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RESEARCH ARTICLE

An integrated data envelopment analysis and life cycle assessment method for performance measurement in green construction management

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Abstract
The construction industry routinely extracts vast quantities of materials and releases deleterious pollutant emissions to the biosphere. In this study, we propose an integrated data envelopment analysis (DEA) and life cycle assessment (LCA) method to measure the performance of eco-friendly building materials in green construction management. Initially, we use the LCA method and environmental impact analysis to identify alternative green flooring systems and relevant sustainability criteria. We then use factor analysis to further evaluate these criteria and choose the most significant sustainability factors. Finally, a DEA model and a new enhanced Russell model (ERM) is proposed to measure the performance of the green flooring systems with factor analysis.

Keywords Green construction management · Data envelopment analysis · Enhanced Russell model · Super-efficiency · Life cycle assessment · Green flooring system

Introduction

The construction industry is an important contributor to global energy consumption and environmental impacts. Therefore, it is important to perform strategies and procedures for reducing its environmental impact (Traverso et al. 2009). Life cycle assessment (LCA) plays a vital role in assessing both energy and environmental effects (Koroneos and Dompros 2007; Kotaji et al. 2003). The LCA has been widely adopted by the construction industry and is recognized as a valuable tool in support of sustainable construction industries (SETAC 2001). Environmental assessment provides information on selecting construction materials (Vince et al. 2008). The construction industry extracts large amounts of raw materials and non-renewable resources for consumption by using energy and releasing pollutants. The LCA is a fact-based performance measurement method commonly used to assess environmental sustainability and identify improvement opportunities in the construction industry (Dylewski and Adamczyk 2014). These effects can be aggregated into three damage categories, including damage to human health, damage to ecosystem diversity, and damage to resource availability. Finally, these effects can be

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aggregated into a single environmental score. As concerns over environmental impacts of construction industry grow, many researchers use LCA (Banar and Çokaygil 2011.

Different floor coverings have been already studied by the LCA method (Souza et al. 2015; Günther and Langowski 1997; Potting and Blok 1995). The LCA of buildings has been extensively studied over the past decade. LCA can be applied in decision making to improve the environmental performance of buildings (Monteiro and Freire 2012). Different types of software are used to calculate the values needed for assessing the life cycle of buildings (Lawania and Biswas 2016; Zhang and Wang 2016; Giama and Papadopoulos 2015; Lewandowska et al. 2015). Here, SimaPro 8.2 software is applied to compare floor coverings from an environmental perspective. A significant number of LCA assessments of building processes and materials have been carried out for at least two decades (e.g., Martínez-Rocamora et al. 2016; Maia de Souza et al. 2016; Souza et al. 2015; Ingrao et al. 2016; Nicoletti et al. 2002; Zare and Izadikhah 2017; and de Klijn-Chevalerias and Javed 2017). Kamble et al. (2017) used the LCA method to measure the technical, hygiene, environmental, and economic aspects of the soil biotechnology system for wastewater treatment. Canaj et al. (2020) performed a complete site-generic and site-dependent environmental assessment using LCA and explained the cradle-farm gate environmental impacts of solar greenhouse tomato production in the farming industry. Rashid and Liu (2020) used LCA to measure the influence of rainfall and the environmental impact of centralized wastewater treatment plants.

The objective of this paper is to compare different types of construction covering over their life cycle to determine their environmental performance using an LCA analysis to choose products with lower environmental impacts. To this end, 41 types of construction coverings are found using the LCA method. Also, 18 main criteria are obtained based on the LCA results. Furthermore, this paper ranks construction coverings and chooses the most important types. We develop a data envelopment analysis (DEA) model. DEA is a mathematical programming method widely used for measuring the relative efficiency of decision-making units (DMUs). DEA was first put forward by Charnes et al. (1978). Hermoso-Orzáez et al. (2020) used DEA to study the environmental efficiency of 28 European Union countries. They proposed a new DEA method called improved analysis method that aimed at a more objective assessment and provided some possible solutions for improvement. Radial DEA models cannot recognize weak efficient DMUs (Izadikhah and Farzipoor Saen (2016a); Izadikhah and Farzipoor Saen (2016b)). Another kind of DEA model is non-radial models (Tone et al. 2020). One of the important non-radial DEA models is the enhanced Russell model (ERM), which was proposed by Pastor et al. (1999). Despite the useful properties of the ERM model, this model fails to present a complete ranking of the DMUs. To remove this difficulty, Izadikhah et al. (2017) proposed a modified version of the ERM model. In this paper, we propose a new version of the modified ERM model under the variable return to scale (VRS) technology. On the other hand, Koopmans (1951) discussed that production processes might generate undesirable outputs such as pollutions and wastes (Yu et al. 2020). Therefore, this paper presents a modified ERM model with undesirable data under VRS technology. To reduce the number of factors, we use factor analysis and DEA to find a final ranking of the green flooring systems. The remainder of this paper is organized as follows. In Section 2, the literature review is presented. Section 3 briefly reviews the preliminaries. Section 4 proposes our new modified ERM model with undesirable factors under VRS. A case study is given in Section 5. In Section 6, conclusions are discussed.

Literature review

DEA models with undesirable outputs

Many industries produce undesirable outputs, such as pollution and noise. In response, a large number of DEA models are proposed in the literature to solve performance measurement problems with undesirable outputs. Figure 1 shows several methods for considering undesirable outputs in DEA.

Figure 1 shows there are two groups of methods for considering undesirable outputs in DEA. These methods include weak disposability and data translation methods. Table 1 depicts DEA works dealing with undesirable outputs. As is seen, many previous works that use undesirable outputs are based on additive inverses.

DEA and LCA

The combined LCA and DEA method is proposed as a framework for evaluating operational and environmental aspects. Lozano et al. (2009) presented a link between

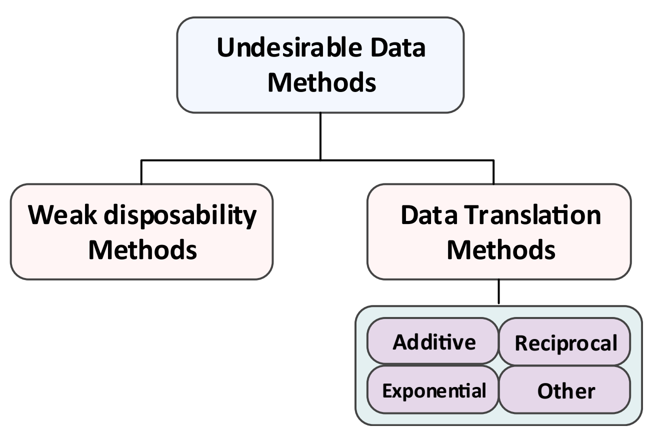


Fig. 1 A classification of the undesirable data methods

Table 1 DEA methods for handling undesirable outputs

Methods		References	Descriptions
Weak disposability		Färe and Grosskopf (2000, 2003, 2004, 2009); Färe et al. (1993); Färe and Grosskopf (2000, 2003, 2004, 2009); Korhonen and Luptacik (2004); Halkos and Petrou (2019); Piao et al. (2019)	Undesirable outputs are treated in their original form.
Transformation	The methods based on reciprocals	Golany and Roll (1989)	Undesirable outputs are treated in a reciprocal form.
	Additive Transformation	Scheel (2001); Seiford and Zhu (2002); You and Yan (2011); Aliakbarpoor and Izadikhah (2012); Cherchye et al. (2015); Rashidi et al. (2015); Wu et al. (2016); Yu et al. (2016); Zha et al. (2016); Liu et al. (2017); Fusco et al. (2019)	Undesirable outputs are treated in their additive inverse form, and undesirable outputs are treated as desirable inputs.
	Exponential Transformation	Zhou et al. (2019)	The exponential relationship between the desirable and undesirable outputs is handled through a transformation process.
	Other Transformation	Toloo and Hančlová (2019)	The multi-valued measures are handled through a directional output distance method.

operational efficiency and environmental impacts using a joint application of LCA and DEA. Iribarren et al. (2010) explained and demonstrated the potentials of a combined application of DEA and LCA via the presentation of brief case studies. Iribarren et al. (2011) applied an LCA and DEA method to identify efficient farms among 72 farms. Vázquez-Rowe et al. (2012) analyzed 40 vine-growing exploitations using the LCA and DEA methods to determine the level of operational efficiency of each producer. Mohammadi et al. (2013) applied the LCA and DEA methods to benchmark the level of operational input efficiency of 94 soybean farms. Avadí et al. (2014) applied a combined use of LCA and DEA in Peruvian fleets. Iribarren et al. (2015) presented a method based on both LCA and DEA for selecting building components according to their environmental impact efficiency. Mohammadi et al. (2015) combined LCA and DEA methods to estimate the technical efficiency of farmers. Lorenzo-Toja et al. (2015) analyzed regions of Spain using LCA and DEA.

Ullah et al. (2016) performed an eco-efficiency analysis using DEA to integrate economic and environmental performance, which were assessed by LCA. Lijó et al. (2017) combined LCA and DEA to analyze the eco-efficiency of 15 agricultural plants in Italy. Beltrán-Esteve et al. (2017) used LCA, a meta-frontier directional distance function, and DEA for performance measurement in production systems. Álvarez-Rodríguez et al. (2019a) and Álvarez-Rodríguez et al. (2019b) developed an integrated LCA and dynamic data envelopment analysis (DEA) to measure the sustainability of retail grocery stores in Spain. Pishgar-Komleh et al. (2020) evaluated the efficiency in the farming industry by using a combined LCA and DEA model. Álvarez-Rodríguez et al. (2020) also proposed an integrated dynamic network DEA and LCA to evaluate the efficiency in supply chains.

Gaps in the literature

To identify the most appropriate construction floor covering based on environmental impact, we propose a new DEA and LCA method. Also, this paper develops a new modified DEA model. Furthermore, we apply LCA using SimaPro software in two phases: (i) specifying the practical criteria for measuring the performance of products; (ii) further analysis on selected products. Factor analysis is used to reduce the number of criteria. This paper applies our new DEA model to evaluate the performance of 41 construction floor coverings identified by SimaPro software.

Preliminaries

Life cycle assessment

ISO 2006a divides LCA into four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. Figure 2 describes the relationship between the phases.

The goal and scope definition depend on the subject of assessment. The second phase, life cycle inventory (LCI), involves creating an inventory of inputs and outputs. Phase 3 evaluates the significance of the potential environmental impacts of

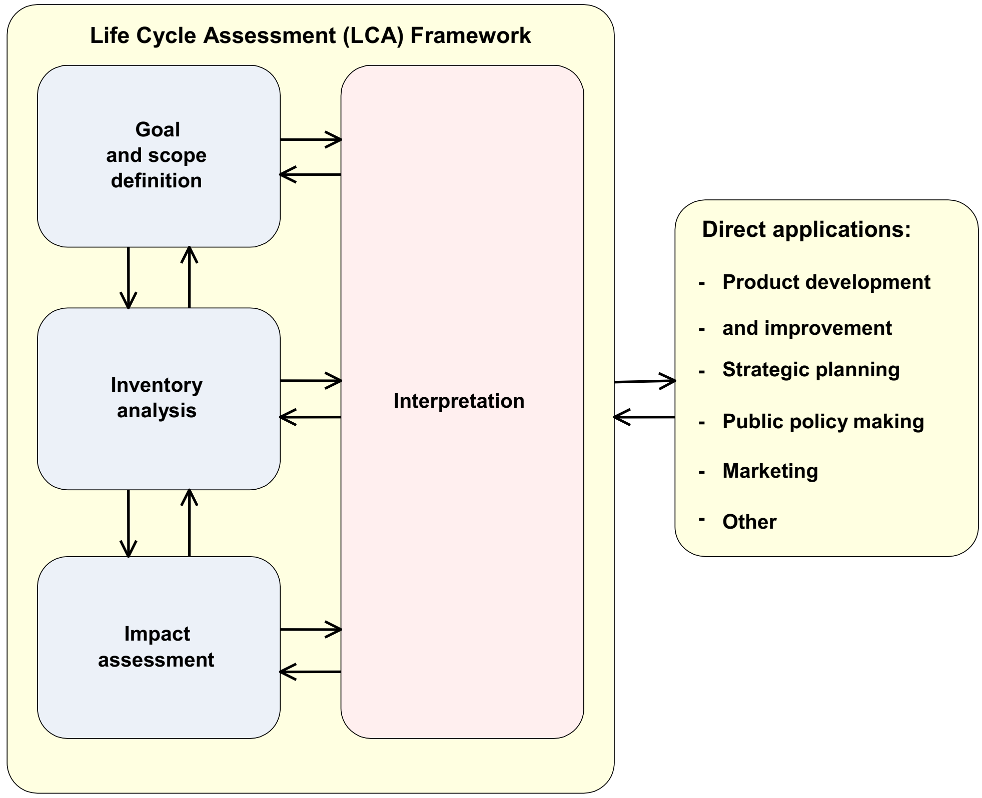


Fig. 2 Four phases of LCA (ISO 2006a)

the previous phase (ISO (2006a)). Phase 3 includes the selection of impact categories, classification, characterization, and normalization. In phase 4, the results of LCI are collected and analyzed for conclusions and recommendations (ISO (2006b). Table 2 reports the nomenclatures used in this study.

Enhanced Russell model

Let us consider n DMUs where each $DMU_j (j = 1, \ldots, n)$ consumes m inputs $x_{ij} (i = 1, \ldots, m)$ to produce s outputs $y_{rj} (r = 1, \ldots, s)$. The non-radial enhanced Russell model (ERM) model could be used to measure the efficiency of the DMUs under consideration (Pastor et al. (1999)):

$$
\begin{aligned}
&\rho_p^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\theta_i}{\frac{1}{s}\sum_{r=1}^{s}\varphi_r} \\
&s.t. \\
&\sum_{j=1}^{n}\lambda_j x_{ij} \le \theta_i x_{ip}, \quad i = 1, \ldots, m, \quad \sum_{j=1}^{n}\lambda_j y_{rj} \ge \varphi_r y_{rp}, \quad r = 1, \ldots, s, \\
&\theta_i \le 1, \ \varphi_r \ge 1, \quad \forall i, r, \\
&\lambda_j \ge 0, j = 1, \ldots, n.
\end{aligned}
\tag{1}
$$

Definition 1 ERM efficiency (Pastor et al. (1999)**).** The optimal ρ_p^* in Model (1) is called the ERM efficiency score of DMU_p. DMU_p is considered ERM-efficient if and only if $\rho_p^* = 1$. This condition is comparable to $\varphi_r^* = 1$ and $\theta_i^* = 1$ for each i and r in the optimal solutions.

Table 2 Nomenclatures

Symbol	Description	Symbol	Description
DMU_p	DMU under evaluation	R^*	Optimal objective value
DMU_j	jth DMU	θ_i	ith input contraction
m	Number of inputs	φ_r	rth desirable output extension
s_1	Number of desirable outputs	γ_t	tth undesirable output contraction
s_2	Number of undesirable outputs	δ_1, δ_2	Binary variables
x_{ij}	ith input of DMU_j	M	Big positive number
y_{rj}^g	rth desirable output of DMU_j	λ_j	Intensity
y_{tj}^b	tth undesirable output of DMU_j		

A DEA super-efficiency method based on the modified ERM

Izadikhah et al. (2017) show we cannot compute the correct super-efficiency score if the DMU under consideration is removed from the reference set of Model (1), and consequently, Model (1) will not be able to rank all DMUs completely. Therefore, the movement direction of DMU should be changed if we want to measure the super-efficiency score of a DMU that lies outside the production possibility set (PPS). Izadikhah et al. (2017) have proposed the following integer programming model to address this problem:

$$
\begin{aligned}
&R^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\theta_i}{\frac{1}{s}\sum_{r=1}^{s}\varphi_r}\\
&s.t.\\
&\sum_{\substack{j=1\\ j\neq p}}^{n} \lambda_j x_{ij} \le \theta_i x_{ip}; \quad i=1,..,m, \qquad \sum_{\substack{j=1\\ j\neq p}}^{n} \lambda_j y_{rj} \ge \varphi_r y_{rp}; \quad r=1,..,s,\\
&\sum_{\substack{j=1\\ j\neq p}}^{n} \lambda_j = 1; \qquad \lambda_j \ge 0, \quad \forall j,\\
&\theta_i - 1 \le M\delta; \quad i=1,..,m, \quad -\theta_i + 1 \le M(1-\delta); \quad i=1,..,m,\\
&-\varphi_r + 1 \le M\delta; \quad r=1,..,s, \quad \varphi_r - 1 \le M(1-\delta); \quad r=1,..,s,\\
&\delta \in \{0,1\}.
\end{aligned} \tag{2}
$$

The binary variable δ in Model (2) guarantees only one of the following constraint sets is satisfied:

$$
(a): \begin{cases} \theta_i \le 1; i=1,..,m, \\ \varphi_r \ge 1; r=1,..,s, \end{cases} \quad or \quad (b): \begin{cases} \theta_i \ge 1; i=1,..,m, \\ \varphi_r \le 1; r=1,..,s, \end{cases}
$$

If the DMU lies inside the PPS, group (a) constraints will be active. However, if the DMU lies outside the PPS, group (b) constraints will be active. As a result, this model can rank all the DMUs.

Modified ERM with undesirable outputs under variable return to scale

We propose a new DEA model under the VRS condition to take both desirable outputs and undesirable outputs under consideration. Consider measuring the performance of n homogeneous DMUs (DMU_j; $j = 1, \ldots, n$) in a performance measurement system where a vector of m inputs x_{ij} ($i = 1,\ldots, m$) is used to produce s outputs where s_1 of them are desirable (denoted by y^g_{rj} ($r = 1,\ldots, s_1$)) and s_2 of them are undesirable (denoted by y^b_{tj} ($t = 1, \ldots, s_2$)), where $s = s_1 + s_2$. We define T as follows (Banker et al. (1984):

$$
T = \left\{ \left(x_j, y^g_j, y^b_j\right) : x_j \text{ can produce } y^g_j \text{ and } y^b_j \right\}
$$

The goal is to maximize the production of desirable outputs and minimize the production of undesirable outputs. The undesirable outputs and inputs are sometimes treated as desirable inputs and outputs, respectively (Liu et al. (2010). We consider this treatment in our model, and define the following PPS under VRS technology:

$$
T^{MERS} = \left\{ \left(x_j, y^g_j, y^b_j\right) \mid \sum_{j=1}^{n} \lambda_j x_j \le x; \sum_{j=1}^{n} \lambda_j y^b_{tj} \le y^b; \sum_{j=1}^{n} \lambda_j y^g_{rj} \ge y^g; \sum_{j=1}^{n} \lambda_j = 1; \lambda_j \ge 0 \right\}
$$

Therefore, a modified ERM model is proposed as the following integer programming model:

$$
\begin{aligned}
&R^* = \min \frac{\frac{1}{m+s_2}\left(\sum_{i=1}^{m}\theta_i + \sum_{t=1}^{s_2}\gamma_t\right)}{\frac{1}{s_1}\sum_{r=1}^{s_1}\varphi_r}\\
&s.t.\\
&\sum_{\substack{j=1\\ j\neq p}}^{n} \lambda_j x_{ij} \le \theta_i x_{ip}; i=1,..,m,\\
&\sum_{\substack{j=1\\ j\neq p}}^{n} \lambda_j y^b_{tj} \le \gamma_t y^b_{tp}; t=1,..,s_2, \quad \sum_{\substack{j=1\\ j\neq p}}^{n} \lambda_j y^g_{rj} \ge \varphi_r y^g_{rp}; r=1,..,s_1,\\
&\sum_{\substack{j=1\\ j\neq p}}^{n} \lambda_j = 1;\\
&\theta_i - 1 \le M\delta_1; \quad i=1,..,m, \quad -\theta_i + 1 \le M(1-\delta_1); i=1,..,m,\\
&\gamma_t - 1 \le M\delta_1; \; t=1,..,s_2, \quad -\gamma_t + 1 \le M(1-\delta_1); t=1,..,s_2,\\
&-\varphi_r + 1 \le M\delta_2; \; r=1,..,s_1, \quad \varphi_r - 1 \le M(1-\delta_2); r=1,..,s_1,\\
&\delta_1 + \delta_2 = 1; \quad \delta_1, \delta_2 \in \{0,1\},\\
&\theta_i, \varphi_r, \gamma_t, \lambda_j \ge 0; \quad \forall i, r, t, j.
\end{aligned} \tag{3}
$$

In Model (3), the binary variables δ_1 and δ_2 assure only one of two the groups of constraints is satisfied:

$$
(I): \begin{cases} \theta_i \le 1; i=1,..,m; \gamma_t \le 1; t=1,..,s_1, \\ \varphi_r \ge 1; r=1,..,s_2; \end{cases} \quad or
$$

$$
(II): \begin{cases} \theta_i \ge 1; i=1,..,m, \gamma_t \ge 1; t=1,..,s_1, \\ \varphi_r \le 1; r=1,..,s_2, \end{cases}
$$

The following definition indicates a useful property for models that can help managers find a convenient target for inefficient DMUs.

Definition 1: $DMU_p = \left(x_p, y_p^g, y_p^b\right)$ is located on the strong efficient frontier, if there is no non-negative vector $\lambda = (\lambda_1, \ldots, \lambda_n)$ such that

$$\begin{cases} \sum_{j=1}^{n} \lambda_j x_{ij} \le x_{ip}, & \forall i \\ \sum_{j=1}^{n} \lambda_j y_{rj}^g \ge y_{rp}^g, & \forall r \\ \sum_{j=1}^{n} \lambda_j y_{tj}^b \le y_{tp}^b, & \forall t \end{cases}$$

with at least one strict inequality.

In Model (3), we use a modified version of T^{MERM}. In other words, DMU_p is removed from PPS, and we call it T_p^{MERM}. If the DMU lies within the PPS, then the constraints of the group (*I*) become active. However, if the DMU lies outside the PPS, the constraints of the group (*II*) become active. Thus, for the DMUs inside the PPS, we have $0 \le R^* \le 1$, and for the DMUs outside the PPS, we have $R^* > 1$. This fact is proved in the following theorem.

Theorem 1 For efficient DMU_p, Category 1 is held; otherwise, Category 2 is held.

Proof.

Suppose that DMU_p is an efficient unit and $\left(\dot{\theta}, \dot{\gamma}, \dot{\varphi}, \dot{\lambda}, \dot{\delta}\right)$ be its optimal solution of Model (3) with the optimal objective $\dot{R}$. In contrast, assume that Category 1 is not held. Without loss of generality, let us consider that there is an index k such that:

$$\begin{cases} \dot{\theta}_k > 1, \\ \dot{\theta}_i \le 1, \quad i = 1, \ldots, m; i \ne k \\ \dot{\gamma}_t \le 1, \quad r = 1, \ldots, s_1 \\ \dot{\varphi}_r \ge 1, \quad r = 1, \ldots, s_2 \end{cases}$$

Clearly, there is an $\alpha_k < 1$ such that $\sum_{j=1,\ j\ne p}^{n} \lambda_j\ x_{ij} = \alpha_k\ \dot{\theta}_k\ x_{kp}$. Now, we define

$$\begin{cases} \overline{\theta}_k = \alpha_k \dot{\theta}_k, \\ \overline{\theta}_i = \dot{\theta}_i, i = 1, \ldots, m; i \ne k \\ \overline{\gamma}_t = \dot{\gamma}_t, r = 1, \ldots, s_1 \\ \overline{\varphi}_r = \dot{\varphi}_r, r = 1, \ldots, s_2 \\ \overline{\lambda}_j = \dot{\lambda}_j, j = 1, \ldots, n \\ \overline{\delta} = \dot{\delta}, \end{cases}$$

where, $\overline{\theta}_k = \alpha_k\ \dot{\theta}_k < \dot{\theta}_k$. Then, clearly $\left(\overline{\theta}, \overline{\gamma}, \overline{\varphi}, \overline{\lambda}, \overline{\delta}\right)$ is a feasible solution for Model (3). If we denote its objective value by $\overline{R}$, then we have

$$\overline{R} = \frac{\frac{1}{m+s_2}\left(\sum_{i=1}^{m}\overline{\theta}_i + \sum_{t=1}^{s_2}\overline{\gamma}_t\right)}{\frac{1}{s_1}\sum_{r=1}^{s_1}\overline{\varphi}_r} < \frac{\frac{1}{m+s_2}\left(\sum_{i=1}^{m}\dot{\theta}_i + \sum_{t=1}^{s_2}\dot{\gamma}_t\right)}{\frac{1}{s_1}\sum_{r=1}^{s_1}\dot{\varphi}_r} = \dot{R}$$

This relation contradicts with the optimality of $\left(\dot{\theta}, \dot{\gamma}, \dot{\varphi}, \dot{\lambda}, \dot{\delta}\right)$ and proves the theorem. □.

According to Theorem 1, the following corollary is concluded.

Corollary 1 For the DMUs inside the PPS, we have $0 \le R^* \le 1$, and for the DMUs outside the PPS, we have $R^* > 1$.

The following theorem guarantees that the proposed model is always feasible.

Theorem 2 Model (3) is always feasible.

Proof:

We consider two cases for $DMU_p = \left(x_p, y_p^g, y_p^b\right)$:

- Case *i*: $\left(x_p, y_p^g, y_p^b\right) \in T_p^{MERM}$.

  In this case, $\exists \overline{\lambda} = \left(\overline{\lambda}_1, \ldots, \overline{\lambda}_{p-1}, \overline{\lambda}_{p+1}, \ldots, \overline{\lambda}_n\right)$ such that

$$\sum_{\substack{j=1\\ j\ne p}}^{n} \overline{\lambda}_j x_{ij} \le x_{ip}; \quad i = 1, .., m, \qquad \sum_{\substack{j=1\\ j\ne p}}^{n} \overline{\lambda}_j y_{tj}^b \le y_{tp}^b; \quad t = 1, .., s_2,$$

$$\sum_{\substack{j=1\\ j\ne p}}^{n} \overline{\lambda}_j y_{rj}^g \ge y_{rp}^g; \quad r = 1, .., s_1, \qquad \sum_{\substack{j=1\\ j\ne p}}^{n} \overline{\lambda}_j = 1;$$

Therefore, $\left(\overline{\lambda}, \overline{\theta}, \overline{\varphi}, \overline{\gamma}, \overline{\delta}_1, \overline{\delta}_2\right)$ is a feasible solution for Model (3) where $\overline{\theta}_i = 1, \forall i$; $\overline{\varphi}_r = 1, \forall r$; $\overline{\gamma}_t = 1, \forall t$; $\overline{\delta}_1 = 0$; and $\overline{\delta}_2 = 1$.

- Case *ii*: $\left(x_p, y_p^g, y_p^b\right) \notin T_p^{MERM}$.

  In this case, for each vector of λ we have $\left(x_p, y_p^g, y_p^b\right) \notin T^{MERM}$. Without loss of generality, assume that $\exists \overline{\lambda} = \left(\overline{\lambda}_1, \ldots, \overline{\lambda}_{p-1}, \overline{\lambda}_{p+1}, \ldots, \overline{\lambda}_n\right)$ such that:

$$\sum_{\substack{j=1\\ j\ne p}}^{n} \overline{\lambda}_j x_{ij} \le x_{ip}; \quad i = 1, .., m; i \ne k, \qquad \sum_{\substack{j=1\\ j\ne p}}^{n} \overline{\lambda}_j x_{kj} > x_{kp};$$

$$\sum_{\substack{j=1\\ j\ne p}}^{n} \overline{\lambda}_j y_{tj}^b \le y_{tp}^b; \quad t = 1, .., s_2, \qquad \sum_{\substack{j=1\\ j\ne p}}^{n} \overline{\lambda}_j y_{rj}^g \ge y_{rp}^g; \quad r = 1, .., s_1,$$

$$\sum_{\substack{j=1\\ j\ne p}}^{n} \overline{\lambda}_j = 1;$$

Thus, $\exists \alpha > 1; \sum_{j=1,\ j\ne p}^{n} \overline{\lambda}_j\ \ x_{kj} \le \alpha x_{kp}$; then, $\left(\overline{\lambda}, \overline{\theta}, \overline{\varphi}, \overline{\gamma}, \overline{\delta}_1, \overline{\delta}_2\right)$ is a feasible solution for Model (3) where

$\overline{\theta}_i = 1, (i{\neq}k)\ ; \overline{\theta}_k = \alpha > 1;\ \overline{\varphi}_r = 1, \forall r;\ \overline{\gamma}_t = 1, \forall t;\ \overline{\delta}_1 = 1;$ $\overline{\delta}_2 = 0.$

This completes the proof. □.

The following theorem provides some information that are useful for practicing managers seeking the best performance.

Theorem 3 Model (3) projects each unit on the strong efficient frontier.

Proof.

Consider that the vector $(\theta^*, \gamma^*, \varphi^*, \lambda^*, \delta^*)$ be the optimal solution of Model (3) in evaluating $DMU_p = \left(x_p, y_p^g, y_p^b\right)$. Thus, the vector $\left(\overline{x}_p, \overline{y}_p^g, \overline{y}_p^b\right) = \left(\theta^* x_p, \varphi^* y_p^g, \gamma^* y_p^b\right)$ is its projection point. In contrast, let us assume that $\left(\overline{x}_p, \overline{y}_p^g, \overline{y}_p^b\right)$ is not located on the strong efficient frontier. Then, according to Definition 1 and without loss of generality, there must be a non-negative vector $\overline{\lambda} = \left(\overline{\lambda}_1, \ldots, \overline{\lambda}_n\right)$ and an index h such that

$$\begin{cases} \sum\limits_{j=1}^{n} \overline{\lambda}_j x_{hj} < \overline{x}_{hp} = \theta_h^* x_{hp} & \\ \sum\limits_{j=1}^{n} \overline{\lambda}_j x_{ij} \leq \overline{x}_{ip} = \theta_i^* x_{ip}, & \forall i;\, i{\neq}h \\ \sum\limits_{j=1}^{n} \overline{\lambda}_j y_{rj}^g \geq \overline{y}_{rp}^{\,g} = \varphi_r^* y_{rp}^g, & \forall r \\ \sum\limits_{j=1}^{n} \overline{\lambda}_j y_{tj}^b \leq \overline{y}_{tp}^{\,b} = \gamma_t^* y_p^b, & \forall t \end{cases}$$

Clearly, there is $\overline{\alpha} < 1$ such that $\sum\limits_{j=1}^{n} \overline{\lambda}_j\, x_{hj} = \overline{\alpha}\theta_h^* x_{hp}$. Let us define $\overline{\theta}_h = \overline{\alpha}\theta_h^*$ and $\overline{\theta}_i = \theta_i^*, (\forall i; i{\neq}h)$, so we have $\overline{\theta}_h < \theta_h^*$. Now, if we set $\left(\overline{\gamma}, \overline{\varphi}, \overline{\delta}\right) = \left(\gamma^*, \varphi^*, \delta^*\right)$, then clearly, the vector $\left(\overline{\theta}, \overline{\gamma}, \overline{\varphi}, \overline{\lambda}, \overline{\delta}\right)$ is a feasible solution of Model (3) in evaluating DMU_p. A simple calculation shows that this feasible solution has a strictly better objective function than the optimal solution. This contradiction proves the theorem. ◻.

Case study

In this case study, we use the integrated DEA and LCA framework depicted in Fig. 3 to evaluate and select the most suitable green flooring system at Eco-Tech[1] Flooring, a green flooring product producer in southern Pennsylvania.

Primary stage: Providing data and variables

Initially, we use the LCA method to identify the most relevant criteria for assessing 41 different green flooring systems. The analysis is performed using SimaPro 8.2 software. Comparative analyses of the environmental impact of various types of coverings are assessed. Boundaries of systems are based upon the "cradle to grave" approach, which includes setup, production, consumption, recycling, and disposal. The analysis is conducted using secondary data obtained from the Ecoinvent 3 database[2] (Wernet et al. 2016; Martínez-Rocamora et al. 2016; Moreno Ruiz et al. 2013; Moreno Ruiz et al. 2016). For each process, the reference flow is 10 kg.

Main indicators

SimaPro 8.2 software and impact assessment called ReCiPe H.A is used to run the cradle to grave approach. ReCiPe is a method for impact assessment in LCA. It converts emissions and resource extractions into a couple of environmental impact scores by characterization factors (Goedkoop et al. 2009). The midpoint level and endpoint level are two different approaches for deriving characterization factors. The midpoint level is used to extract characterization factors from single environmental problems. The endpoint level is used to extract characterization factors from higher-level environmental problems involving resource scarcity, biodiversity, and human health considerations. It is recommended to convert midpoints to endpoints to simplify the interpretation of the ReCiPe results.

Environmental impacts for each unit of green flooring products based on the Ecoinvent 3 database are collected. In this paper, the impact of different types of green flooring products on the environment is assessed in 3 endpoint categories and 12 midpoint categories. The quality of the LCI data for generating life cycle stages is assessed according to ISO 14044 (ISO (2006a). Categories based on the ReCiPe H.A method are represented in Table 3 (Wernet et al. 2016; Moreno Ruiz et al. 2016). In this paper, the endpoints consist of three categories, including human health, ecosystems, and resources. These 15 indicators can be considered as undesirable outputs (Iribarren et al. 2015).

Also, two resource indicators are considered as inputs that are metal depletion and fossil depletion. Furthermore, 15 undesirable outputs are considered. We set the weight of each kind of material as desirable output (for more details, see Iribarren et al. 2015; Lozano et al. 2010). In summary, we have 18 inputs and outputs. To reduce the number of factors, we run a factor analysis on 17 inputs and undesirable outputs. As a result, 12 factors are found as the most important factors. Table 4 shows the result generated by SPSS software. Three factors are found, and the criteria with a load factor greater than 0.5 in the first factor are selected.

[1] The name of the green flooring manufacturing company is changed to protect their anonymity.

[2] www.ecoinvent.org

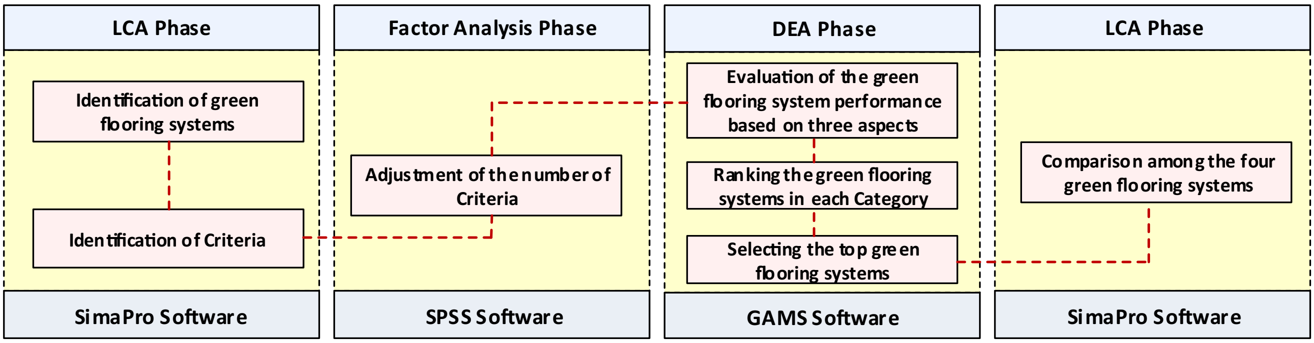


Fig. 3 Proposed integrated framework

The obtained 12 criteria and the desirable output are selected for final evaluation by the proposed DEA model.

Data and variables

Thirteen criteria are considered to assess the green flooring products with respect to the human health and ecosystem criteria. The inputs and outputs are depicted in Table 5.

Fifty-five different kinds of green flooring products are specified, and 41 of them could be produced by Eco-Tech using the LCA method. The data obtained for these 41 products are reported in Table 5. These data are obtained by implementing the LCA method using the Simapro software. Three categories of data are also shown in Table 6.

Main stage: Final results

Here, we present the results in two stages. In the first stage, we show the results of the DEA model and determine the most important products. In the second stage, to compare selected products of the DEA, we conduct an in-depth analysis based on LCA. The results of the proposed DEA model are reported in Table 7. Using our DEA model, these products are compared in three aspects.

The results of the DEA model obtained with GAMS software are presented in Fig. 4. The general case results show that the green flooring product 35 is the best (with the lowest damage), and products 40 and 32 are the second and third best flooring types. The healthcare case results show again that the green flooring product 35 is the best, and products 40 and 34 are the second and third best products. The ecosystem case results show that the green flooring product 35 is the best, and flooring products 32 and 1 are the second and third best products. Considering all three aspects of general, healthcare, and ecosystem, the green flooring product 35 is the best product.

Given Table 7 and Fig. 4, it is clear that product numbers 40, 35, 34, and 32 are the top-rated green flooring products.

Further analysis based on LCA on DEA results

Thus far, we found out that four products have outstanding rankings in terms of three aspects. Now, we conduct an in-depth analysis based on the LCA. The flooring is referred to as a building complex after the completion of tight-fitting operations in the building to make the building a habitable place. Flooring is one of the important issues in construction projects. After leveling a floor, or the execution of a roof, flooring is done to enhance both its beauty and its durability. Various materials and compounds can be used for this purpose.

In this research, four types of products are used in the process of building flooring (two types are almost similar products but different from environmental patterns) were studied based on environmental criteria, which are briefly described below:

- **Anhydrite floor:** Anhydrite floor is a construction covering based on a mixture of sand aggregate and a calcium

Table 3 Endpoint and midpoint categories

Endpoint category	Midpoint indicators	
Damage to human health	Particulate matter formation	Photochemical oxidant formation
	Human toxicity	Human health
Damage to ecosystem diversity	Agricultural land occupation	Marine ecotoxicity
	Terrestrial ecotoxicity	Freshwater eutrophication
	Terrestrial acidification	ecosystems
Damage to resource availability	Fossil fuel depletion	Mineral resource depletion

Table 4 Factor analysis results

Rotated component matrix			
Criteria	Component		
	1	2	3
C1	.901		
C2			.873
C3	.833		
C4	.879		
C5	.610		
C6		.970	
C7	.901		
C8	.838	.503	
C9	.828		
C10	.907		
C11		.897	
C12	.561	.825	
C13	.821		
C14		.879	
C15			.910
C16	.675	.654	
C17	.844		

The principal component analysis is used as the extraction method and the varimax with Kaiser normalization is used as the rotation method where the rotation converged in 5 iterations

sulfate binder. Anhydrite floor has higher thermal conductivity allowing you to reduce heat input vs. heat output.

- **Cement cast plaster floor [CH]:** The Cement cast plaster floor, which in this case, Switzerland database module [CH] is used, consists of a mortar layer lying on top of a thermal or on an insulation layer. The process of building flooring includes mixing of the raw materials (Portland cement, sand, and water), casting (pumping or by bucket), ramming, and finishing. The output of this unit process is the Cement cast plaster as floor covering.
- **Cement cast plaster floor [RoW]:** The Cement cast plaster floor, which in this case, the Rest-of-the-World database module [RoW], is used consists of a mortar layer lying on top of a thermal or on an insulation layer. The process of building flooring (As in the previous case) includes mixing of the raw materials (Portland cement, sand, and water), casting (pumping or by bucket), ramming, and finishing. The output of this unit process is the Cement cast plaster as floor covering. (The difference between these two products is in the environmental databases and the geographical range that is being used).
- **Cement tile:** Cement tiles or hydraulic tiles are colorful handmade tiles used as floor tiling. In the case of construction covering systems, Cement tile production involves inputs such as clay, concrete, and water. Cement tile used as floor coverings. It derives its durability from the combination of finely dehydrated ground Portland cement layer and a coarser layer of sand and cement. The pigment layer is hydraulically pressed into the surface and becomes a part of the tile.

Comparing four products

We wish to compare different construction coverings. Given endpoint categories, relative contributions to environmental impacts of 10 kg construction coverings are given in Fig. 5. SimaPro software sets products with the highest impact on the environment as 100%, and the impact percentage of remaining products is set based on the product with the highest impact to compare products in each category. Consider, for example, cement tile [RoW] that has the highest impact on

Table 5 Input and output description

Criteria		Descriptions	Abbreviations
Inputs	Resources	Metal depletion	MD
		Fossil depletion	FD
Undesirable outputs	Human health	human health	CCHH
		Human toxicity	HT
		Photochemical oxidant formation	POF
		Particulate matter formation	PMF
	Ecosystems	ecosystems	CCE
		Terrestrial acidification	TA
		Freshwater eutrophication	FE
		Terrestrial ecotoxicity	TE
		Marine ecotoxicity	ME
		Agricultural land occupation	ALO
Desirable output		Weight of each product	

Table 6 Dataset

Product number	Resources		Human health				Ecosystems					
	MD	FD	CCHH	HT	POF	PMF	CCE	TA	FE	TE	ME	ALO
1	2.83E−04	1.22E−01	5.08E−06	3.16E−07	3.70E−10	1.17E−06	2.88E−08	6.06E−11	1.54E−11	1.84E−11	1.12E−12	6.70E−10
2	4.72E−04	1.22E−01	4.88E−06	2.97E−07	3.37E−10	7.21E−07	2.76E−08	4.34E−11	1.69E−11	1.44E−11	1.03E−12	1.03E−09
3	5.48E−03	1.69E−01	5.70E−06	6.44E−07	4.87E−10	3.24E−06	3.23E−08	1.33E−10	4.43E−11	5.88E−11	4.59E−12	1.29E−08
4	1.70E−03	1.49E−01	5.46E−06	6.96E−07	4.49E−10	3.44E−06	3.09E−08	1.25E−10	5.69E−11	5.18E−11	3.74E−12	1.29E−08
5	2.57E−02	1.02E−01	3.18E−06	7.08E−07	3.11E−10	2.48E−06	1.80E−08	6.93E−11	3.98E−11	8.61E−11	4.50E−12	1.52E−08
6	7.44E−01	5.46E−01	1.78E−05	2.43E−05	2.91E−09	1.55E−05	1.01E−07	8.52E−10	7.14E−10	8.52E−10	2.30E−10	1.89E−08
7	7.14E−01	5.03E−01	1.81E−05	2.36E−05	2.86E−09	1.56E−05	1.02E−07	8.43E−10	7.00E−10	8.16E−10	2.20E−10	1.68E−08
8	6.42E−01	6.08E−01	1.96E−05	7.26E−06	2.11E−09	1.08E−05	1.11E−07	4.82E−10	3.68E−10	2.52E−10	5.17E−11	8.42E−09
9	6.27E−01	6.97E−01	2.02E−05	1.66E−05	2.80E−09	1.43E−05	1.15E−07	8.11E−10	5.25E−10	3.29E−10	2.36E−10	1.31E−08
10	5.97E−01	3.32E−01	1.15E−05	1.55E−05	2.07E−09	1.15E−05	6.51E−08	6.20E−10	4.93E−10	2.39E−10	2.26E−10	1.22E−08
11	1.59E+00	1.58E+00	5.93E−05	7.40E−05	8.13E−09	4.28E−05	3.36E−07	2.35E−09	2.07E−09	4.08E−09	3.14E−10	4.94E−08
12	2.14E−03	3.94E−01	1.74E−05	8.53E−07	1.33E−09	3.78E−06	9.84E−08	2.04E−10	5.47E−11	8.99E−11	5.36E−12	1.93E−08
13	1.88E−03	3.84E−01	1.74E−05	8.09E−07	1.33E−09	3.70E−06	9.85E−08	2.01E−10	5.20E−11	8.25E−11	4.86E−12	1.96E−08
14	2.54E−03	3.40E−01	1.73E−05	1.22E−06	1.31E−09	4.71E−06	9.77E−08	1.94E−10	1.02E−10	7.08E−11	7.28E−12	2.06E−08
15	3.83E−03	2.04E−01	1.26E−05	7.11E−07	9.75E−10	2.10E−06	7.15E−08	1.04E−10	5.06E−11	6.27E−11	1.23E−11	2.00E−08
16	2.36E−03	3.96E−01	1.72E−05	8.72E−07	1.28E−09	3.77E−06	9.72E−08	2.04E−10	5.73E−11	8.42E−11	5.61E−12	1.91E−08
17	2.86E−03	3.63E−01	1.71E−05	1.19E−06	1.27E−09	4.55E−06	9.66E−08	1.98E−10	9.60E−11	7.51E−11	7.49E−12	1.99E−08
18	3.95E−03	2.43E−01	1.31E−05	7.74E−07	9.81E−10	2.36E−06	7.41E−08	1.21E−10	5.48E−11	6.73E−11	1.29E−11	1.94E−08
19	2.23E−03	3.96E−01	1.73E−05	8.66E−07	1.32E−09	3.79E−06	9.82E−08	2.05E−10	5.58E−11	9.03E−11	5.51E−12	1.93E−08
20	3.53E−02	3.92E−01	1.82E−05	2.25E−06	1.44E−09	5.34E−06	1.03E−07	2.29E−10	1.32E−10	1.03E−10	1.81E−11	2.26E−08
21	2.78E−03	3.60E−01	1.72E−05	1.21E−06	1.30E−09	4.63E−06	9.75E−08	1.98E−10	9.75E−11	8.05E−11	7.53E−12	2.01E−08
22	3.30E−02	2.94E−01	1.24E−05	1.64E−06	9.53E−10	3.34E−06	7.00E−08	1.80E−10	7.15E−11	9.00E−11	1.16E−11	2.13E−08
23	4.59E−03	2.30E−01	1.15E−05	1.03E−06	8.26E−10	3.69E−06	6.49E−08	1.46E−10	8.54E−11	5.92E−11	5.71E−12	1.98E−08
24	9.38E−03	1.21E−01	7.53E−06	5.85E−07	5.44E−10	1.44E−06	4.27E−08	6.79E−11	3.99E−11	5.86E−11	3.48E−12	1.97E−08
25	1.33E−03	1.71E−01	2.97E−06	3.60E−07	3.07E−10	1.10E−06	1.68E−08	5.86E−11	2.26E−11	3.77E−11	2.11E−12	1.12E−09
26	1.48E−03	1.60E−01	2.70E−06	3.61E−07	2.87E−10	1.03E−06	1.53E−08	5.27E−11	2.33E−11	3.61E−11	2.12E−12	1.18E−09
27	2.03E−03	5.77E−02	1.84E−06	1.81E−07	1.83E−10	1.63E−06	1.04E−08	3.70E−11	1.01E−11	2.06E−11	1.47E−12	3.17E−09
28	2.67E−04	4.95E−02	1.73E−06	1.81E−07	1.64E−10	1.65E−06	9.77E−09	3.38E−11	1.30E−11	1.79E−11	1.04E−12	3.19E−09
29	3.48E−04	4.22E−02	1.47E−06	1.42E−07	1.46E−10	1.49E−06	8.33E−09	2.87E−11	8.82E−12	1.75E−11	8.17E−13	3.14E−09
30	6.89E−02	3.35E−01	8.80E−06	1.13E−06	6.70E−10	2.55E−05	4.98E−08	1.81E−10	4.35E−11	9.02E−11	8.55E−12	1.59E−09
31	9.80E−02	3.69E−01	1.00E−05	2.31E−06	8.26E−10	2.63E−05	5.67E−08	2.24E−10	8.19E−11	1.17E−10	1.91E−11	5.97E−09
32	3.98E−04	4.18E−02	3.41E−06	1.59E−07	2.01E−10	6.61E−07	1.93E−08	3.05E−11	1.10E−11	1.13E−11	7.58E−13	1.03E−09
33	3.91E−03	3.48E−02	2.65E−06	1.87E−07	1.63E−10	5.57E−07	1.50E−08	2.58E−11	9.99E−12	1.26E−11	1.30E−12	2.89E−09
34	3.16E−04	3.12E−02	2.54E−06	1.25E−07	1.47E−10	4.83E−07	1.44E−08	2.25E−11	8.18E−12	1.06E−11	6.37E−13	2.78E−09
35	4.09E−04	1.92E−02	2.12E−06	9.36E−08	1.16E−10	3.05E−07	1.20E−08	1.55E−11	6.27E−12	9.71E−12	5.28E−13	2.75E−09
36	2.26E−03	6.36E−02	3.81E−06	2.35E−07	2.45E−10	8.37E−07	2.16E−08	4.35E−11	1.35E−11	2.11E−11	1.67E−12	3.27E−09
37	4.44E−04	5.55E−02	3.70E−06	2.26E−07	2.25E−10	8.62E−07	2.09E−08	4.02E−11	1.63E−11	1.83E−11	1.18E−12	3.25E−09
38	6.21E−04	3.57E−02	3.01E−06	1.55E−07	1.75E−10	5.11E−07	1.70E−08	2.77E−11	1.04E−11	1.69E−11	8.56E−13	3.17E−09
39	2.08E−03	4.81E−02	1.24E−06	1.52E−07	1.45E−10	8.53E−07	7.00E−09	2.97E−11	7.81E−12	1.94E−11	1.31E−12	3.06E−09
40	2.48E−04	4.00E−02	1.12E−06	1.44E−07	1.27E−10	8.81E−07	6.36E−09	2.65E−11	1.06E−11	1.67E−11	8.30E−13	3.07E−09
41	1.91E−02	3.57E−01	6.81E−06	1.30E−06	7.21E−10	2.92E−06	3.85E−08	1.52E−10	7.52E−11	8.59E−11	1.27E−11	3.09E−09

human health. Its effect is set as 100%, and the impacts of other products are set 59%, 73%, and 50%, respectively. For the endpoint category of the ecosystem, for 4 selected products, ratios are 100%, 70%, 84%, and 44%, respectively. It is seen that in the ecosystem category, anhydrite floor [RoW] (49%) has the lowest environmental impact, and cement tile [RoW] (100%) has the highest environmental impact.

Figure 6 shows the environmental impacts of 10 kg of construction coverings based on midpoint indicators. It shows that, for example, in climate change (HH), anhydrite floor has the least environmental impact (34%), and cement tile [RoW] has the most impact (100%). Cement cast plaster floor [RoW] (74%) has the second-highest environmental impact. Due to higher CO_2 emission, this product has a more detrimental impact on the environment than the cement cast plaster floor [CH] (62%). Therefore, midpoint categories, including ozone depletion, photochemical oxidant formation, marine ecotoxicity, terrestrial ecotoxicity, freshwater eutrophication, and terrestrial acidification, are insignificant.

Managerial implications

Mathematical models provide important information that can be used by managers in making strategic and operational decisions. Joint consideration of multiple criteria and life cycle assessment complicate product evaluation. One of the popular methods for assessing the environmental performance of construction floor coverings is DEA. Classical DEA models cannot rank DMUs and assume that inputs and outputs are desirable. This is far beyond the real situation. In fact, in the real-world, some factors are undesirable. Our proposed DEA model can evaluate the performance of products and presents a complete ranking in the presence of undesirable data. Our DEA model uses information obtained by the LCA process. SimaPro 8.3 software is used to analyze cradle to grave life cycle of construction coverings. Inputs and outputs of products such as anhydrite floor are obtained from Ecoinvent 3 database. Every activity in Ecoinvent has a geographical location. Geographical locations are abbreviated. For instance, Switzerland is abbreviated as CH.[3] ReCiPe method is also applied. This method converts results in some indicators. One analysis is based on endpoint indicators, and the other is based on midpoint indicators. Endpoint indicators tend to be more uncertain, and midpoint indicators tend to have a shorter perspective. For both, hierarchical approaches, along with average weights, are used (Anthony et al. 2019; Biswas et al. 2019). Given the results, the human health category has a major contribution to environmental impacts. Climate change (HH), ozone depletion, human toxicity, particulate matter, and photochemical oxidant formation are consequences of environmental damages. Furthermore, all products have the same trend for other midpoint categories.

By performing LCA analysis on the four best products by DEA model, the following results are obtained. Overall, the cement tile [RoW] has the highest impact in all categories. Cement cast plaster floor [CH] and cement cast plaster floor [RoW] have a moderate impact. Anhydrite floor [RoW] is the most environmentally friendly product. Results show that in the human health category, anhydrite floor has the lowest impact, and cement tile has the highest impact. In the ecosystem quality category, cement tile has the highest impact, and anhydrite floor has the lowest impact. In the resources

[3] Confoederatio Helvetica (CH)

Table 7 Results

Product number	General case		Human health case		Ecosystem case	
	Score	Rank	Score	Rank	Score	Rank
1	1.078	4	0.493	12	1.118	3
2	0.716	11	0.424	13	0.726	11
3	0.180	22	0.173	20	0.164	22
4	0.200	19	0.207	18	0.192	19
5	0.247	17	0.250	17	0.208	18
6	0.044	40	0.036	39	0.043	40
7	0.045	39	0.037	38	0.045	39
8	0.064	37	0.039	37	0.065	37
9	0.048	38	0.034	40	0.050	38
10	0.069	36	0.055	36	0.069	35
11	0.015	41	0.012	41	0.015	41
12	0.108	28	0.107	26	0.113	28
13	0.113	27	0.112	24	0.119	25
14	0.098	31	0.095	30	0.103	31
15	0.128	23	0.128	21	0.122	24
16	0.107	30	0.104	28	0.111	30
17	0.097	32	0.093	31	0.100	32
18	0.120	24	0.119	23	0.114	27
19	0.107	29	0.105	27	0.111	29
20	0.069	35	0.059	35	0.067	36
21	0.096	33	0.093	32	0.099	33
22	0.096	34	0.087	33	0.088	34
23	0.119	25	0.112	25	0.117	26
24	0.183	21	0.178	19	0.166	21
25	1.000	9	0.341	16	1.000	9
26	1.017	7	0.357	15	1.013	7
27	0.607	14	0.525	10	0.593	14
28	0.778	10	0.749	6	0.824	10
29	1.002	8	0.808	4	1.003	8
30	0.222	18	0.095	29	0.226	17
31	0.116	26	0.077	34	0.123	23
32	1.104	3	0.636	7	1.156	2
33	0.614	13	0.536	9	0.601	13
34	1.019	6	1.023	3	1.029	6
35	1.272	1	1.334	1	1.236	1
36	0.439	16	0.380	14	0.435	16
37	0.524	15	0.521	11	0.554	15
38	0.641	12	0.628	8	0.641	12
39	1.024	5	0.775	5	1.036	5
40	1.148	2	1.195	2	1.105	4
41	0.189	20	0.121	22	0.189	20

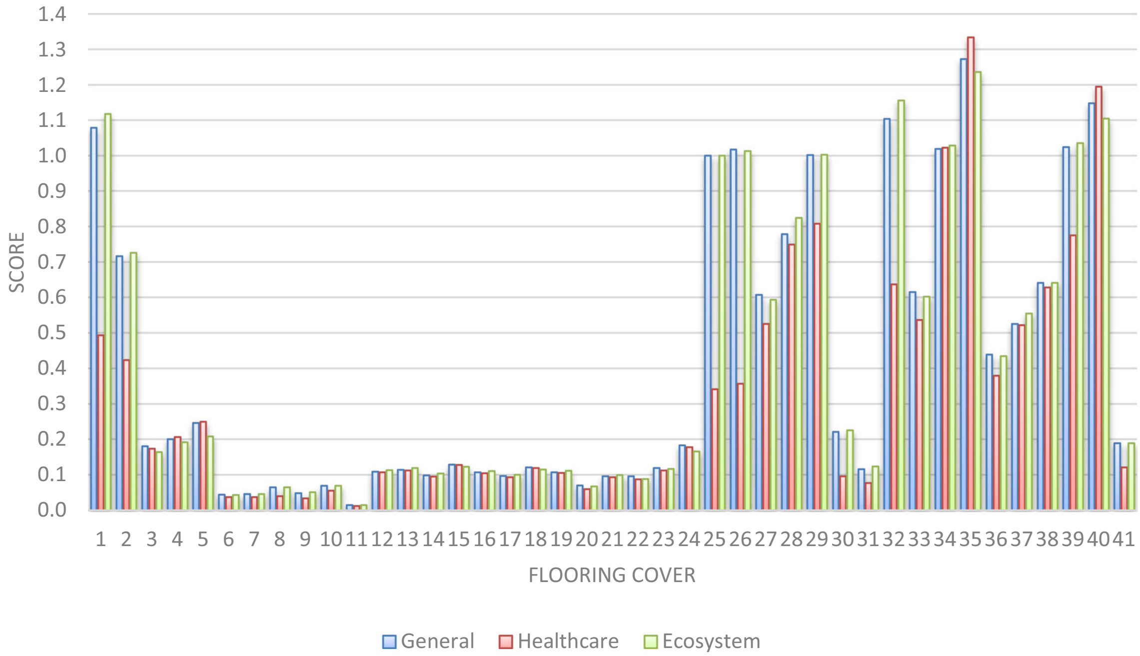


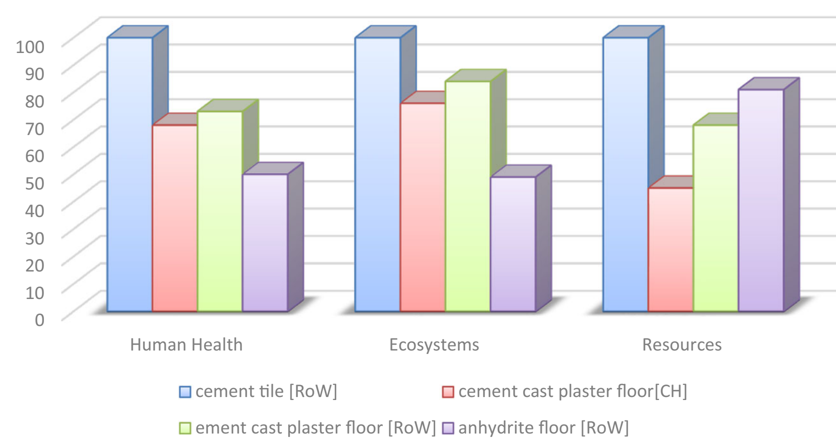
Fig. 4 DEA results for general, healthcare, and ecosystem cases

category, cement tile has the highest environmental impact. Cement cast plaster floor [CH] has the second-highest environmental impact, followed by cement cast plaster floor [RoW] and anhydrite floor. Cement cast plaster floor [CH] has less environmental impact than the cement cast plaster floor [RoW]. This implies that the anhydrite floor has the lowest impact. A surprising result from this comparison is that the anhydrite floor has the second-highest impact on mineral depletion and resource depletion.

Conclusions

Identification of the most appropriate construction floor covering systems based on environmental impact analysis is an important concern in the construction industry. Life cycle assessment plays a vital role in assessing both energy and environmental effects in the construction industry and is recognized as a valuable tool in support of sustainable construction industries. On the other hand, data envelopment analysis is a mathematical programming method that has been widely applied for assessing the performance of firms and options. We identified key performance criteria for evaluating alternative construction floor covering systems and evaluated these alternative floor coverings with DEA and LCA. Given the LCA method, 41 types of construction coverings and 18 main criteria were obtained. To rank these products and choose the most suitable one, DEA was applied. To this end, a new version of the modified DEA ERM model under VRS was proposed. The new model was non-radial and had some good properties. It was observed that some of the obtained criteria were undesirable, and we extended our proposed DEA model to deal with such data. Also, factor analysis was run on the data for a decreasing number of criteria to obtain more

Fig. 5 Normalized results for 10 kg construction coverings based on endpoint categories



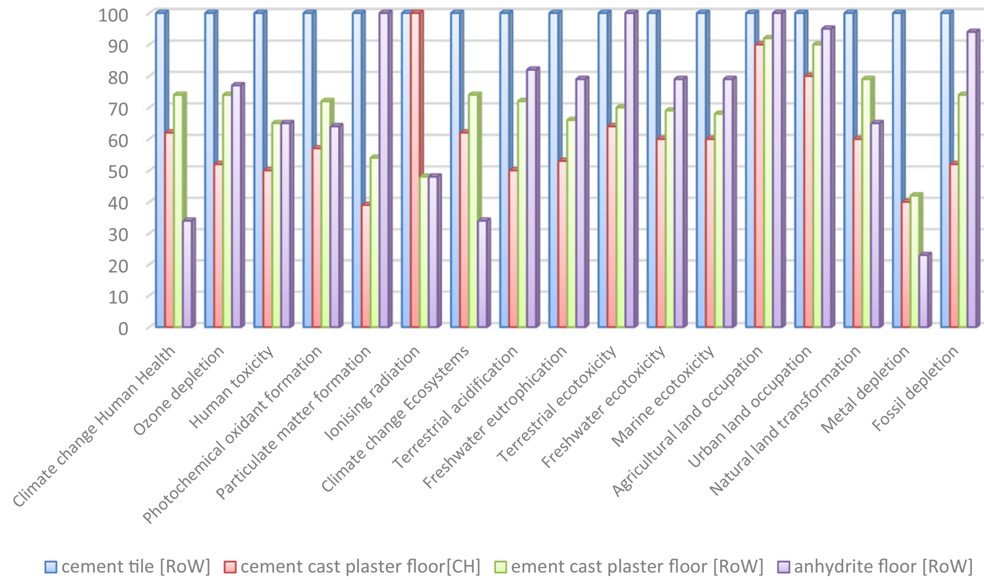


Fig. 6 Normalized results for 10 kg construction covering based on midpoint categories

reasonable results. In this way, two inputs, ten undesirable outputs, and one desirable output were selected for assessing the performance of products. We analyzed these selected products using our proposed DEA model given three main aspects, i.e., human health case, ecosystem case, and both. Because of the capabilities of the LCA methodology and to analyze the best product from the environmental viewpoint, we compared the four best construction coverings using LCA in the second stage. SimaPro software was set product with the highest impact on the environment as 100%, and the impact percentage of remaining products was set based on the product with the highest impact to compare products in each category.

The analyses showed that cement tile has the highest impact on the environment in all the categories. Anhydrite floor had the second-highest impact. It was found that the resources damage category is the main issue for all the discussed products. Therefore, it is recommended to have more studies in this area. Also, our method can be applied to other building components. As well, the following researches can be done based on the results of this paper:

- Since there might be numerous DMUs, similar work can be repeated using a fuzzy inference system to decrease the number of DMUs.
- Similar models can be developed in the presence of fuzzy data and stochastic data.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

Appendix

In this appendix, we quantify the potential environmental impacts of construction coverings and to compare environmental impacts. We consider all stages of building life cycle. Ecoinvent 3 database is used. Tables 8 and 9 depict LCI.

Table 8 Inputs (raw materials) for 10 kg construction coverings

Inputs (raw materials)	Unit	Anhydrite floor	Cement cast plaster floor [CH]	Cement cast plaster floor [RoW]	Cement tile
Coal, hard	kg	0.165	0.113	0.139	0.193
Coal, brown	kg	0.098	0.045	0.093	0.050
Oil, crude	kg	0.055	0.044	0.037	0.123
Gas, natural	M^3	0.067	0.012	0.027	0.035
Energy, gross calorific value	MJ	1.482	1.285	1.301	0.487
Energy, potential (in hydropower reservoir)	MJ	0.314	0.512	0.035	0.047
Energy, kinetic (in wind)	MJ	0.052	0.027	0.270	0.368
Energy	%	28.055	13.326	16.781	18.426

Table 9 Outputs (emissions) for 10 kg construction coverings

Outputs (emissions)	Unit	Anhydrite floor (RoW)	Cement cast plaster floor [CH]	Cement cast plaster floor [RoW]	Cement tile
Carbon dioxide, fossil	kg	7.2425E−01	1.4724E+00	1.7570E+00	2.3745E+00
Nitrogen oxides	kg	2.9085E−03	3.1948E−03	3.1948E−03	4.3985E−03
Sulfur dioxide	kg	2.5343E−03	1.1609E−03	1.9457E−03	2.6166E−03
Particulates, > 2.5 μm, and < 10 μm	kg	1.2497E−03	2.0077E−04	7.6080E−04	1.0362E−03
Particulates, < 2.5 μm	kg	9.6610E−04	1.8142E−04	5.0385E−04	7.0477E−04
Particulates, > 10 μm	kg	3.5512E−03	5.7595E−04	2.4208E−04	3.2453E−04
Benzo(a) pyrene	kg	9.3519E−09	4.2786E−09	4.9676E−09	5.3900E−09
Benzene	kg	6.4585E−06	2.7348E−06	3.9075E−06	3.8351E−06
Arsenic	kg	7.6938E−08	9.7513E−08	4.5397E−08	6.0722E−08
Lead	kg	4.4603E−07	2.2808E−07	3.4687E−07	4.2935E−07
Nickel	kg	6.1049E−07	2.0007E−07	2.2021E−07	2.5958E−07
Mercury	kg	1.4421E−08	2.3042E−08	6.1861E−08	8.3208E−08
Polycyclic aromatic hydrocarbons (PAH)	kg	7.1936E−08	3.4901E−08	4.7546E−08	7.5395E−08
Non-methane volatile organic compounds (NMVOC)	kg	3.0710E−04	2.3922E−04	2.8581E−04	3.8975E−04
Furan	kg	5.3956E−08	5.9877E−08	4.8020E−08	1.5394E−08
Ozone	kg	2.0479E−06	1.8475E−06	1.2639E−06	1.7364E−06
Hydrogen chloride	kg	1.1050E−04	1.2908E−05	4.4606E−05	6.3432E−05
Heat, waste	kg	3.1571E−01	3.1738E−01	5.8145E−01	3.8284E−01
Water emissions					
BOD5[1]	kg	1.2943E−03	8.6249E−04	1.3574E−03	1.3560E−03
COD[2]	kg	2.5323E−03	2.0608E−03	2.5577E−03	1.6172E−03
DOC[3]	kg	1.6592E−03	1.5137E−03	1.6641E−03	6.9218E−04
TOC[4]	kg	1.6610E−03	1.5147E−03	1.6656E−03	6.9394E−04
Heat, waste	MJ	7.8280E−02	7.8711E−02	7.8229E−02	6.1770E−03

[1] Biological oxygen demand (5 days)

[2] Chemical oxygen demand

[3] Dissolved organic carbon

[4] Total organic carbon

Life cycle inventory (LCI)

Data in Tables 8 and 9 are complemented by LCI data in *SimaPro 8.2* software. Figure 7 represents a snapshot of the map for 10 kg construction coverings (*SimaPro* software).

As Table 8 shows in Appendix 1, raw materials related to energy (28.05%) are more than two times of (13.32%). Environmental impacts of cement tile [RoW] are mainly due to emission of CO_2 with 2.37 kg. Environmental impacts of cement cast plaster floor [RoW], cement cast plaster floor [CH], and anhydrite floor [RoW] for each 10 kg are 1.75 kg, 1.47 kg, and 0.72 kg, respectively. As a result, there is a significant increase in energy consumption for anhydrite floor [RoW] (1.48 MJ) compared with cement tile [RoW] (0.49 MJ), cement cast plaster floor [RoW] (1.30 MJ), and cement cast plaster floor [CH] (1.29 MJ).

Life cycle impact assessment for selected products

Given endpoint and midpoint categories, environmental impacts of cement tile [RoW], cement cast plaster floor [CH], cement cast plaster floor [RoW], and anhydrite floor [RoW] are shown in Fig. 8 to Fig. 15.

Anhydrite floor Figure 8 displays normalized results for anhydrite floor and includes endpoint categories (human health, ecosystem, and resources). It is evident that resources with 0.0012 are the main contributors, and the second contributor is the human health impact category (0.0005). The most important result that can be seen in Fig. 9 is that the midpoint categories including climate change (HH), human toxicity, particulate matter, climate change (E), agricultural land occupation, mineral resource, and fossil fuel depletion are main

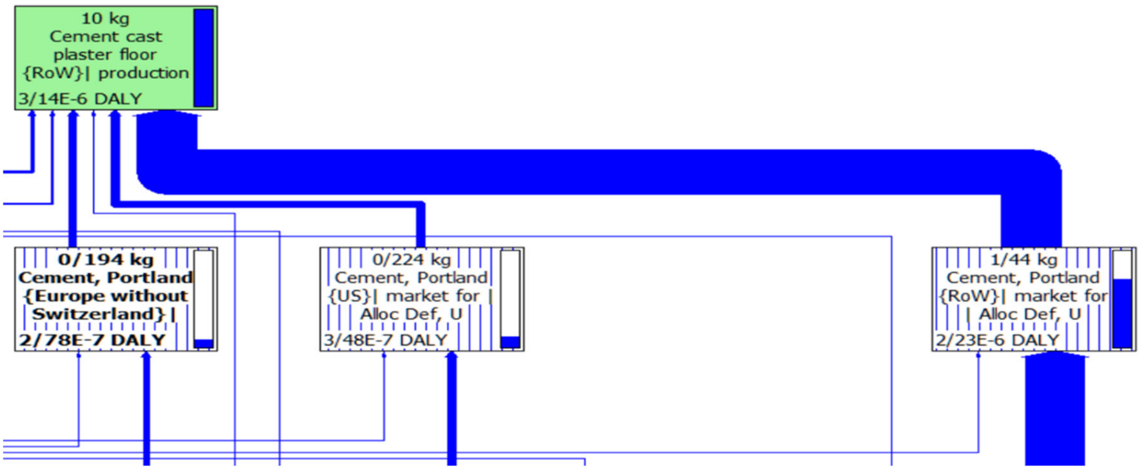


Fig. 7 A snapshot of the map for 10 kg (SimaPro software)

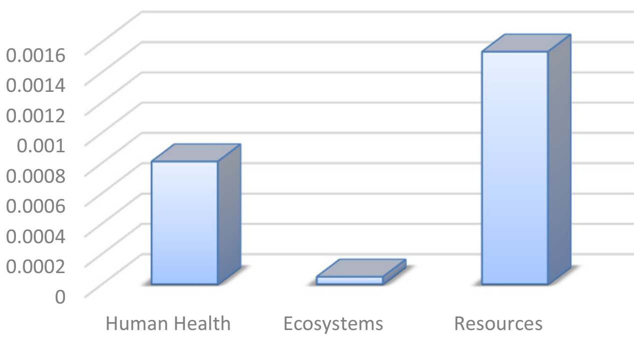
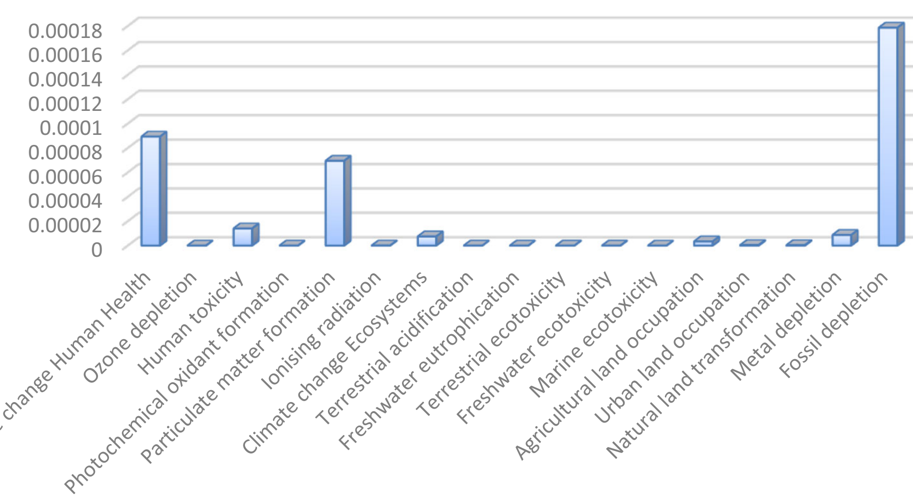


Fig. 8 Results of endpoint categories for 10 kg anhydrite floor [RoW]

Fig. 9 Normalized results for 10 kg anhydrite floor [RoW] based on midpoint categories



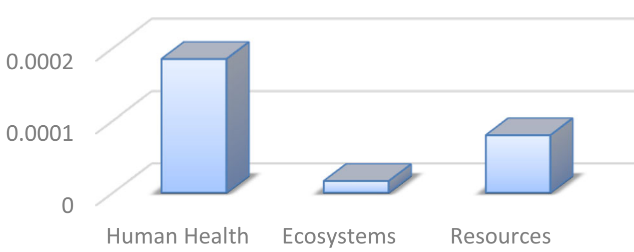
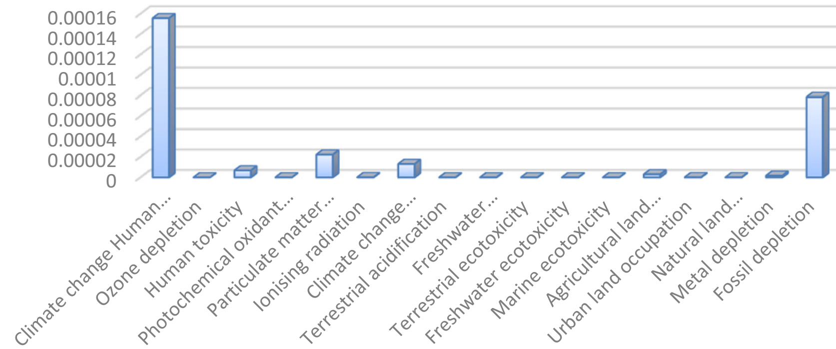


Fig. 10 Normalized results for 10 kg cement cast plaster floor[CH] based on endpoint categories

reasons of environmental impacts. Results of anhydrite floor are included in the third column of Tables 8 and 9.

Cement cast plaster floor [CH] Figure 10 shows normalized results based on endpoint categories for the cement cast plaster floor [CH]. Figure 10 clearly shows that human health (0.00016) is accountable for the main impacts. Ecosystems are insignificant for the cement cast plaster floor [CH]. It is about 0.0002 and is less than 0.001% for all

Fig. 11 Normalized results for 10 kg cement cast plaster floor [CH] based on midpoint categories



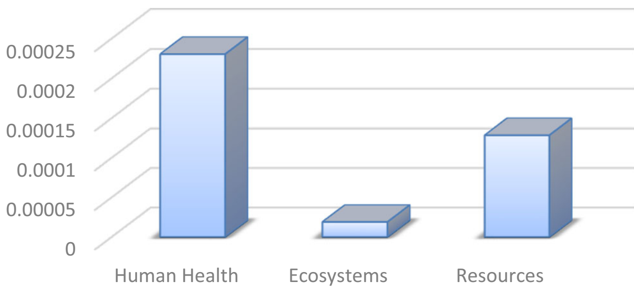
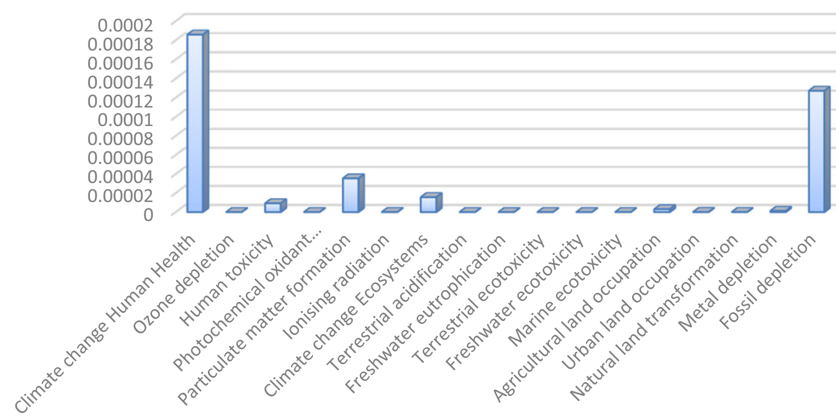


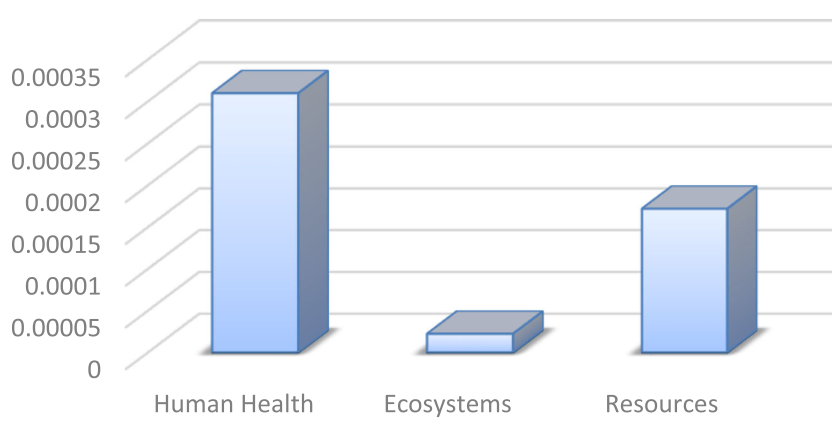
Fig. 12 Normalized results for 10 kg cement cast plaster floor [RoW] based on endpoint categories

Fig. 13 Normalized results for 10 kg cement cast plaster floor [RoW] based on midpoint categories



categories. Also, Fig. 11 displays normalized results based on midpoint categories for the cement cast plaster floor [CH]. Results are included in the fourth column of Tables 8 and 9.

Fig. 14 Normalized results for 10 kg cement tile [RoW] based on endpoint categories



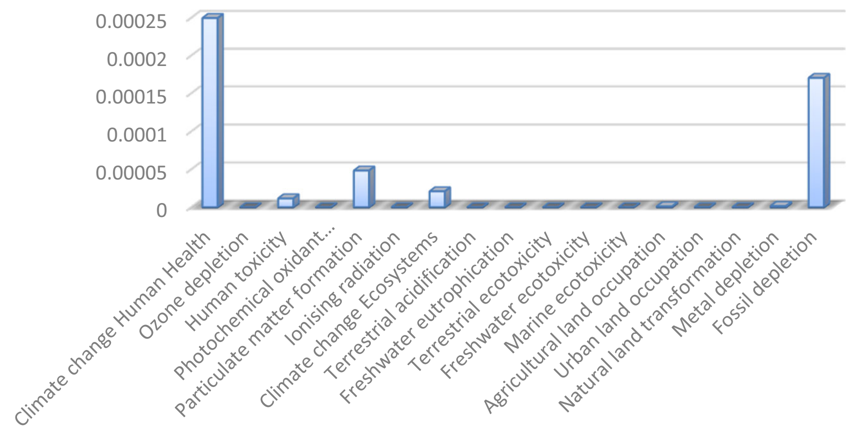


Fig. 15 Normalized results for 10 kg cement tile [RoW] based on midpoint categories

Cement cast plaster floor [RoW] Figure 12 shows normalized results based on endpoint categories for the cement cast plaster floor [RoW]. It clearly shows that human health (0.00013) is accountable for the main impacts. Ecosystems are insignificant for this product**.** The results of midpoint categories for this product are also included in Fig. 13. It shows that ozone depletion, photochemical oxidant formation, marine ecotoxicity, terrestrial ecotoxicity, freshwater eutrophication, and terrestrial acidification are insignificant for this product. Results for this product are included in the fifth column of Tables 8 and 9.

Cement tile [RoW] Figure 14 demonstrates normalized results based on endpoint categories for cement tile [RoW]. The environmental impacts of this product include human health (0.00022), ecosystem (0.00012), and resources (0.00018). Figure 15 depicts normalized results based on midpoint categories. It shows that impacts from cement tile [RoW] for some categories are still negligible and are also the same as three previous products. The results of this product are in the sixth column of Tables 8 and 9.

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