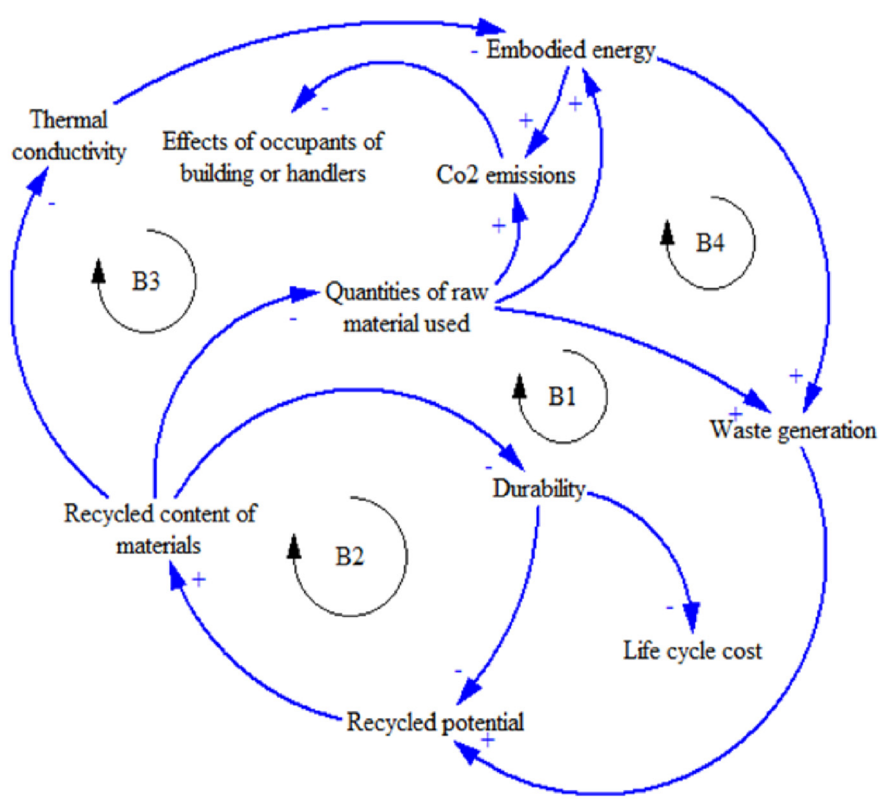

Fig. 1. Causal loop diagram for SBMs. SBM, sustainable building material.

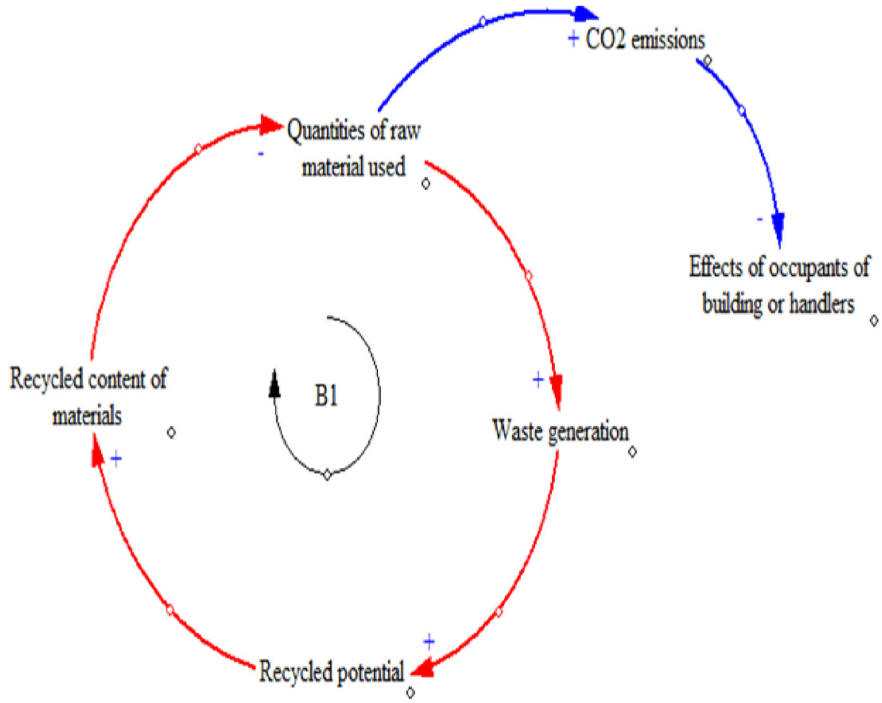

Fig. 2. The first balanced loop B1.

influenced by the durability of material. The increase of durability decreases the LCC (Boulos et al., 2015).

The third loop 'B3' (Fig. 4) draws attention to the embodied energy (EE), which is influenced by thermal conductivity of building materials. The loop advises that the increase of thermal conductivity decreases the EE (Chel and Tiwari, 2009). Also, the increase of EE increases the amount of waste generation (Khiabani and Hasani, 2010). Also, the recycling potential increases when waste generation increases and the duly recycled potential increase draws the recycled content of material to increase. Finally, thermal conductivity decreases as a result of increase of materials' recycled content and closes the loop (Majumder et al., 2021). The out-of-the-

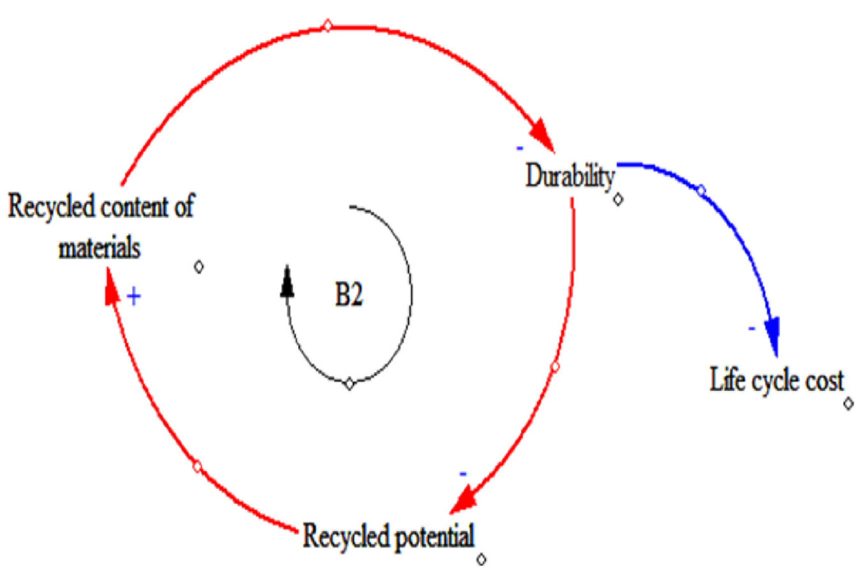

Fig. 3. The second balanced loop B2.

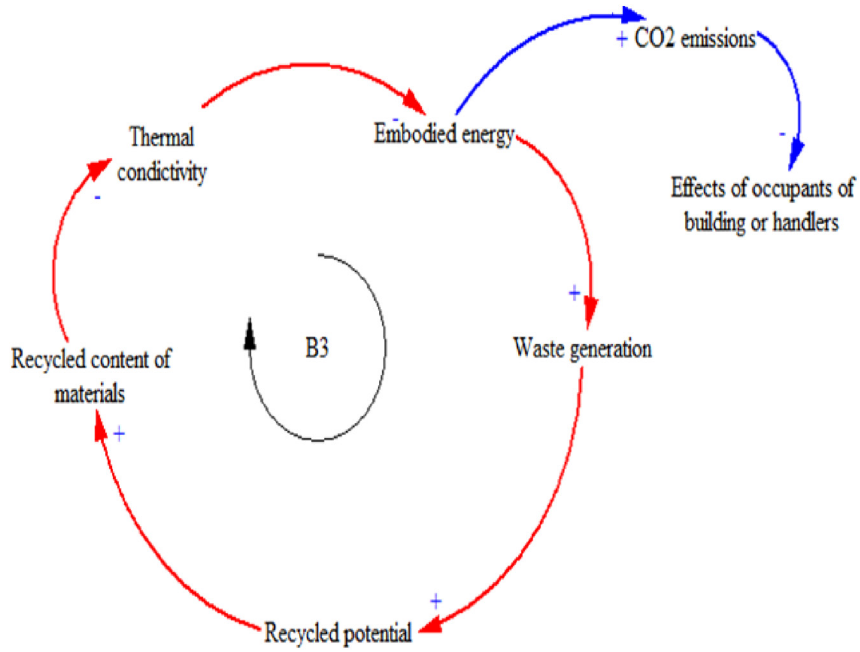

Fig. 4. The third balanced loop B3.

loop parameter 'CO$_2$ emissions' are influenced by the EE. The increase in EE increases CO$_2$ emissions (Taffese and Abegaz, 2019). Also, CO$_2$ emissions have a negative impact on buildings' occupants and handlers.

The fourth loop 'B4' (Fig. 5) draws attention to EE, which is influenced by quantities of the raw materials used. The loop advises that the increase of quantities of the material used increases the EE (Jayasinghe, 2011). EE as well increases the amount of waste generation. Also, recycling potential increases when waste generation increases and the duly recycled potential increase draws the recycled content of material to increase and further lowers the quantities of the material used to close the loop. The out-of-the loop 'CO$_2$ emissions' are influenced by EE. The increase in EE increases CO$_2$ emissions, which subsequently has a negative impact on buildings' occupants or handlers.

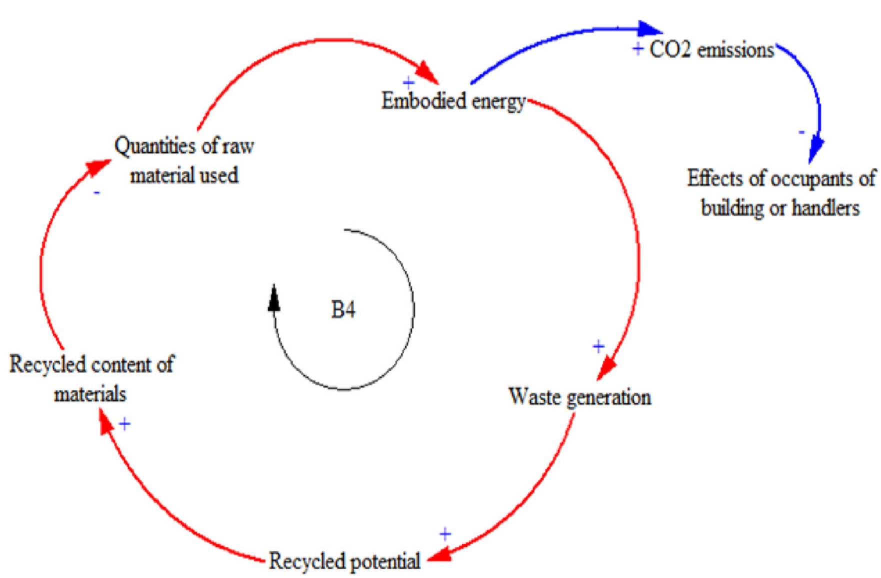

Fig. 5. The fourth balanced loop B4.

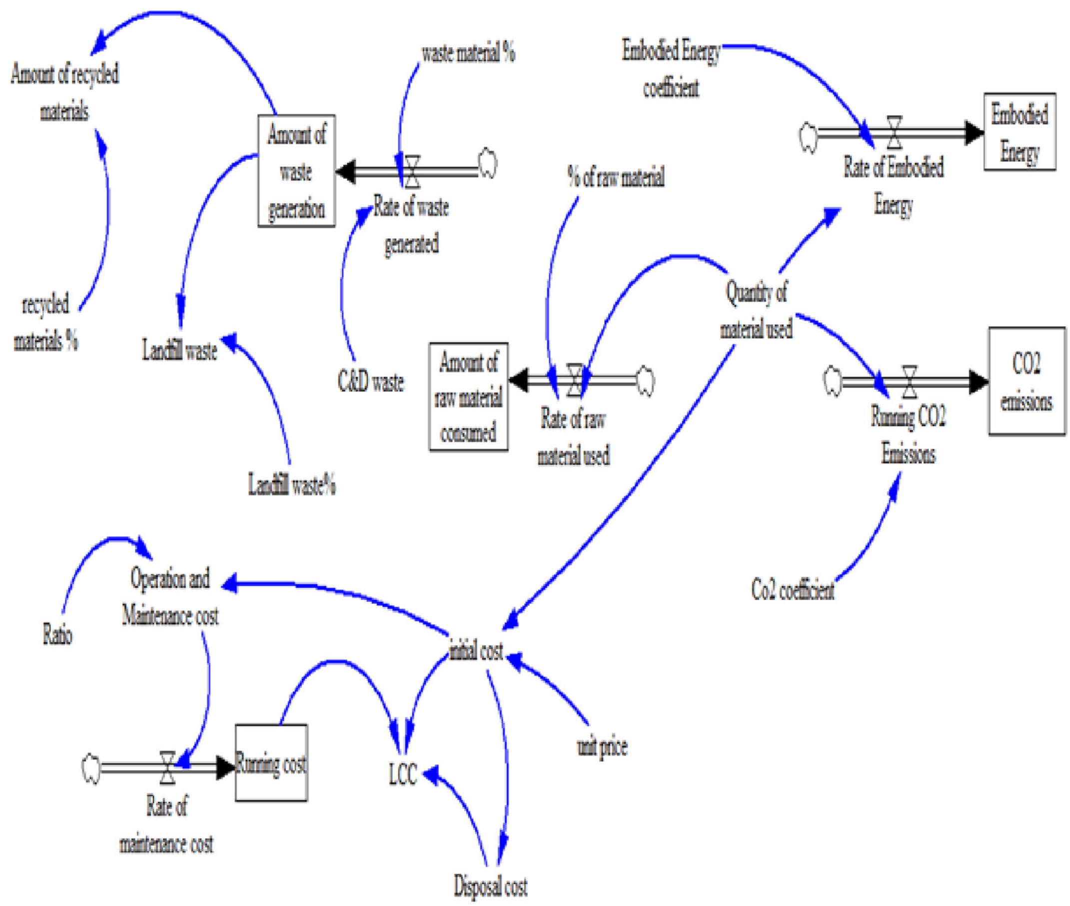

Fig. 6. The stock and flow diagram.

4.2. Stock and flow diagram

The concept of stocks and flows (SF) is considered as a central idea in dynamic system theory (Sterman, 2000). SF are considered the essential building blocks of SD models. Stocks are used to accumulate resources such as quantities of raw materials used in construction, while flow is the rate of change in such resources. The SF diagram represents integral finite difference equations including the variables of the feedback loop structure of the system and simulates the dynamic behavior of the system. Based on the CLD, all variables that affect the performance of the model were identified. Then, the CLD is converted to the SF diagram. The system boundary and system equations are described in the next subsections. Fig. 6 shows the SF diagram using VENSIM software.

4.2.1. Quantities of raw material used

Raw materials are the basic materials from which products are manufactured. It comes from nature in an unprocessed or minimally processed state. The kind of raw materials inventory used in building material production depends on the factors of production such as labors and capital. Quantities of raw materials used in the production process differ from one product to another. The percentage of raw material used depends on the nature of manufactured products. Quantities of raw materials used within any product can be estimated by determining the percentage of raw material used in the manufacturing process. Quantities of raw materials can be calculated using Eq. (1):

$$\begin{aligned}&\text{Amount of raw material used (kg)}\\&\quad=\text{quantity of material used (kg)}\\&\quad\times\text{percentage of raw materials used in a building (\%)}\end{aligned} \tag{1}$$

4.2.2. Waste generation and recyclable potential

The construction industry is one of the largest consumers of primary raw materials globally and generates almost 30% of all wastes (Pavlu et al., 2019). Recycling process and use of construction and demolition wastes are one of the principles of sustainable construction. At the end-of-life cycle, most of the construction materials can be recycled and used as secondary raw material for the production of new construction products (Pavlu et al., 2019). It is of great importance to find ways to minimize waste generation as this is the most favorable solution to waste problems. The generated waste can be either transferred to landfills or to waste recycling centers. The amount of waste generation, amount of recycled materials, and amount of landfill waste, respectively, can be estimated using Eqs. (2)–(4).

$$\text{Amount of waste generation (kg)} = \text{construction and demolition waste (C\&D) (kg)} \times \text{building material's waste \%} \quad (2)$$

$$\text{Amount of recycled materials (kg)} = \text{Amount of waste generated (kg)} \times \text{\% of recycled materials} \quad (3)$$

$$\text{Amount of landfill waste (kg)} = \text{amount of waste generation (kg)} \times (1 - \text{\% of recycled materials}) \quad (4)$$

4.2.3. CO_2 emissions

In the building industry, a wide range of materials are used during the production process and large amounts of energy is consumed in turn emitting large amounts of CO_2. Buildings and the construction sector has the largest proportion of global energy and emissions than other sectors. According to Syngros et al. (2017), buildings and construction are responsible for 40% of the total energy used in Europe and about 45% of energy-related CO_2 emissions. CO_2 emissions can be estimated by multiplying the material masses with the corresponding CO_2 coefficients (kg CO_2/kg) (Syngros et al., 2017), Eq. (5).

$$\text{CO2 (kgCO2)} = \text{Quantity of material used (kg)} \times \text{CO2 Coefficient (kg CO2 / kg)} \quad (5)$$

4.4.4. Embodied energy

EE is the total energy required for the extraction, processing, manufacture, and delivery of building materials to building sites. EE produces CO_2 emissions, which contribute to green house gas emissions, so EE is considered an indicator of the overall environmental impact of building materials and systems. As such, it must be considered over the service life of a building. Higher EE building material reduces the operating energy requirements of buildings. EE is measured as the quantity of nonrenewable energy per unit of building material, component, or system. It is expressed in mega joules (MJ). EE for any building material can be estimated from Eq. (6) (Fay et al., 2000).

$$\text{EE (MJ)} = \text{Quantity of material used (kg)} \times \text{EE coefficient (MJ / kg)} \quad (6)$$

4.4.5. Life cycle cost

LCCs are summations of the total cost estimates during the whole life cycle. It includes initial production, operation, maintenance, and disposal. Usually operation, maintenance, and disposal costs exceed all other costs many times. The objective of LCC analysis is to choose the most effective cost from a set of alternatives. LCC analysis helps to justify material selection based on total costs rather than the initial cost. The total LCC can be calculated using Eq. (7):

$$\text{LCC} = \text{Initial cost} + \text{operation cost} + \text{maintenance cost} - \text{disposal cost} \quad (7)$$

5. Model application for evaluating buildings' materials

SD model is used to simulate and analyze different building materials. Twelve common building materials are examined. These materials are concrete, wood, and steel; marble tiles, ceramic tiles and oak wood; clay brick and cement brick; aluminum and wood and precast concrete and cast-in-site concrete materials. The model has the ability to evaluate the performance of building materials according to six indicators. These indicators are the amount of waste generated, amount of landfill waste, amount of recycled materials, CO_2 emissions, EE, and LCC. It helps in estimating and comparing different building material alternatives. The model simulates the behavior of these materials over 50 years and the resulting parameter behavior is recorded.

Data required for running the model are collected for the examined material. In this study, quantity of materials used and C&D waste are assumed for all examined materials and their value are 1000 and 10 000 kg, respectively. CO_2 coefficients and EE

Table 2. CO_2 and embodied energy coefficients for examined materials.

No	Material name	Embodied energy coefficient (Mj/kg)	CO2 Emissions coefficient (kg CO_2/kg)	References
1	Aluminum	155	8.24	Sabnis et al. (2015)
2	Wood	8.5	0.46	Sabnis et al. (2015)
3	Reinforced concrete	1.21	0.148	Sabnis et al. (2015)
4	Precast concrete	2	0.215	Sabnis et al. (2015)
5	Clay bricks	3	0.22	Sabnis et al. (2015)
6	Cement bricks	0.177	0.112	Sabnis et al. (2015); Hammond et al. (2011)
7	Steel	24.4	1.77	Sabnis et al. (2015)
8	Ceramic tiles	2.5	0.7	Bastianoni et al. (2006); Hammond et al. (2011)
9	Marble tiles	3.3	0.64	Sabnis et al. (2015); Hammond et al. (2011)
10	Oak wood	1.2	0.3	Hammond et al. (2011)

Table 3. Values of raw material, waste material, and recycled material percentages.

Material name	Raw material used (%)	Waste material (%)	Recycled material (%)
Aluminum	80–90	2–10	80
Wood	90	13	50
Reinforced concrete	80	60–70	30
Precast concrete	60–75	60–70	30
Clay brick	90	7–10	20
Cement bricks	80–90	7–10	50
Steel	80–90	5–8	80
Ceramic tiles	50–60	10–15	30
Marble tiles	60–70	10–15	40
Oak wood	80–90	10–15	60

coefficients are determined from previous studies. Table 2 shows the CO_2 coefficients and EE coefficients for all examined materials. The values of waste material percentage, percentage of recycled material, percentage of raw material are changeable, and their values depend on the material type. These values are determined from literature review and from experts in the construction industry. Table 3 shows the values of waste material, raw material, and recycled material percentages. The unit price of the examined materials is determined from suppliers.

5.1. Comparison among concrete, wood, and steel

The construction industry uses a variety of materials for different aspects of home construction. There are three main commonly used materials in the construction industry. These materials are concrete, wood, and steel. So, it is necessary to assess the performance of these materials to assist decision-makers to select the appropriate materials.

The obtained results of the model are shown in Fig. 7. From the results, it is clearly noticed that steel has the highest EE and CO_2 emissions compared with wood and concrete. The increase of EE used in the manufacturing of each material causes CO_2 emissions to increase. Also, steel has the highest LCC and reinforced concrete has the lowest value. The high value of LCC of steel is due to its high initial cost. Also, reinforced concrete consumes the lowest amount of raw materials compared with steel and wood. The concrete industry seeks waste products that it can safely use to replace virgin raw materials (Kawai and Osako, 2012). However, reinforced concrete recorded the highest amount of waste generated, recycled materials, and landfill waste.

5.2. Comparison between ceramics tiles, marble tiles, and oak wood

Ceramic, marble, and oak wood are the most common flooring materials used in Egypt. These materials are compared using the developed model. The obtained results of this comparison are shown in Fig. 8. The results show that that oak wood has the lowest EE and CO_2 emissions. Using wood flooring as an alternative of ceramic tiles can reduce a lot of energy consumption and CO_2 emissions and this confirms with what is reported in the study by Geng et al. (2017). Also, oak wood has the highest LCC and ceramics tiles have the lowest value. The higher value of wooden tiles is

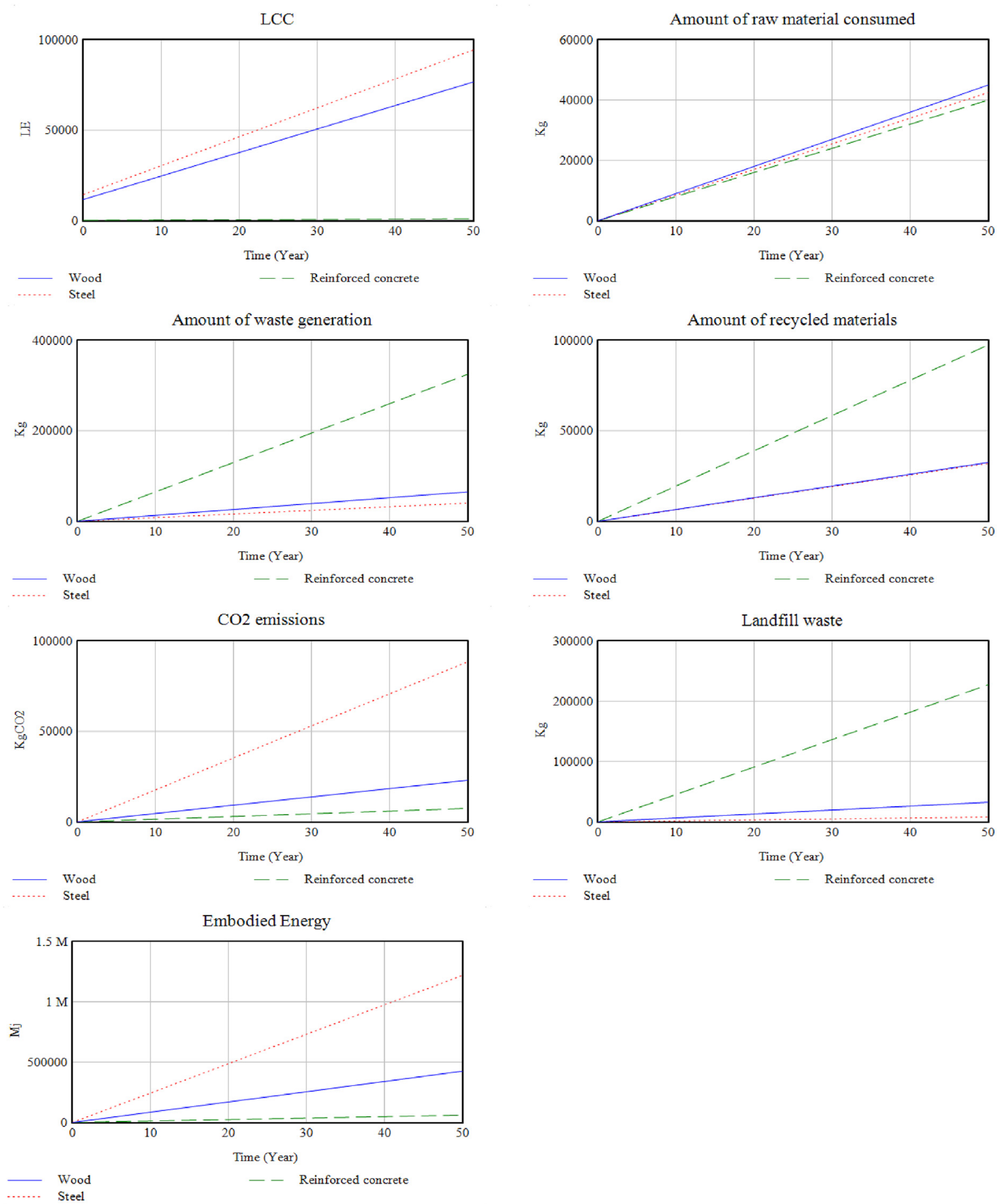

Fig. 7. Performance evaluation of reinforced concrete, steel, and wood.

due to the value of its initial cost and maintenance cost. Also, oak wood has the highest value of recycled materials and the lowest value of landfill waste. Recycling wooden materials constitute a source of abundant and inexpensive raw material for the production of new materials and this in line with that reported in the study by Besserer et al. (2021). Also, ceramic tiles consume the lowest amount of raw materials compared with oak wood and marble tiles. The total amount of waste generated is equal for three materials after demolition of construction.

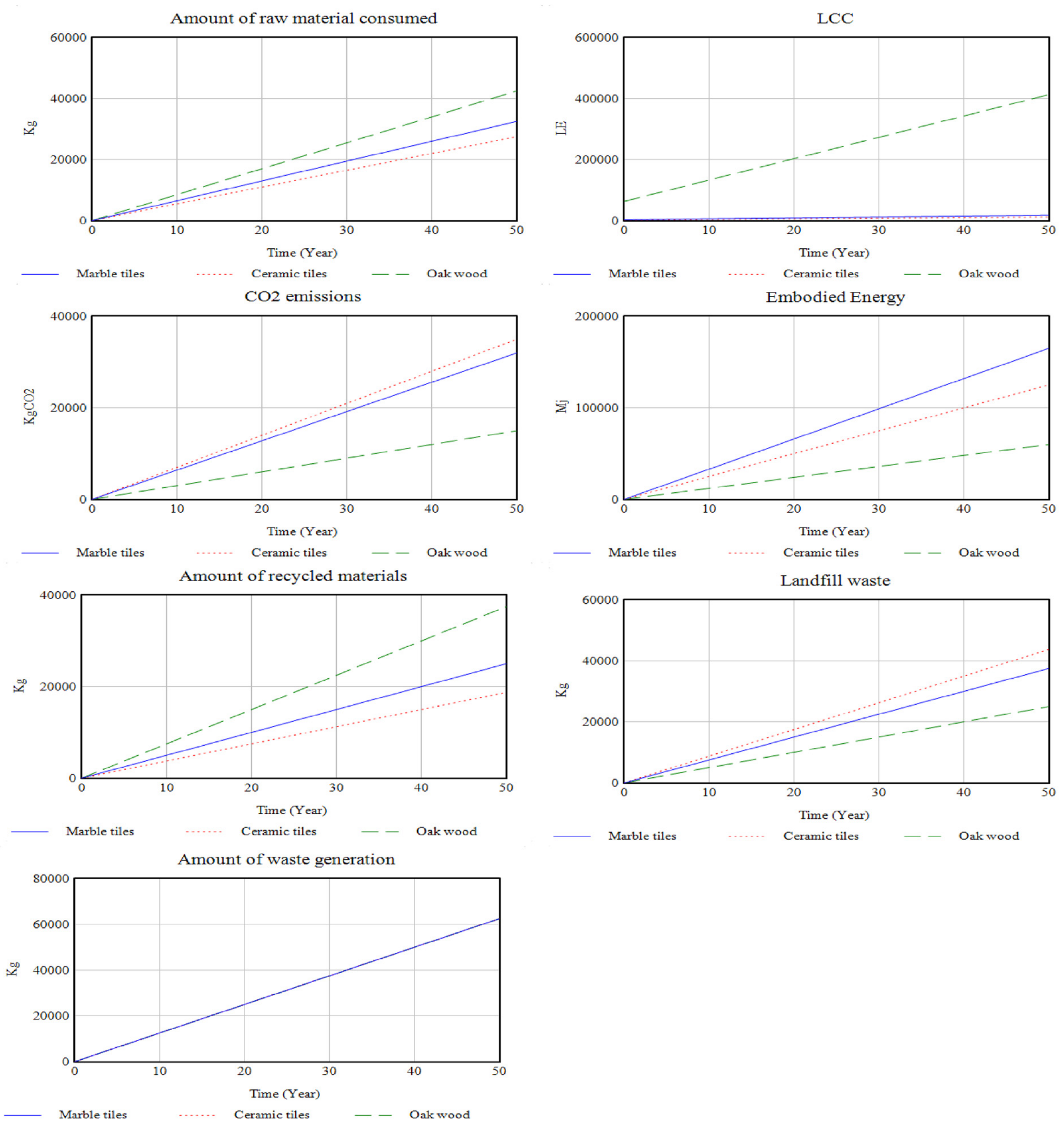

Fig. 8. Performance evaluation ceramic tiles, marble tiles, and oak wood.

5.3. Comparison between clay bricks and cement bricks

Bricks are a type of block used to construct walls, pavements, and other components in masonry construction. Properly, the brick refers to a block made of dried clay. Clay bricks and cement bricks are the most common types of bricks used. So, performance evaluation of clay bricks and cement bricks are performed to compare them.

The results of this comparison are shown in Fig. 9. It is obviously noted that clay bricks have the highest EE and CO_2 emissions. The production of cement bricks uses less energy compared with burnt clay brick because cement bricks do not need to be fired after being formed. The traditional burned clay brick produces higher value of CO_2 emissions than cement bricks and this confirmed with that reported in the study by Pina et al. (2009). Also, cement bricks have the lowest value of raw materials consumed. Cement bricks can be generated through using clay brick wastes. Clay brick waste could be used in construction products to reduce landfill waste and preserve natural materials. In addition, cement

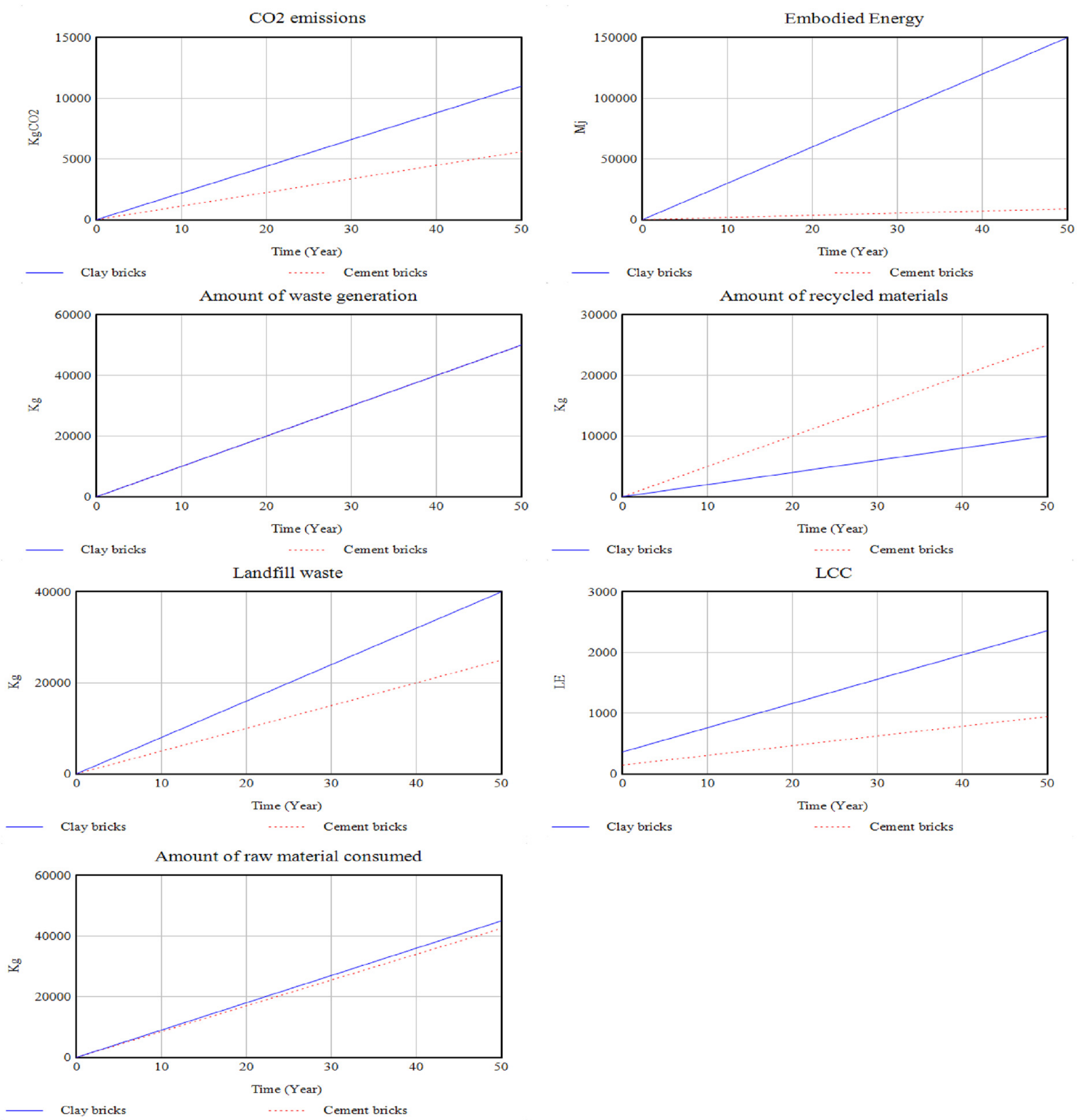

Fig. 9. Performance evaluation of cement bricks and clay bricks.

bricks have the lowest LCC compared with clay bricks that have a higher value. Also, energy costs can be reduced through the production of cement bricks, so the LCC of cement bricks is lower than that of clay bricks. Therefore, clay bricks have the highest value of landfill waste and the lowest value of recycled materials. Many tons of construction and demolition wastes are produced from clay brick wastes (Kongkajun et al., 2020). Generally, brick waste is either taken to a landfill or recovered as aggregate in concrete. The amount of waste generation of both materials is the same after demolition of the building.

5.4. Comparison between aluminum and wood materials

Aluminum is widely used in the building industry due to its substantial properties of high strength, moisture resistance, and corrosion resistance. It is used in external facades, in windows and doors, and other several applications. In this study, a

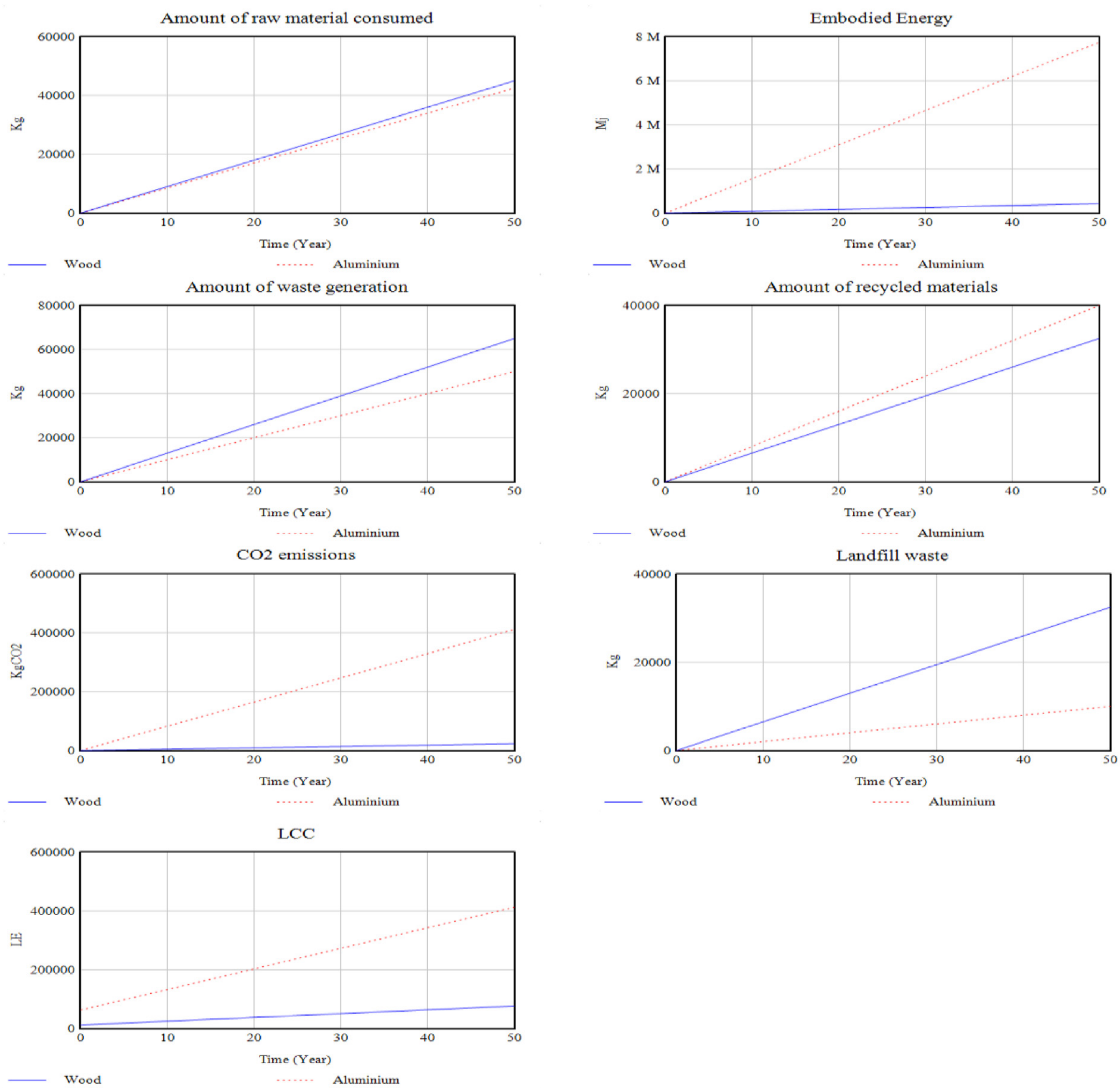

Fig. 10. Performance evaluation of aluminum and wood materials.

comparison between aluminum and wood as two alternative building materials for windows and doors is made.

The results of this comparison are shown in Fig. 10. The results show that aluminum has the highest EE and CO_2 emissions compared with wood. Also, wood has the lowest value of recycled materials and the highest amount of waste generation and landfill waste. The recycled rate of aluminum is higher than wood. Materials such as wood is not diverted for recycling, it is sent to an incinerator or sent to landfill (Pina et al., 2009). In addition, wood has the highest value of raw material consumed. Wood products produced from trees range from a minimally processed home building site to a highly processed wood composite manufactured in large production plants (Falk, 2009). Wood is a renewable resource. If sustainable forestry management and harvesting practices are followed, wood resources will be available forever. Also, wood has the lowest LCC compared with aluminum. Wood windows offer lower lifetime cost option rather than other types of window frame materials.

5.5. Comparison between precast concrete and (cast-in-site) concrete

In the construction industry, concrete is most commonly used as the foundation for most

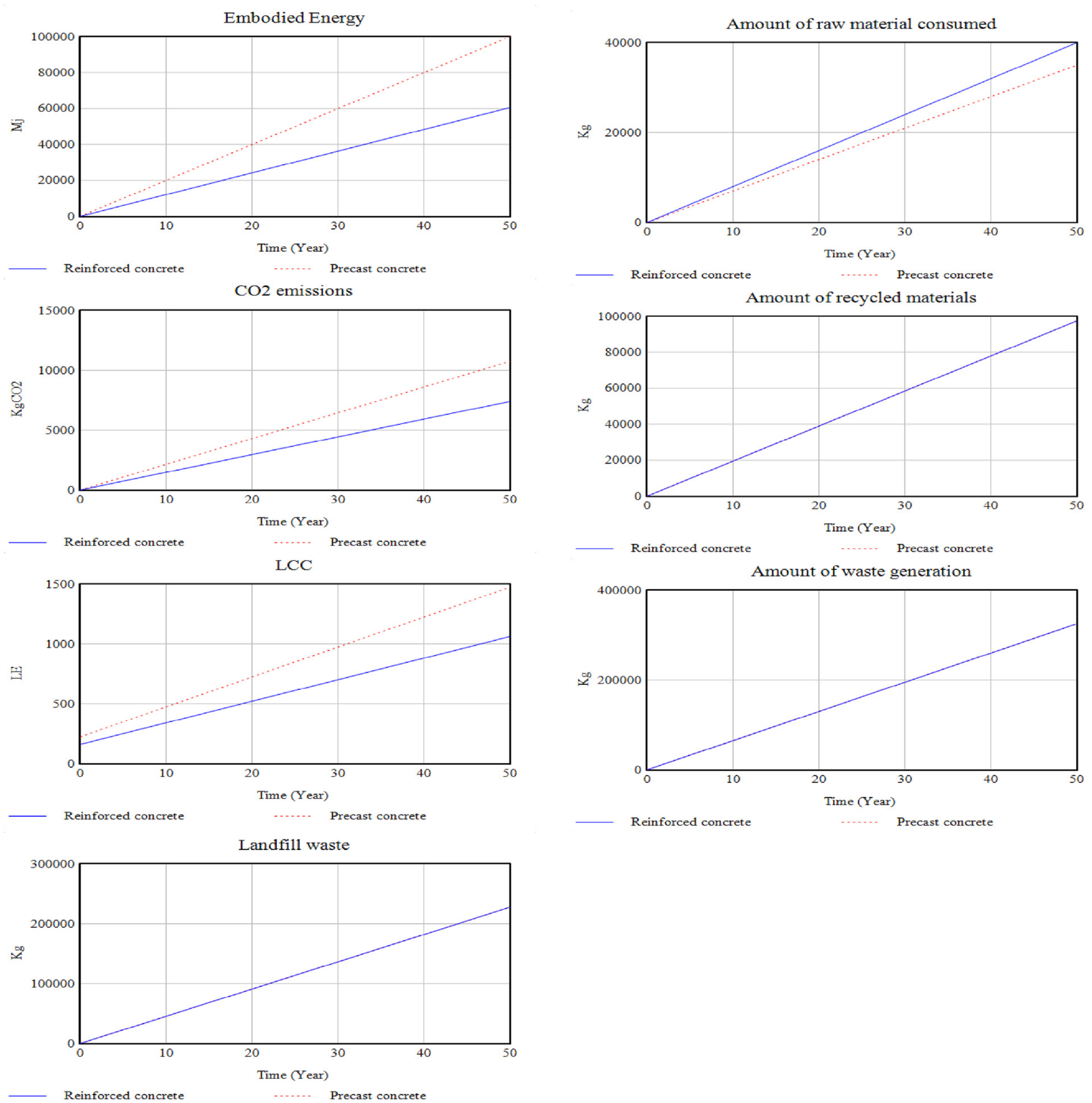

Fig. 11. Performance evaluation of precast concrete and cast-in-site concrete.

structures. It is also used in superstructure construction through the use of structural concrete, slabs, stairs, and architectural features. There are two ways that concrete is implemented in construction. These ways are the precast concrete and cast-in-site concrete. Precast concrete is used in construction because of space restrictions or a need to complete projects more quickly, all the while potentially improving quality control. In this study, the performance evaluation of precast concrete and cast-in-site concrete is performed.

The results of the simulation model are shown in Fig. 11. The simulation shows that cast-in-site concrete has provided better results and consumed less EE and carbon emissions, as compared with the precast concrete. The EE of the precast concrete recorded a strength of 1.65 times than the conventional in-situ concrete. Also, precast concrete has the lowest raw material consumption compared with caste-in-site concrete. Precast concrete can save concrete quantities and steel requirements rather than the conventional in-site concrete (Yee, 2001).

However, precast concrete has the highest LCC compared with cast-in-site concrete. When precast concrete is used, construction costs are slightly higher than with conventional construction; as reported in the study by Yee (2001). However, this is offset by better quality, shorter building times, and better environmental performance on-site. Also, the values of waste generation, recycled materials, and landfill waste are the same for both types of material.

6. TOPSIS method for selecting highest sustainable building materials

Selection of SBMs is considered as a MCDM process (Hatefi et al., 2021). In this research, the TOPSIS method is applied to solve the MCDM problem and help decision-makers to select the most appropriate material. The TOPSIS method was first developed by Yoon and Hwang (1981). Its basic concept is that the chosen alternative should have the shortest distance from the positive-ideal solution and the farthest from the negative-ideal solution.

6.1. Steps of applying the TOPSIS method

According to Chen's approach (Chen, 2000), the procedure of TOPSIS can be expressed in the following steps.

6.1.1. Step 1. construct the decision matrix and determine the weight of criteria

The decision matrix is a numerical matrix which is expressed as $X=(x_{ij})$ and $W=(w1, w2, \ldots, wn)$ is a weight vector, where x_{ij} is the decision-maker rating of alternative Ai with respect to the criterion Cj and w_j is the decision maker weight of criterion Cj. The sum of decision-maker weights of all criteria must be equal one. Criteria of the functions can be benefit functions (more is better) or cost functions (less is better).

6.1.2. Step 2. calculate the normalized decision matrix

This step transforms various attribute dimensions into nondimensional attributes, which allows comparisons across criteria (Roszkowska, 2011). Because various criteria are usually measured in various units, the scores in the evaluation matrix X have to be transformed to a normalized scale. The normalization of values can be calculated using Eq. (8) (Roszkowska, 2011):

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (8)$$

where n_{ij} is the normalized value; x_{ij} is the value of alternative A_i with respect to criterion C_j; and m is the number of alternatives.

6.1.3. Step 3. calculate the weighted normalized decision matrix

The weighted normalized value V_{ij} is calculated using Eq. (9) (Roszkowska, 2011):

$$V_{ij} = n_{ij}. \left(W_j \middle/ \sum_{j=1}^{n} w_{ij} \right) for\ i = 1, \ldots.., m, j = 1, \ldots, n \quad (9)$$

where w_j is the weight of the jth criterion, $\sum_{j=1}^{n} w_j = 1$

6.1.4. Step 4. determine the positive ideal and negative ideal solutions

The ideal positive solution is the solution that maximizes the benefit criteria and minimizes the cost criteria, whereas the negative ideal solution maximizes the cost criteria and minimizes the benefit criteria. The ideal positive and ideal negative solutions have the forms in Eqs (10) and (11), respectively (Roszkowska, 2011).

$$A^+ = (v_1{}^+, v_2{}^+, \ldots\ldots\ldots, v_n{}^+) \quad (10)$$

$$A^- = (v_1{}^-, v_2{}^-, \ldots\ldots\ldots\ldots, v_n{}^-) \quad (11)$$

where A^+ is the positive ideal solution; $(v_1{}^+, v_2{}^+, \ldots\ldots.., v_n{}^+)$ is the maximum values of criteria (v_j) in the weighted normalized decision matrix; A^- is the negative ideal solution; and $(v_1{}^-, v_2{}^-, \ldots\ldots.., v_n{}^-)$ is the minimum values of criteria (v_j) in the normalized decision matrix.

6.1.5. Step 5. calculate the separation measures from the positive ideal solution and the negative ideal solution

The separation of each alternative from the positive ideal solution and the negative ideal solution can be calculated using Eqs (12) and (13), respectively (Roszkowska, 2011):

$$di^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j{}^+)^2}, i = 1, 2, \ldots.., m \quad (12)$$

$$di^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j{}^-)^2}, i = 1, 2, \ldots.., m \quad (13)$$

Table 4. Decision matrix for sustainable material selection.

Material	Embodied energy (MJ)	CO_2 emissions ($kgCO_2$)	Raw materials consumed (kg)	Waste generation (kg)	Recycled materials (kg)	Landfill waste (kg)	LCC (LE)
Reinforced concrete	60 500	7400	40 000	325 000	97 500	227 500	1062
Wood	425 000	23 000	45 000	65 000	32 500	32 500	76 700
Steel	1 220 000	88 500	42 500	40 000	32 000	8000	94 400
Aluminum	7 750 000	412 000	42 500	50 000	40 000	10 000	413 000
Oak wood	60 000	15 000	42 500	62 500	37 500	25 000	413 000
Ceramic	125 000	35 000	27 500	62 500	18 750	43 750	11 800
Marble	165 000	32 000	32 500	62 500	25 000	37 500	17 700
Precast concrete	100 000	10 750	35 000	325 000	97 500	227 500	1475
Clay bricks	150 000	11 000	45 000	50 000	10 000	40 000	2360
Cement bricks	8850	5600	42 500	50 000	25 000	25 000	944

LCC, life cycle cost.

6.1.6. Step 6. calculate the relative closeness to the positive ideal solution

The relative closeness of the i-th alternative di^{+} with respect to di⁻can be calculated using Eq. (14) (Roszkowska, 2011).

$$R_i = \frac{d_i^-}{d_i^- + d_i^+} \tag{14}$$

6.1.7. Step 7. rank the preference order or select the alternative closest to 1

A set of alternatives now can be ranked by the descending order of the value of R_i.

6.2. Applying the TOPSIS method for selecting the most sustainable building material

The first step of applying the TOPSIS method is to create the decision matrix, which includes all alternatives and criteria of the problem. The values of decision matrix are collected from the SD model results. Table 4 shows the decision matrix for sustainable material selection. Also, the first step includes creating the weight vector, which includes the decision-maker weights of all criteria. A questionnaire survey was created and sent to 10 experts to get their opinion on the relative weights of the selection criteria. Each expert is requested to assign a relative weight to each criterion, whereas the sum of all weights must be equal one. After all the responses of questionnaire are received, the results are analyzed. The mean value of the responses to each criterion is calculated using Eq. (15) (Whitley and Ball, 2001). Table 5 shows the relative weights of the sustainable criteria:

$$\bar{x} = \frac{\sum_{j=1}^{n} w_j}{n} \tag{15}$$

where $\bar{x} = (wj / \sum_{j=1}^{n} w_i j)$ is the relative weights of each criterion: $\sum_{j=1}^{n} w_i j$. The mathematical notation for the sum of all values ($w_1, w_2, \ldots, w_n$), n: the total number of values.

Internal consistency should be determined before a test to be used for research or examination purposes to ensure validity (Tavakol and Dennick, 2011). Cronbach's alpha is widely applied in statistics to evaluate the reliability of tests (Jain and Angural, 2017). Cronbach's alpha provides a measure of the internal consistency of a test or scale (Jain and Angural, 2017). Internal consistency of questionnaire survey is tested through Cronbach alpha using SPSS software version 26. The results show that the alpha coefficient of reliability is 0.89. The resulting alpha coefficient of reliability ranges from 0 to 1. The closer Cronbach alpha coefficient is to 1, the greater the internal consistency of the items in the scale (Jain and Angural, 2017). Jain and Angural (2017) provide the following rules of thumb: ($\alpha \geq 0.9$) excellent, ($0.9 > \alpha \geq 0.8$) good, ($0.8 > \alpha \geq 0.7$) acceptable, ($0.7 > \alpha \geq 0.6$) questionable, ($0.6 > \alpha \geq 0.5$) poor, and ($\alpha < 0.5$) unacceptable.

After the decision matrix and vector weight matrix were constructed, the normalized decision matrix is determined using Eq (8). The normalized decision matrix for all comparisons is shown in Table 6. Then, the weighted normalized decision matrix is calculated by multiplying each normalized value in

Table 5. Relative weights of the sustainable criteria.

Criterions	The relative weight
Embodied energy	0.13
CO_2 emissions	0.17
Raw materials consumed	0.127
Waste generation	0.157
Recycled materials	0.162
Landfill waste	0.122
LCC	0.132
$\sum$	1.0

LCC, life cycle cost.

Table 6. Normalized decision matrix.

Alternatives	Material	Embodied energy (MJ)	CO2 emissions ($kgCO_2$)	Raw materials consumed (kg)	Waste generation (kg)	Recycled materials (kg)	Landfill waste (kg)	LCC (LE)
1	Reinforced concrete	0.046779	0.080664	0.54276	0.97352	0.90579	0.98935	0.00873
	Wood	0.32861	0.25071	0.61061	0.1947	0.30193	0.14134	0.63057
	Steel	0.94331	0.9647	0.57669	0.11982	0.29729	0.03479	0.77608
2	Oak wood	0.27829	0.20157	0.7065	0.57725	0.76822	0.29801	0.99868
	Ceramic	0.57999	0.70267	0.45714	0.57725	0.28411	0.69652	0.02852
	Marble	0.76558	0.64335	0.54026	0.57725	0.51215	0.59702	0.0428
3	Clay bricks	0.99826	0.89116	0.72701	0.70711	0.37139	0.848	0.92848
	Cement bricks	0.058898	0.45368	0.68662	0.70711	0.92848	0.53	0.37139
4	Wood	0.054756	0.055738	0.72701	0.79262	0.63059	0.95578	0.18259
	Aluminum	0.9985	0.99845	0.68662	0.60971	0.77611	0.29409	0.98319
5	Precast concrete	0.8556	0.82371	0.63059	0.70711	0.70711	0.70711	0.81152
	Reinforced concrete	0.51764	0.56702	0.77611	0.70711	0.70711	0.70711	0.5842

LCC, life cycle cost.

the normalized decision matrix by the relative weight of each criterion. Table 7 shows the weighted normalized decision matrix for material alternatives. Therefore, the positive and negative ideal solution is determined for each criterion. The positive and the negative ideal solution are the maximum and minimum values of criteria, respectively, among building material alternatives. Also, the Euclidean distance from ideal best and worst is calculated using Eq. (12) and Eq. (13). Then, the performance score is calculated for all building material alternatives using Eq. (14). Finally, all alternatives are ranked by the descending order of the value of performance score. Table 8 shows the performance score and ranking for building material alternatives. All calculations of the TOPSIS method are determined using MATLAB software and the results are discussed.

The results of the TOPSIS model showed that wood materials record a higher performance score of 0.61251, reinforced concrete 0.57181, and steel 0.42838. Therefore, wood is ranked the highest SBM; reinforced concrete is ranked second; and steel is ranked lowest. Also, for brick alternatives, cement bricks have higher performance score (with score of 1) than clay bricks (with a score of 0). Accordingly,

Table 8. Performance score and ranking for building material alternatives.

Alternatives	Material	Performance score (R_i)	Rank
1	Reinforced concrete	0.57181	2
	Wood	0.61251	1
	Steel	0.42838	3
2	Oak wood	0.47178	3
	Ceramic	0.55665	2
	Marble	0.56862	1
3	Clay bricks	0	2
	Cement bricks	1	1
4	Wood	0.71905	1
	Aluminum	0.28095	2
5	Precast concrete	0.78827	1
	Reinforced concrete	0.21173	2

Table 7. Weighted normalized decision matrix (V_{ij}).

Alternatives	Material	Embodied energy (MJ)	CO_2 emissions ($kgCO_2$)	Raw materials consumed (kg)	Waste generation (kg)	Recycled materials (kg)	Landfill waste (kg)	LCC (LE)
1	Reinforced concrete	0.0060812	0.013713	0.068931	0.15284	0.14674	0.1207	0.00115
	Wood	0.042719	0.042621	0.077547	0.030568	0.048913	0.017243	0.08323
	Steel	0.12263	0.164	0.073239	0.018811	0.04816	0.004244	0.10244
2	Oak wood	0.036191	0.051267	0.089725	0.090644	0.12445	0.048558	0.13183
	Ceramic	0.075398	0.11962	0.058057	0.090644	0.062226	0.084976	0.00376
	Marble	0.099526	0.10937	0.068613	0.090644	0.082968	0.072837	0.00564
3	Clay bricks	0.12977	0.1515	0.092331	0.11102	0.060165	0.10346	0.12256
	Cement bricks	0.0076567	0.077126	0.087201	0.11102	0.15041	0.06466	0.04902
4	Wood	0.1298	0.16974	0.08720	0.095752	0.12573	0.035878	0.12978
	Aluminum	0.0071183	0.00947	0.092331	0.12444	0.10216	0.11661	0.02410
5	Precast concrete	0.11123	0.14003	0.080085	0.11102	0.11455	0.086267	0.10712
	Reinforced concrete	0.06729	0.096393	0.098566	0.11102	0.11455	0.086267	0.07712

LCC, life cycle cost.

cement bricks are more sustainable than clay bricks. In addition, for the flooring material alternatives, marble tiles (with a score of 0.56862) are preferred than ceramics tiles (with a score of 0.55665) and oak wood (with a score of 0.47178). Furthermore, regarding alternative material for windows, wood records a higher performance score (0.71905) than aluminum (0.28095). Finally, for concrete alternatives, reinforced concrete (cast-in-site) records a higher performance score (0.78827) than precast concrete (0.21173).

6.3. Conclusions

Sustainability is considered a wide and complex concept that considers all fields. It is one of the major concerns in the construction industry. The construction industry has serious impacts on the environment throughout the whole life cycle due to the huge amounts of materials used. So, selection of SBMs can enhance the adverse impacts on the environment. This research presents an SD model to aid decision-makers in SBMS. The system boundary includes sustainable criteria that are determined from previous studies and experts' opinions. CLD is created among the sustainable criteria to show the interrelation between these criteria. Therefore, the SF diagram is generated from the CLD to simulate the sustainable criteria and illustrate the behavior of building material alternatives. This model is applied on some common building materials to estimate the performance of the building materials according to the EE, CO_2 emissions, the amount of raw material consumed, the amount of waste generation, amount of landfill waste, amount of recycled materials, and LCC. Then, the TOPSIS method is applied using MATLAB software to select the most SBMs. The results show that wood, cast-in-site concrete, marble tiles, and cement bricks are the best SBMs.

Conflicts of interest

There are no conflicts of interest.

Credit authorship contribution statement

Authors contribution: The following is a summary of the author statement, which highlights their contributions to the paper based on their respective roles: 1. Shimaa Elshoubaky: data collection and tools, data analysis and interpretation, inquiry, methodology, and article writing. Furthermore, the corresponding author is in charge of ensuring that the descriptions are correct and that all authors agree on them. 2. Emad Elbeltagi: work conception and design, data interpretation, supervision, and article critical revision, and final approval of the published version. 3. Mohammed Abd Elrahman: work conception and design, data interpretation, supervision, and article critical revision. 4. Islam Elmasoudi: work conception and design, data interpretation, supervision, and article critical revision.

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