Enhancing Life Cycle Assessment for Circular Economy Measurement of Different Case Scenarios of Modular Steel Slab

*Prince Antwi-Afari
pantwiaf@connect.hku.hk
Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong
*Corresponding author

S. Thomas Ng
thomasng@cityu.edu.hk
Department of Architecture and Civil Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon Tong, Hong Kong

Ji Chen
jichen@hku.hk
Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong

Benjamin I. Oluleye
benjamin.oluleye@connect.polyu.hk
Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

Maxwell F. Antwi-Afari
m.antwiafari@aston.ac.uk
Department of Civil Engineering, College of Engineering and Physical Sciences, Aston University, B4 7ET, Birmingham, UK

Benjamin K. Ababio
bababio@connect.hku.hk
Department of Real Estate and Construction, The University of Hong Kong, Pokfulam, Hong Kong

Abstract

Life cycle assessment (LCA) has emerged as an essential method to evaluate materials' environmental impact. However, using LCA for assessing other dimensions of circular economy (CE), such as the technical, social, system, and functional dimensions, is fraught with several challenges. In this study, the LCA system boundary was extended to cradle-to-cradle and combined with the predictive building systemic circularity indicator to determine the environmental, technical, functional, and system dimensions of different case scenarios of the product system of a modular steel slab of a residential building in China. It was identified that the base scenario of the case slab could lead to about 50.4% of the mass of the slab being recyclable at EoL. In comparison, 0%, 70.8%, and 38.8% of the mass of the slab being recyclable were recorded for case scenarios one to three, respectively. The environmental impact of the scenarios showed that the base scenario would induce 38.64 kg CO_2 / m^2 in global warming potential, while 68.2, 28.2, and 44.95 kg CO_2 / m^2 were noted for case scenarios one to three, respectively. The simple additive weighting method was used to select the optimal scenario for the product system of the case slab. Adopting the optimal scenario for the case slab should lead to positive impacts and high recoverability at EoL. Implementing this iterative integrative method for assessing product systems enables considering the environmental, technical, systems, and functional dimensions of CE in assessments, which should lead to inclusive, sustainable decision-making.

Keywords: Life Cycle Assessment, Circular Economy, Cradle-to-Cradle, Construction Industry, Modular building, Steel Slab

1. Introduction

The construction industry (CI) is well-known for its effects on the environment, including high energy consumption, massive waste production, excessive greenhouse gas emissions, and depletion of natural resources [1]. However, the advent of the circular economy (CE) concept could decouple the production system of industries, including the CI, to reduce its effects on the environment through a restorative and regenerative design process [2]. Furthermore, adopting total/systemic circularity in the CI should also enhance the reduction of natural resource consumption through efficient nutrient cycling systems, closed-loop supply chains, and digitalized end-of-life (EoL) waste management schemes [3]. However, appreciating the implementation of CE principles within the CI would require an effective methodological tool that should evaluate the environmental, functional, systems, and technical implications of decisions across materials/product systems.

Life cycle assessment (LCA) is a crucial scientific methodological tool used to evaluate the environmental impacts of materials. However, its effectiveness in assessing the circularity of materials is hampered by several challenges, such as lack of practical application at the design and development stage, challenges with system boundaries and allocation of impacts, inability to assess the social implication of materials, and biases and inconsistency with results [4, 5]. Antwi-Afari *et al.* [6] also reviewed several circularity indicators which could be adopted to assess the various dimensions of CE in assessments. The study purported that considering only one indicator or method to assess the impacts of circularity across multiple dimensions was not feasible. However, a combination of different indicators or methods could suffice to assess some critical dimensions of CE.

Existing methodological approaches of extant studies have been on combining industrial ecology methods such as LCA, life cycle cost (LCC), social LCA (SLCA), material flow analysis (MFA), and input-output analysis (IOA) to assess the impacts of things across product lifecycles. For example, Meglin et al. [7] combined LCA, MFA, and IOA to determine the economic and environmental impacts of construction materials at the regional economy level. Janjua et al. [8] also adopted a life cycle sustainability assessment (LCSA) framework to assess the environmental, cost, and social impacts of alternative materials and by-products used in residential buildings. Other studies also combine operation research methods such as analytic hierarchy process (AHP), the technique for order of preference by similarity to ideal solution and game theory with industrial ecology methods or complex science methods such as system dynamics, agent-based modeling, and discrete event simulation to understand the impacts of decisions across the environment, economic, and social dimensions of circularity assessments. For instance, Kamali et al. [9] combined AHP and LCA to develop environmental indices to determine the environmental impacts of conventional and modular residential buildings. McAvoy et al. [10] also showed how life cycle inventory could be improved by merging LCA and system dynamics to enhance impact assessments across product lifecycles.

However, irrespective of the improvement in assessments, using LCA with other indicators or methods for evaluating the environmental, functional, systems, and technical dimensions of CE, such as design and disassembly parameters, reverse cycles, system conditions, and business models, remain unexplored in the CI. Existing indicators for technical dimensions, such as material circularity indicators (MCI), circular economy toolkit, and circular economy indicator prototypes, need to be revised for long-term infrastructures such as buildings. Therefore, Verberne [11] enhanced the MCI to develop the building circularity indicators (BCI) to determine the functional, technical, and physical recovery potentials of construction materials. Cottafava and Ritzen [12] also improved the BCI to develop a predictive BCI by using the design criteria for circularity assessments and adopted it with embodied carbon (EC) and embodied energy (EE) assessments to determine the technical and environmental impact of different conventional residential buildings in Europe. Antwi-Afari *et al.* [13] further enhanced the BCI equations by using the four building blocks of CE, *viz.* circular product design, reverse cycles, system conditions, and business models with LCA to assess the environmental, technical and recovery impact potentials of a modular residential building in China.

In this study, to determine the environmental, technical, functional, and systems dimensions of different scenarios of the modular steel slab, the LCA system boundary was extended to C2C and combined with the predictive building systemic circularity indicator (PBSCI), which helps to evaluate the four building blocks CE to determine the recoverability potentials of the assessed scenarios across the product lifecycles. The extension of LCA to C2C enables the assessment of the potential impacts of reusing/recycling the materials into the next production system after the EoL. The PBSCI method quantifies the product systems' recoverability across technical, functional, and systems dimensions. Hence, combining these two methods provides a better way of making decisions between the different scenarios of the modular steel slab based on the assessed dimensions of CE in this study (Fig. 1).

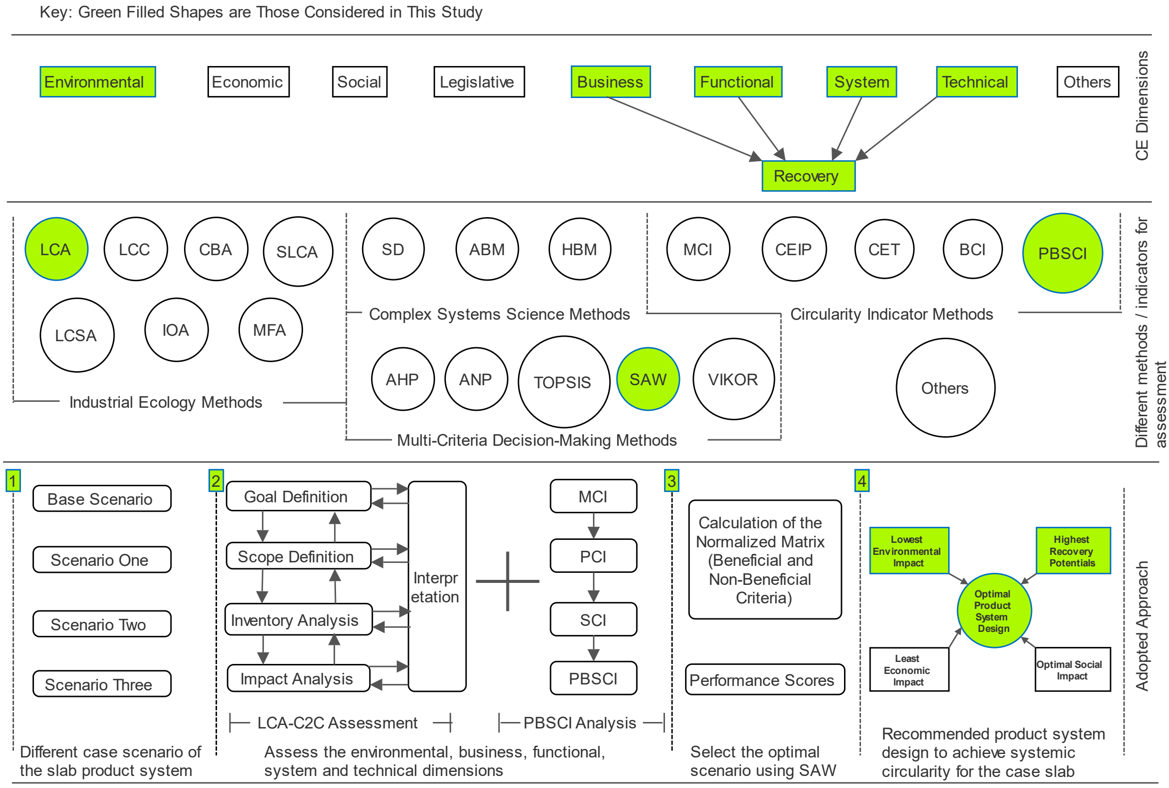


Fig. 1. Adopted Research Approach

2. Literature Review

2.1 Assessment of impact potentials of construction materials, components, or systems

Extant studies have proposed several methods which could be adopted to assess the impact potentials of construction materials, components, or systems. For example, LCA has been established as a standard scientific assessment tool used to determine the environmental impact potentials of things. LCA could be interpreted through different impact categories using different impact assessment methods based on the goal and scope of the study [14]. LCC and the SLCA should also be adopted to evaluate the economic and social impact of things. However, their usage and standardization are in constant development. Other studies also implement an integrative approach, such as adopting LCSA with building information modeling (BIM) [15], using MFA with LCA [16], or merging IOA with LCA or life cycle energy analysis to make decisions on the impact potentials of construction materials, components, or systems [17].

For example, to make decisions on the impact potentials of plastic wastes and their EoL management, Hossain *et al.* [18] conducted a study on the different plastic waste management strategies which should be adopted in Hong Kong. LCA was used in the study to assess the environmental impact of the various waste management strategies toward selecting the most sustainable approach to be adopted. Industrial incineration of plastic wastes was seen as the most sustainable strategy leading to savings of 2256 kg CO_2 eq in climate change. The study led to the formulation of strategic plastic waste management plans and guidelines that should be implemented in Hong Kong to curb its plastic waste problem. To assess and select the most sustainable materials for high-performance buildings, Carvalho *et al.* [19] also adopted LCA, LCC, and BIM to enhance the consideration of the cost and impact potentials of materials from the beginning of life (BoL) / design stage of construction. Adopting this approach helps automate the LCA and the LCC process from the BoL of buildings to reduce assessment errors and delays. The final decision on the best scenario considering equal importance for both cost and environmental impact dimensions was the scenario with the highest environmental impact performance (98.03 global LCA score) and cost-effectiveness (17.90 global LCC score) among the assessed scenarios.

Zhan *et al.* [20] adopted a hybrid LCA (IOA-LCA) to quantify the EC and EE of an urban conventional residential building in China. The EC and EE of the case building from cradle-to-grave (C2G) were 2983.87 kg CO_2 / m^2 and 17.14 GJ / m^2, respectively. The study opined that hybrid LCA should enhance the quantification of building materials' emissions to provide adequate input data for ecocity development. LCA was also used to evaluate the emission reduction potentials of cross-laminated timber for residential buildings compared to reinforced concrete. The cradle-to-gate (C2Ga) comparative assessments of the case buildings showed that timber reduces EC by 25% compared to concrete for residential buildings [21]. The eight floors of cross-laminated timber buildings had an EC and EE of 221.34 kg CO_2 / m^2 and 1.93 GJ / m^2, respectively. The study helped to accelerate policies for timber construction and propose pathways to optimize the timber supply chain to reduce its environmental impacts further.

Dauletbek and Zhou [22] also employed a BIM-based LCA to evaluate the environmental potentials, cost-effectiveness, and energy efficiency of retrofitting existing buildings. The study used real-monitored data to decide on the recycling and reusability of the materials and their potential impact. The study concluded that materials with high recycling potentials but low cost should be adopted to enhance energy efficiency in retrofitted buildings. A BIM-based

LCA approach was also adopted to automate the EC and EE assessments of a semi-prefabricated residential building in Hong Kong. The C2G EC and EE of the 40floors reinforced concrete case building (40% by volume prefabricated) was 4141.70 kg CO_2 / m^2 and 30.22 GJ / m^2, respectively. The use of the BIM-based LCA approach enhanced the robustness of the assessment. However, to lessen emissions from the transportation of modules, map applications, and detailed case-specific site surveys are commended [15].

Francis and Thomas [23] assessed the sustainability performance of a residential building project in India using a dynamic-based LCSA system to capture the dynamics in the building sustainability indicators while determining the building's economic, social, and environmental impact potentials. Using a dynamic LCSA showed the importance of considering the changes in materials characteristics, infrastructure, and energy mix on buildings' sustainability and environmental impacts over time. Soust-Verdaguer *et al.* [24] also integrated BIM with LCSA to estimate buildings' environmental, social, and economic potentials during the early design stage of construction. The study estimated that the use of BIM in the early design stage of buildings could determine about 60% of LCSA inventory details. In contrast, full inventory details could be determined at the complete design stages. However, the use of LCSA as a key impact potentials method is faced with several challenges, such as a lack of integration of the methods of the three dimensions of sustainability, unreliable databases for economic and social impact assessments, and difficulty in functional unit characterization.

2.2 Enhancing Methods for Circularity Assessments

Implementing CE principles across product lifecycles presents an opportunity to achieve sustainable development. Several indicators, methods, and models have been proposed in extant literature to determine the effects of CE principles on a product system. For example, Saidani *et al.* [25] reviewed 55 circularity indicators that could be applied to assess the circularity of products across system levels. The identified indicators were grouped into criteria that could be adopted to assess specific dimensions of CE. However, the complexity of CE measurement requires a robust method that should measure the impacts of the product system across several dimensions and not just a single dimension at a time. Iacovidou *et al.* [26] also reviewed several methods that could be applied to measure the circularity of materials across the product lifecycle towards developing a complex value assessment for resource recovery measurement. The study showed that existing methods need to be more robust to measure the circularity of materials without neglecting negative trade-offs.

For instance, Niero and Kalbar [27] adopted LCA to assess the relationship between LCA and C2C indicators. The use of LCA was able to show the potential positive impacts of recycling materials but needed to account for the effect of different design criteria on impact assessments. Magrini *et al.* [28] combined LCA, LCC, and SLCA to identify the economic impact of waste prevention schemes to guide the decision to employ waste prevention strategies in communities. The use of the industrial ecology methods was able to provide decisions on project prioritization based on the reduction of impacts. However, it could not show the key design criteria that should be targeted to enhance waste prevention and reuse in the project. Franklin-Johnson *et al.* [29] proposed a performance assessment indicator to assess the reusability of materials in the next production system. Adopting the indicator could provide a value-based approach for decisions on materials usage but could not account for the environmental impacts of materials at EoL. McAvoy *et al.* [10] also adopted system dynamics and LCA to improve the impact assessment of some long-term materials. This approach provides means whereby the dynamism in LCA impact assessments could be catered for in performance evaluations. However, its usage provides an extension in environmental impact assessment only and not any other dimensions of CE.

Therefore, to enhance the assessment for CE, existing studies such as Cottafava and Ritzen [12] combined EE and EC with predictive BCI to determine the impacts and recovery potentials of eight European residential buildings. Adopting this approach provided means considering the recovery potentials of the case buildings and their EE and EC after demolition. Peralta *et al.* [30] also combined the endpoint indicators of LCA and C2C to develop an enhanced assessment model to determine the impact potentials of an eco-design product. The combination of LCA and C2C enables a double-edge assessment whereby the LCA evaluates the rate of reduced adverse effects on the environment. At the same time, the C2C measurement assesses the rate of positive impacts of applying circularity principles to the product system. Eberhardt *et al.* [31] also extended the LCA system boundary to C2C and adopted the EoL allocation approach to determine the impacts of the reusability of buildings at EoL. The study opined that the material composition catalog influences the savings in environmental impact, the number of use lifecycles, and the service lifecycle of the building components. Saade *et al.* [32] also adopted MCI, LCA, and MFA to determine urban projects' circularity and environmental impacts. It was assayed that circularity indicators could be assessed alongside environmental impact indicators to provide a systemic overview of impact assessments for urban projects.

In this study, the LCA system boundary is extended to C2C to capture the potential impacts of the reuse/recycling of materials after EoL while also considering the impact indicators of C2C as a method in PBSCI assessment to determine the recovery potentials of modular steel slabs. Adopting this iterative method should help assess the environmental, functional, systems, and technical dimensions of applying circularity principles to the product system of the modular slab. Also, the use of this combined method enhances the identification of the processes in the circular design of the product, which influences its circularity and environmental impact potentials and provides guidance to the selection of alternative processes which should augment the circularity and lessen the environmental impacts of the assessed material or product system.

3. Methodology

The outline for the research is shown in Fig. 2. The LCA-C2C-PBSCI method was adopted to evaluate the different scenarios of the modular steel slab.

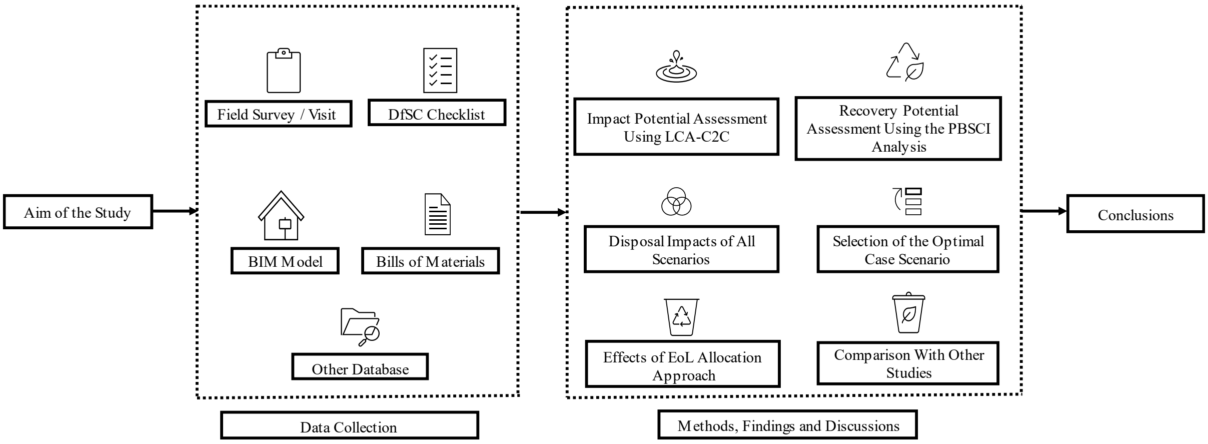


Fig. 2. Research Study Outline

3.1 LCA-C2C

LCA was adopted to assess the potential environmental impacts of the different scenarios of the modular steel slab based on ISO 14040 and ISO 14044 standards. The LCA comprises four main steps: goal and scope definition, lifecycle inventory analysis, lifecycle impact assessment, and interpretation [14, 33]. The essence of circularity means that the end-of-life reuse pathways need to be considered in the whole LCA of the modular steel slab. EN 15978 [34] opined that the system boundary of LCA needs to be extended to C2C to cater to the beyond system boundaries impacts. However, the impacts from such a phase should be reported separately. However, eliminating the beyond-system boundary impacts from the whole LCA of the modular steel slab exhibit the limitations of LCA for assessing the circularity of materials. Allocation of impacts could be adopted by using any of the EoL allocation equations, as exhibited in extant works, to overcome this barrier [35, 36]. Therefore, in this study, the system boundary of the LCA was extended to C2C to cater to the impacts of reuse/recycling of the materials at EoL while crediting the product system for potential impacts of the EoL activities. Therefore, only material-related impacts were assessed, and the attributional LCA method, which quantifies the potential environmental impact on the product system, was adopted for this study.

3.2 EoL Allocation Methods

For a C2C system boundary, the impacts from reuse, recycling, or energy recovery of the materials at EoL are modeled as avoided impacts according to EN 15978 [34] guidelines. For example, the impacts beyond the system boundary could be credited in detail for substituting virgin materials. The quantity of materials disposed of at the landfill and those recycled were modeled based on the adopted recyclability plan of the case company using the PBSCI tool. Two EoL allocation approaches were adopted to express the allocation of impacts beyond the system boundary: the 0/100 and 50/50 EoL allocation approaches. The 0/100 EoL allocation approach credits the EoL reuse pathways' impacts on the product system producing the recycled material.

In contrast, the 50/50 EoL allocation approaches equally share the impacts of the EoL reuse pathways between the product system producing recyclable materials and the next product system using recycled materials. Therefore, 0/100 was used for the whole analysis. At the same time, the effects of the adopted EoL allocation approach were shown by comparing the two EoL allocation approaches on the lifecycle of the base scenario of the case slab.

The LCA-C2C impacts for the two allocation approaches are expressed as follows:

$EI_{c2c} = EI_M + EI_P + EI_C + EI_U + EI_{EoL} + EI_{next\ production\ system}$ ---- Eq. (1) for the 0/100 allocation approach

$EI_{c2c} = EI_M + EI_P + EI_C + EI_U + EI_{EoL} + \frac{EI_{next\ production\ system}}{2}$ ---- Eq. (2) for the 50/50 allocation approach

$EI_{M,\ P,\ C,\ U,\ EoL,\ and\ next\ production\ system}$ are the environmental impacts at the material stage, production of modules, construction, use phase, EoL, and next production system, respectively.

3.3 Goal and Scope Definition

This study aims to enhance LCA to determine the potential environmental impacts of different scenarios of modular steel slabs designed for circularity and compare with different construction methods and system boundaries of LCA of extant studies. The lifespan of the modular steel slab was set to 100 years according to the specification of the prefabrication company, which used special stainless steel for producing the modular slabs, which are like the conventional honeycomb panels used in spacecraft. Furthermore, the functional unit of assessment to enable comparison with other similar studies was set at 1m^2 gross floor area per year.

3.4 Lifecycle Inventory Analysis

The lifecycle inventory stage of the LCA framework is very keen on ensuring a streamlined study that relates to the goal and scope definition. Quantitative and qualitative methods were adopted to obtain the requisite data for the study in a well-coordinated manner. The primary data for the analysis were obtained from the company's experts through ad-hoc spreadsheets of design criteria, EoL strategies, and bills of quantities of the modular steel slab. Documents from the company were examined to identify the adopted waste rates, transportation modes and distances, equipment catalogs and capacities, and the material supply chain; this helps to model the right processes in the SimaPro software v. 7 and enhances the choice of other alternatives when the local database is insufficient in modeling the actual processes. Surveys were conducted to decipher the criteria adopted in the construction processes towards achieving systemic circularity, such as the considerations for the circular product design, reverse cycles, system conditions, and adopted business models of the modular steel slabs.

The lifecycle inventory of the background system was based on the Ecoinvent database embedded in the SimaPro software [37 – 39]. The lifecycle inventory of the foreground system was modeled using the primary data obtained from the construction company for the modular slab. Data for the energy requirement for collection and sorting at the EoL phase is shown in supplementary data (Table S2), while the data on the equipment used in the production of the modular steel slab is also shown in supplementary data (Table S3). Local databases such as China Light and Power and Chinese Lifecycle Database were used as much as possible. However, where it was lacking, it was supplemented with other databases in eco-invent, such as the European Reference Life Cycle Database (ELCD) and the United States Life Cycle Inventory (USLCI).

3.5 Life Cycle Impact Assessment

The obtained data from the lifecycle inventory phase of the LCA were modeled into the SimaPro software, and the potential environmental impacts of the modular steel slab were assessed using the IMPACT 2002+ life cycle impact assessment (LCIA) method. The IMPACT 2002+ LCIA method measures 15 midpoint indicators and four endpoint indicators: human health, ecosystem quality, climate change, and resources. The problem-oriented approach factors of the adopted LCIA method are shown in supplementary data (Table S4). At the same time, the weighting and normalization factors of the four damage-oriented approach of the chosen LCIA method is also shown in supplementary data (Table S5). The problem-oriented approach uses the lifecycle inventory data to present detailed sets of impact categories, but they have less environmental meaning and are challenging to understand.

On the other hand, the damage-oriented approach presents results with more environmental and practical meaning but high uncertainty. To reduce burden-shifting, the LCA of this study was conducted using the IMPACT 2002+ LCIA method, which combines both the midpoint and endpoint impact indicators in assessments [40]. The study also considered all the midpoint impact characterization of IMPACT 2002+ in assessment. Hence, impact scores could be obtained and used based on the required results for assessment and comparison. The total impacts were expressed as a single score by applying the damage and weighting factors to compare different scenarios.

3.6 PBSCI Analysis

To determine the recovery potentials of the case slab, the DfSC checklist (Table S6) was given to the system designers of the modular steel slab, and the results were fed into the PBSCI model. The PBSCI measures the case slab's circularity index using CE's four building blocks. The PBSCI consists of four main stages, *viz.*, the material circularity index (MCI), product circularity index (PCI), system circularity index (SCI), and building circularity index. Since the case study is not the whole building but the slabs, the system circularity index is the final index used for comparison in this study; this does not affect the PBSCI analysis since the recyclability plan of the case slab is inputted at the first stage of the analysis (during the calculation of the MCI). A more detailed explanation of the PBSCI analysis can be found in Antwi-Afari *et al.* [6, 13].

$$MCI_p = \max\left(0, 1 - (\frac{0.9}{X_p})(\frac{1}{N}\ X\ \frac{\left(1-NV_{RC_{(p)}}\right)+\left(1-F_{RU_{(p)}}\right)}{2})\right) \text{ ---- Eq. (3)}$$

Where $NV_{RC_{(p)}}$ is the fraction of feedstock from non-virgin sources for the material p; $F_{RU_{(p)}}$is the fraction of the material or product used for reuse, refurbishing, remanufacturing, and recycling; N is the normalization factor; X_p is the product utility.

$$\mathrm{N} = \sum_{i=1}^{n_b} \frac{F_{i\ total_{(p)}}}{F_{d\ total_{(p)}}} \text{ ---- Eq. (4)}$$

where n_b is the number of building blocks of CE (4 in this case).

$$F_{d\ total_{(p)}} = \sum_{i=1}^{n_b} F_{btotal_{(p)}, \max\ = n_b} \text{ ---- Eq. (5)}$$

Where $F_{btotal(p)}$ is the number of building blocks considered for the assessment in product p.

$$F_{i_{\ total\ (p)}} = \sum\left(\frac{f_{i_{CPD_p}}}{f_{d_{CPD_p}}} + \frac{f_{i_{RC_p}}}{f_{d_{RC_p}}} + \frac{f_{i_{SC_p}}}{f_{d_{SC_p}}} + \frac{f_{i_{NBM_p}}}{f_{d_{NBM_p}}}\right) \text{ ---- Eq. (6)}$$

where $fi_{(\mathrm{CPD,RC,SC,or\ NBM})_p}$ is the sum of the assigned weights to the design for systemic circularity (DfSC) criteria *i* of a particular building block for product p,

where $f_{d_{CPD,RC,SC,or\ NBM_{(p)}}} = \sum_{i=1}^{n} f_{i_{\left(CPD,RC,SC,or\ NBM_{(j)}\right),max}} = n$ ---- Eq. (7)

thus, the sum of the number of the assigned weights of DfSC criteria *i* of a particular building block for product p.

$\propto = 0.9$, ---- Eq. (8), i.e., a constant established by the Ellen McArthur Foundation [2].

$X_p = (\frac{L_p}{L_{av_p}})(\frac{U_p}{U_{av_p}})$ ---- Eq. (9)

where L_p is the product lifetime; L_{av_j} is the average lifetime of similar products on the market; U_p is the intensity per use of the product; U_{av_p} is the average intensity per use of similar products on the market. The intensity-per-use ratio is usually set to one due to a lack of data.

By considering the recyclability plan in the MCI calculations, MCI becomes the same as the PCI. Also, because the modular steel slab is the only material that is being considered in the structural system of the building in this study, the SCI becomes the same as the MCI (Appendix B).

3.7 Sensitivity Analysis

Scenario analysis was adopted to assess the effects of different plans of designing for the circularity of the modular steel slab. The recyclability plan obtained from the case company was used for the base scenario. In addition, three other case scenarios were modeled for the PBSCI and compared to the base scenario results to understand the influence of the recyclability plan on the potential recoverability of materials at EoL. Scenario one was modeled after a linear case model at EoL (0% recyclable and lowest weighting for all criteria in the recyclability plan). Scenario two was modeled after an absolute circular model at EoL (100% recyclable at EoL and highest weighting for all criteria in the recyclability plan). In comparison, scenario three was modeled after an ideal case model (at least 80% of the steel slabs should be recycled at EoL and ideal weighting for all criteria in the recyclability plan). The examined scenarios and the resultant processes were also modeled in the SimaPro software to determine the lifecycle environmental impact and end-of-life impact potentials of all the case study scenarios.

3.8 Simple Additive Weighting Method

Considering the environmental impact, retainability, systems, and technical dimensions of the different scenarios of the modular steel slab, a simple additive weighting method was employed to evaluate the performance score for selecting the optimized scenario. The simple additive weighting method is a multi-criteria decision-making method that uses a linear scoring weighting approach proposed by Fishburn [41] and MacCrimmon [42]. It has been used in enhancing the decision-making process in extant studies, such as different sustainable concrete mixes [43] and fiber-reinforced cement deposits [44]. In this method, the weighted average was assessed by considering the weightings for each criterion and the normalized values of the various scenarios. For the beneficial criteria (technical, systems, retainability, and business), higher values are preferred, i.e., the closer the value is to 1, the better it leads the product system to circularity. The normalized matrix is calculated as follows:

$$(X_{ij})_{normal} = \frac{x_{ij}}{Max\ (x_{ij})} \quad \text{---- Eq. (10)}$$

Moreover, lower values are preferred for non-beneficial criteria (environmental impacts), i.e., identifying the scenarios that should cause lower impacts on the environment.

$$(X_{ij})_{normal} = \frac{Min\ (x_{ij})}{x_{ij}} \quad \text{---- Eq. (11)}$$

The performance score for each scenario is calculated as

$$P_s = \sum_{j=1}^{m} wj_{(x_{ij})_{normal}} \quad \text{---- Eq. (12)}$$

Where P_s is the performance score, X_{ij} is the normalized matrix of the different dimensions, $and\, wj$ is the specific weight for each dimension (i.e., 0.25 was assigned to all four dimensions in the assessment).

3.9 Interpretation

The last phase of the LCA framework is interpretation. Thus, to interpret the results of the enhancement of the LCA to cater to the EoL reuse pathways and to interpret the recovery potentials of the modular steel slab. The results of the LCA-C2C are interpreted in line with the goal and scope of the study. The lifecycle inventory and the LCIA are also considered iteratively in interpreting the results. Sensitivity analysis enhances the interpretation of the results towards identifying the optimal areas for further improvement.

3.10 Case Slab

The case slab area is 2505.204m^2 for an 11-floor modular steel structure in Changsha, China. The slab is made up of enhanced stainless steel of a similar structure to the conventional honeycomb panels used in spacecraft. The slab is designed for a six-degree seismic fortification and grade-two fire resistance. The slab is manufactured and assembled in the factory for the construction of the modules of the building. Dry connections were used to join the parts of the modules together to enhance their disassembly at EoL. Table 1 lists some essential inventory information about the modular building and the modular steel slabs specifically.

Table 1. Characteristics of the case slab

Parameters	Specifications
Structure	Modular Steel
Gross floor area	2505.204m^2
Number of households	33
Number of floors	11
Apartment type	One ladder, three households per floor
Percentage of prefabrication	100%
Fire resistance	Grade two
Seismic intensity resistance	six-degrees
Lifespan	100years
Quantity	94.332 tons
Transport distance	91.60Km (from Xiangyin to Changsha)
Recycled content	Recycled content (35%) recyclability at EoL (100%)

Source [45]

4. Findings and Discussions

4.1 Recovery Potentials of the Case Slab

The average product utility of the case slab was modeled at 100 years. The designers of the modular slab also assayed that the slab should be 100% recyclable at EoL due to the enhanced technology and materials used to produce it at the factory. By inputting the obtained weightings of the DfSC checklist based on the company's recyclability plan for the product system (Table 2) and the forecasted recyclability of the slab at EoL into the PBSCI model, it could be deduced from Appendix B that the MCI of the case slab at EoL would be 50.4% of mass recyclable. The normalization factor (N), which shows the rate of circularity of the recyclability plan of the product system, was also 0.59 for the base scenario. The closer N is to one, the circular the recyclability plan, and vice versa. Since the case slab had no other sub-assemblies, the MCI was the same as the SCI. Also, because N is already considered in the MCI, the PCI is the same as the MCI. The non-circularity of the case slab at the base scenario was 49.6%; this shows that despite the design effort to attain 100% recoverability of the slab at EoL, the modular steel slabs cannot be said to be 100% circular when other KPIs of obtaining a systemic circularity are considered in the assessment. Hence, the recoverability potential percentage of the case slab at EoL from the PBSCI analysis should reflect the product's circularity and not just the forecasted circularity based on design.

Table 2. The company's recyclability plan for the modular building is based on the DfSC checklist

Building Blocks	**Key Performance Indicators (KPIs)**	**Design for System Circularity (DfSC) Criteria**	**Weightings**
Circular Product Design (CPD)	Connection Type	Dry connections (e.g., click, magnetic, Velcro)	1.00
	Connection Accessibility	Freely accessible	1.00
	Production	Producer-non-consumer (what is made may come from what has already been made, but producers have systems in place to reuse what has been made)	0.67
	Entropy Production	Compensated product transformations, i.e., designing products for easy disassembly and easy return to their natural state	1.00
	Product EoL Reference Value	The products performance and EoL are determined and set from the design stage	1.00
	Expert Systems	Expert systems are available but not for all materials and processes in the product system	0.75
	Material Toxicology	The toxicology of some of the materials of the product is known and substituted	0.67
	Energy for Operations	Renewable energy is used for the EoL stage only	0.25
	Water Stewardship	Water from the production system is treated and cleaned, let to flow into water streams.	0.67
System Conditions (SC)	Company's Integration	Transdisciplinary thinking along value chains only	0.67
	Product Pricing	Product pricing does not include environmental elements, but initiatives are put in place to give back to the environment	0.50
	Stakeholders Collaboration	There exists collaboration between only a few key stakeholders	0.33
	Regulations and Incentives	Some key regulations and a few incentives are available	0.50
	Job Allocation	The product system is made in such a way that jobs could be available, but getting the materials back is the main priority	0.50
	Procurement Routes	Improved procurement routes where materials sources are known but the effects of their processes are barely considered in decision making	0.50
	Materials Sourcing	Vernacular materials are considered, but they are compared with others, and the least costly is chosen	0.50
	Effects of Production Activities	Controlled and sustainable activities benefit locally only, but their global effects may not be known and vice versa.	0.50
Reverse Cycles (RC)	Material Traceability	Product / material passport is available only at the design/production stage and not linked to the product throughout its life cycle	0.33

	Material Banks	Some of the building designs and materials are available to be sampled by buyers online	0.50
	Materials Production	The product is made of > 20% of recycled materials	0.50
	Materials Upcycling	> 50% of the materials or components of the product will be upcycled at EoL	0.75
	Take-back Systems	A take-back system is available, but not a fully integrated EoL logistics which could get all recyclable materials/components back to the material processing firms	0.50
	Waste Collection	Only minimal technologies, such as QR codes for informal waste collection and payments, are employed	0.33
	Linking of Data at EoL	Enabling technologies are used to feed some generic products to a database for general processing	0.33
	Materials Collateral Effects	The company with the licensed product only has the right to reuse its materials at EoL	0.10
	Nutrient Cycling System	Nutrient cycling is not considered in the design but is considered during the recycling process to separate biological from technical nutrients	0.50
New Business Models (NBM)	EoL Business model	Business models where producers close the loop of their production system through servicing of materials or parts of the products are adopted	1.00
	Firms Collaborations	The business model adopted for the product is such that it can work within several different economic and market settings	1.00
	After-sales Strategies	Aftersales services are not considered during the design stage but only considered for marketing purposes	0.67
	Partnerships	No partnership of any sort is established	0.10
	Service Business Model	Product as a service is not considered at the design stage and is only adopted during sales/marketing. Hence, trade-offs of adopting a particular product as a service approach may be unknown	0.50

Three other scenarios were modeled and compared to the base scenario to examine the effects of designing the slab for disassembly and the adopted recyclability plan of the product system on the overall circularity of the product at EoL. Scenario one (the linear case) was modeled as having 0% of the modular steel slab recyclable at EoL and using the lowest weightings for all criteria in the recyclability plan. The obtained normalization after the PBSCI analysis was 0.10. Scenario two (the total circular case) was also modeled as having 100% of the modular steel slab recyclable at EoL and using the highest weightings for all criteria in the recyclability plan. N was obtained as 1.00 after analysis. Finally, scenario three (the ideal case) was also modeled as having at least 80% of the modular steel slabs recyclable at EoL and using the ideal weightings for all criteria in the recyclability plan based on the existing technologies and possibilities as expounded in the current discourse. The N was obtained as 0.625. The circularity indices of the compared scenarios are presented in Fig. 3.

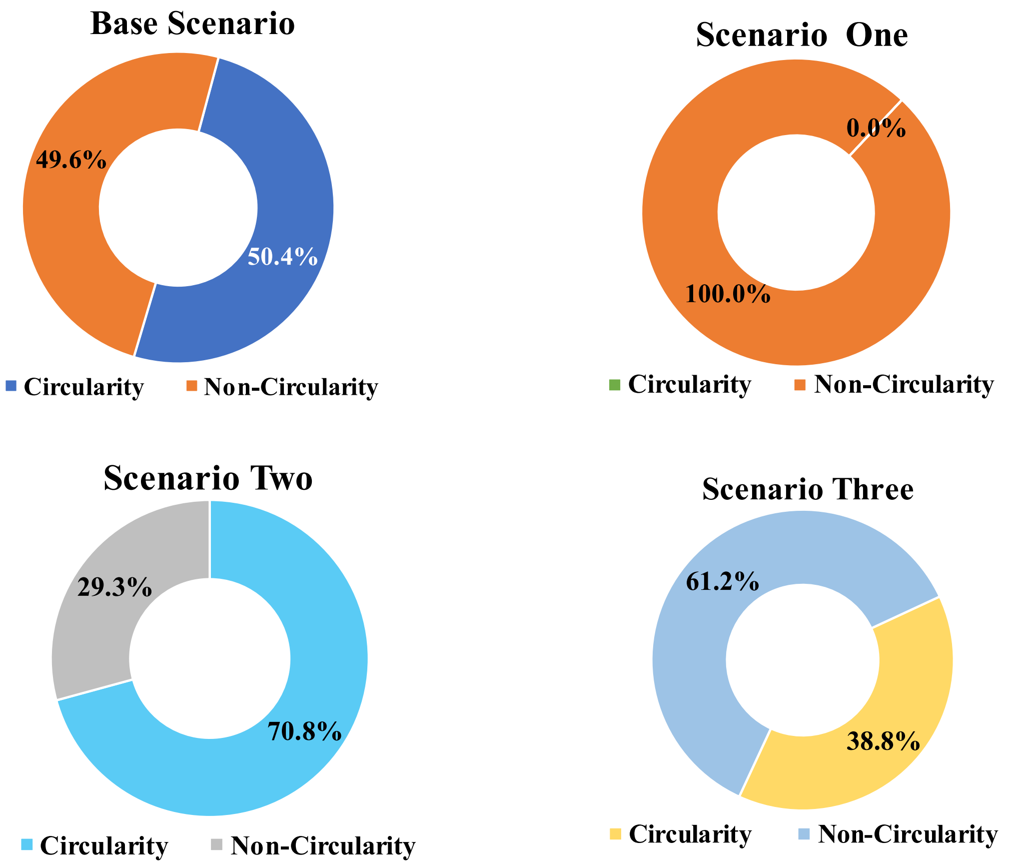


Fig. 3. Circularity index of the modular steel slab

It can be deduced from Fig. 3 that the MCI of case scenario one was 0% at EoL with a non-circularity of 100%; this means that eventually, the slab would be sent to a landfill at its EoL since it was not designed or produced to be reused. The product system needed to have well-established recyclability plans to ensure its circularity at EoL. For scenario two, despite having forecasted recyclability at 100% and the highest weightings for all DfSC criteria, the MCI of the case slab was 70.75% of mass recyclable while 29.25% of the mass was non-recyclable at EoL; this is because the case slab comprised 35% recycled content and 65% virgin sources. Hence, despite the EoL design plan forecasted at 100%, the whole slab product system cannot be said to be circular because a majority of the materials were obtained from raw materials extraction, which may have other impacts on other dimensions such as the environment, economic and social impacts which need to be considered beyond the technical circular product design capabilities. In case scenario three, the MCI of the slab would be 38.8% of mass recyclable, while 61.2% would be non-recyclable at EoL. The MCI of scenario three is less than that of the base scenario because it was modeled that only 80% of the case slab should be recycled at EoL amidst the claims of the prefabrication company to be able to achieve 100% recyclability. The assumptions in the ideal case were made based on the existing technologies, the opportunity to use recycled content in the production of the slab, the present design for disassembly factors, the surrounding system conditions, and the current reverse cycles available for the case product system. The findings corroborate the notion that achieving 100% circularity of a product system may not be possible in an absolute sense. However, the right product utility, reverse cycles, business models, and disassembly factors should all be considered from the beginning of life of a product system design to ensure a total/systemic circularity across the whole product system [6]. Not considering these from the beginning of life may lead to a circular technical product, which may not be circular or sustainable across other dimensions in the product system.

Apart from considering the circularity/recoverability potentials of the case slab, one key aspect to evaluate is the impacts these various scenarios emit on the environment. Hence, how does one decide between two products/scenarios with similar circularity potentials at EoL, and how does one know the impacts of one’s recyclability plan as adopted during the production, construction, use, EoL and beyond the system boundary of the product system. To do this, the LCA is adopted, and the system boundary of the LCA is extended to C2C to consider the reuse/recycling pathways after the EoL of the case slab.

4.2 Environmental Impact of All Scenarios

By adopting the 0/100 EoL allocation approach, the environmental impact of all the scenarios across the product lifecycle from C2C was determined using the LCA method. The midpoint results of the case slab are shown in Table 3 and are expressed in percentages concerning the highest impacts in each category in Fig. 4. It can be deduced from Table 3 that scenario one (the linear case) would induce higher impacts across several impact categories such as global warming (170856 kg CO_2 eq.), non-renewable energy (1749987 MJ primary), mineral extraction (329.39 MJ surplus) and respiratory inorganics (164.20 kg PM2.5 eq.). Furthermore, it could be examined from Table 3 that scenario two (the circular case) would also induce impacts in other impact categories when compared to the other scenarios, such as aquatic ecotoxicity (5467481 kg TEG water), respiratory organics (25.55 kg C_2H_4 eq.) and land occupation (932.86 m^2org.arable). Most studies [*c.f.*, 9, 46, 47] focus on assessing impact categories related to the built environment without considering the effects of the built environment activities on other industries. Hence, despite the circular case leading to more circularity of the slab at EoL than the other scenarios based on the PBSCI results, it could still lead to impacts in other impact categories which may not be the primary concern now considering the existing planetary boundaries. Even so, to prevent burden shifting, it is advisable to look at all the impacts of the LCA to influence the choice of materials or scenarios in decision-making.

It should be reiterated that the impacts of the scenarios in the LCA-C2C assessment do not accurately match the adopted recyclability plan as used in the PBSCI analysis; this is because some key technologies and renewable energy usage, which were assumed to be adopted for some scenarios, could not also be assumed in the LCA. Hence, the data of the base scenario was used for all the other three assumed scenarios, which were compared to the base scenario in the PBSCI analysis. Thus, a true circularity of a product system of 70.8% with all the available data should produce impacts that should be less than that obtained in this study. Even so, using only a percentage of the mass of materials recyclable at EoL in the LCA-C2C assessment still show how designing for systemic circularity could improve the circularity of products and reduces its overall environmental impacts, especially in global warming, mineral extraction, and non-renewable energy consumption.

The global warming potential per m^2 of the modular steel slabs in the case building was 38.64 kg CO_2 / m^2 for the base scenario, 68.2, 28.28, and 44.95 kg CO_2 / m^2, respectively, for scenarios one to three. Therefore, compared with the base scenario, scenario one would induce 76.5% kg CO_2 / m^2 more in global warming potentials. Also, comparing the linear case (scenario one) and the circular case (scenario two), scenario two should save at least 141% kg CO_2 / m^2 in global warming potentials. The EoL waste management impacts were also identified and modeled separately to understand the impacts of the scenarios of the case slab in detail.

Table 3. Midpoint results of lifecycle impacts of all the scenarios of the case slab

Impact category	Base Scenario	Scenario 1	Scenario 2	Scenario 3
Carcinogens	2120	4195	1296	2593
Non-carcinogens	11266	22124	7006	13727
Respiratory inorganics	101.24	164.20	82.33	113.71
Ionizing radiation	247866	234356	262323	241984

Ozone layer depletion	0.010	0.004	0.013	0.009
Respiratory organics	22.72	16.06	25.55	21.15
Aquatic ecotoxicity	4986721	4005907	5467481	4735392
Terrestrial ecotoxicity	1022794	1548532	823264	1139890
Terrestrial acid/nutri	2051.11	3240.85	1676.52	2292.02
Land occupation	816.87	576.21	932.86	755.76
Aquatic acidification	645.5	1065.19	516.82	729.48
Aquatic eutrophication	3.65	6.46	2.73	4.23
Global warming	96803	170856	70851	112617
Non-renewable energy	1026349	1749987	772525	1180965
Mineral extraction	277.84	329.39	260.71	288.59

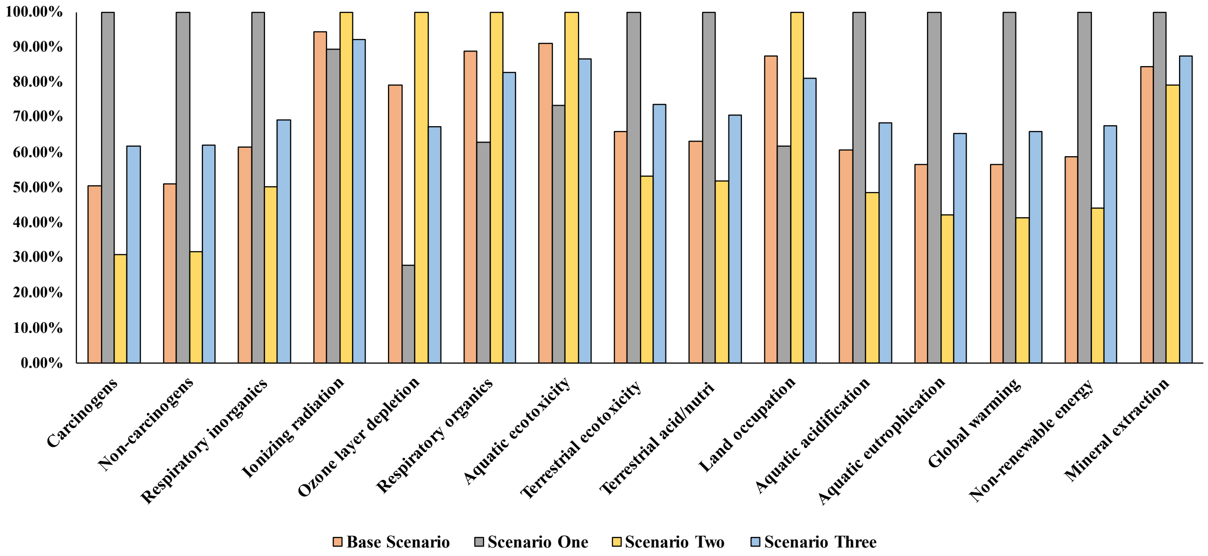


Fig. 4. Lifecycle of all scenarios of the modular steel slab

4.3 Disposal Impacts of the Scenarios of the Case Slab

It was modeled for the base scenario that 50.4% of the case slab should be disassembled and reused in the next production cycle. However, all impacts of the EoL reuse pathway should be attributed to the current production system (0/100 EoL allocation approach). The rest of the slab should be incinerated at an incineration facility 36.8 km from Changsha. The distance to the recycling facility in Shenzhen from Changsha was 757.9 km. For scenarios two and three, 70.8% and 38.8% of the case slab were modeled to be reused in the next production system, respectively. However, in scenario one, 0% of the case slab was modeled to be reused. Hence, at EoL, the case slabs for scenario one should be demolished and incinerated. The endpoint results of the disposal scenarios of the case slab are shown in Table 4 and expressed in percentages based on each damage category in Fig. 5.

It can be deduced from Table 4 that the EoL impacts of scenario one would induce higher impacts across all the endpoint damage categories compared to the other scenarios. When comparing the three disposals' impact scenarios with the base scenario, it can be deduced that scenario three would induce 31.2% DALY in human health. In contrast, scenario two should save 50.6% DALY in human health. Scenario one would also induce 97.125% kg CO_2 eq. in climate change compared to the base scenario. However, scenario two should save 36.1% kg CO_2 eq. in climate change should that scenario be adopted for the product system of the modular steel slabs as compared to the base scenario.

Table 4. Endpoint results of the disposal scenarios of the case slab

Damage category	**Disposal S3**	**Disposal S2**	**Disposal S1**	**Disposal BS**
Human health	-5.264	-11.523	3.665	-7.651
Ecosystem quality	-0.228	-0.441	0.063	-0.308
Climate change	-5.673	-9.891	0.209	-7.270
Resources	-3.479	-6.166	0.266	-4.496
Total	-14.643	-28.022	4.203	-19.725

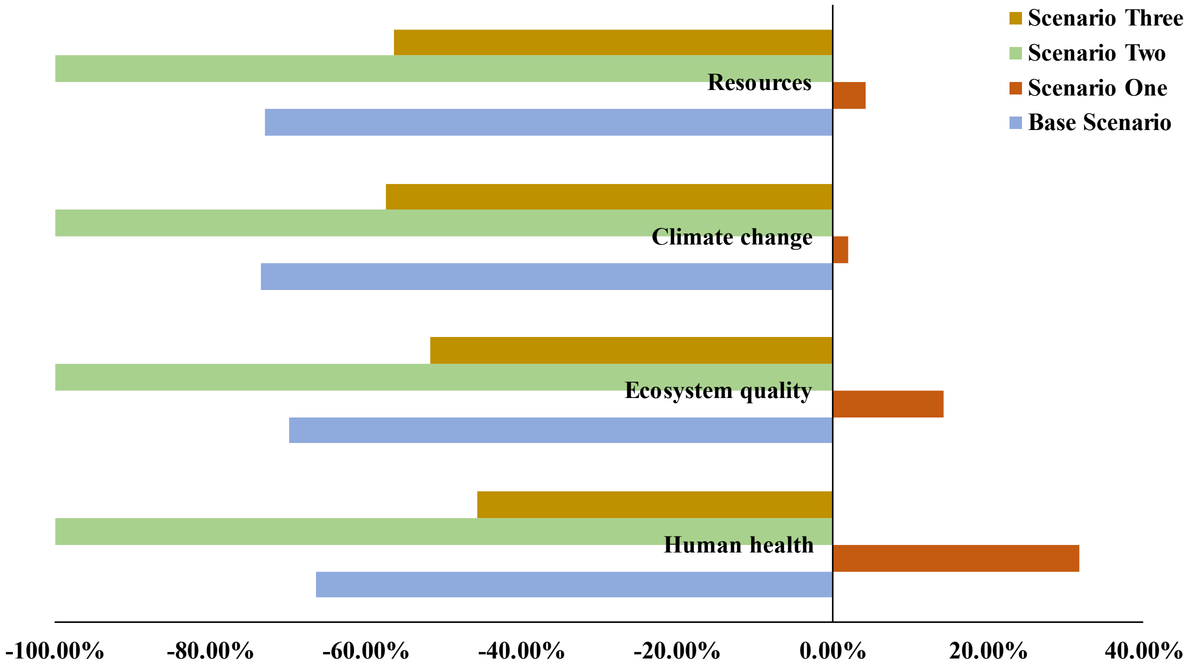


Fig. 5. Disposal impacts of the scenarios of the case slab

By combining the PBSCI analysis with the LCA-C2C, the decision to select a particular material, product, or scenario of a product system design should now incorporate the product's environmental, technical, functional, and systems dimensions. The extension of the LCA to C2C should also enhance the consideration of EoL impacts and provide more intricate details on the impacts of the materials or product system after EoL. However, the chosen EoL allocation approach influences how much of the impacts are considered in the assessment. Hence, the adopted EoL allocation approach should be well-documented in the assessment and agreed on by assessors.

4.4 Selection of the Optimal Product System Scenario for the Case Slab

Based on the scenario analysis, three different plans for the modular steel slab were assessed. The aim was to identify whether different recyclability plans for the designed modular slab would have any effects on its recoverability potentials and environmental impacts at EoL. The recyclability plan is expressed in the technical, functional (rate of retainability and circular business model), and system dimensions. Therefore, selecting the optimal scenario could be made subjectively by comparing the different scenarios' environmental impacts and recoverability potentials. However, the simple additive weighting method was used to provide a more detailed insight into the recoverability potentials. Equations 10 – 12 in section 3.8 were used to assess the environmental, technical, business, and retainability dimensions of the base scenario, scenario one (linear case), scenario two (circular case), and scenario three (ideal case) of the modular steel slab. The final performance score of the case scenarios is presented in Table 5. In contrast, the normalization matrix and performance scores of each dimension of the scenarios are shown in the supplementary information (Table S7).

It can be deduced from Table 5 that scenario two had the highest performance score of 1.25 when compared to the other scenarios. Hence, it is the optimal scenario for the modular steel slab. Further inspection of the KPIs and DfSC criteria, which led to the optimal scenario (Table S6), shows that achieving a circular product system design for the modular slab would require the highest weighting for all the required criteria under the KPIs. For example, the design of the modular slab should adopt dry connections as its connection type, and the connections should be freely accessible with modular zoning of objects while adopting a producer-reproducer system. The circular product should also have a well-established material requirement planning, adopt renewable energy for all its operations, and have compensated product transformation. Other studies, such as Geldermans [48] and Favi [49], proposed similar characteristics for circular designed components and buildings. For systems and retainability dimensions, achieving a circular product design of the modular steel slab would require transdisciplinary thinking within the activities of the product development, enhanced CE procurement routes through intelligent resource pooling, a take-back system comprising of EoL coordination and recycling routes of materials, and the use of digitalized waste collection system such as global positioning systems, radio-frequency identification, and computer vision to enhance waste segregation and retrieval at EoL.

The business dimensions of the optimal scenario have features such as servicing of materials or parts throughout the product lifecycle by the manufacturers, designing the business model of the product to function appropriately in different economies of the world, partnering among the processing, manufacturing, and reprocessing firms/department to keep materials within a closed loop and designing the product around it service base (user, result, or product-oriented) to guarantee key proof and implementation. The rate at which this is attained for the product system design of the modular steel slab should enhance its overall circularity/recoverability potential at EoL and reduces its environmental impacts throughout its lifecycles. Though less impact and more reusability are expected if the optimal scenario is adopted for the modular steel slab compared to the base scenario, obtaining 100% decoupling may pose a challenge due to the thermodynamics and entropy of materials. Also, other impacts of the product system of the optimal scenario are not measured in the LCA due to the unavailability of data. For example, transportation impacts for routine repair and maintenance, refurbishment impacts, and credits impact virgin materials for reusability of materials in the next production cycle.

Table 5. Performance Scores and Overall Ranking of the Different Scenarios of the Case Slab

Different Scenarios	**Base Scenario**	**Scenario One**	**Scenario Two**	**Scenario Three**
Performance Scores (P_s)	0.773	0.204	1.250	0.783
Overall Ranking	3rd	4th	1st	2nd

4.5 Comparison of the Optimal Case Scenario with Others in Extant Literature

The case slab was a modular steel slab designed for circularity. The global warming potential (GWP) of the optimal scenario of the modular steel slab in the case building was 28.28 kg CO_2 / m^2. The optimal scenario slab GWP impact was compared to other GWPs of other slabs of different construction methods and system boundaries to validate the results, identify any significant deviations and draw relevant conclusions from the analysis. The results of the comparison are shown in Table 6. It must be noted that a direct one-for-one comparison of LCA of different studies is difficult due to different geographical contexts, energy mixes, data quality, waste management systems, system boundaries, and EoL scenarios. However, comparing the results of this study to other LCA studies is necessary to draw various reasonable deductions.

Table 6. Comparison of case slab environmental impacts with other slabs

Study	**Location**	**Construction Method**	**Material**	**System Boundary**	**GWP (Kg CO2 / m2)**
Present Study	China	Modular Construction	Steel	C2C	28.28
Teng and Pan [50]	Hong Kong	Prefabrication	Reinforced Concrete	C2G	277
Ansah *et al.* [15]	Hong Kong	Semi-Prefabricated	Reinforced Concrete	C2G	175.19
Chen *et al.* [21]	China	Conventional	Timber	C2Ga	92.96
Balasbaneh *et al.* [51]	Malaysia	Semi-Prefabricated	Reinforced Concrete	C2G	123.53

From Table 6, the differences in the impacts of the GWP of extant studies can be attributed to the different system boundaries used, diverse floor areas, types of materials, construction methods, energy mixes, and data quality. The present study had the lowest GWP due to manufacturing the whole slab modules in the factory and transporting them to the construction site. Hence, the significant impacts in the processes are the production and transportation of modular steel slabs. Other studies, such as Balasbaneh *et al.* [51], had GWP higher than the present study because of the several varied materials used in the slab production and the unit of analysis adopted in the study. Ansah *et al.* [15] also had a higher GWP for the slabs in the 40-story building, which their study analyzed as compared to the 11 floors of the present study. Comparatively, the GWP of their study is slightly higher than the GWP of the base scenario per unit of analysis. Teng and Pan [50] also employed process-based LCA to assess the scenario and uncertainty parameters of a prefabricated residential building in which the connecting slab of the 30-floors residential building had a GWP of 277 kg CO_2 / m^2. In conclusion, the result of this study is in line with the range of residential buildings per unit of analysis. However, the GWP of this study is lesser than others because of the construction method adopted for the study.

4.6 Effects of EoL Allocation Approach on Impact Assessments

Two EoL allocation approaches, i.e., the 0/100 and the 50/50 allocation approaches, were adopted for the LCA-C2C of the optimal scenario of the modular steel slab. It can be deduced from Fig. 6 that the 0/100 EoL allocation approach, which credits the benefits or burdens of the reuse pathways of the material to the current production system producing the recyclable materials, has more impacts at the endpoint than the 50/50 EoL allocation approach. However, the 50/50 EoL allocation approach shares the burdens of the EoL reuse pathways 50/50 across the current production system and the subsequent production system. Since this study focused on the current production system only, the lifecycle of the modular steel slab for the 0/100 EoL allocation approach should induce 7.16 kg CO_2 eq. in climate change. In contrast, the same processes should induce 3.58 kg CO_2 eq. when the 50/50 EoL allocation approach is adopted. Thus, different EoL allocation approaches produce different results in the impact category when measuring the impacts at EoL in a C2C system boundary. Allacker *et al.* [35] expatiated several EoL allocation approaches such as the 100/100, linearly degressive, 100/0, and 50/50 adapted. Hence, for a C2C system boundary, one EoL allocation approach should always be adopted. However, it must be well-documented and explained so that the impacts of the analysis are well-interpreted.

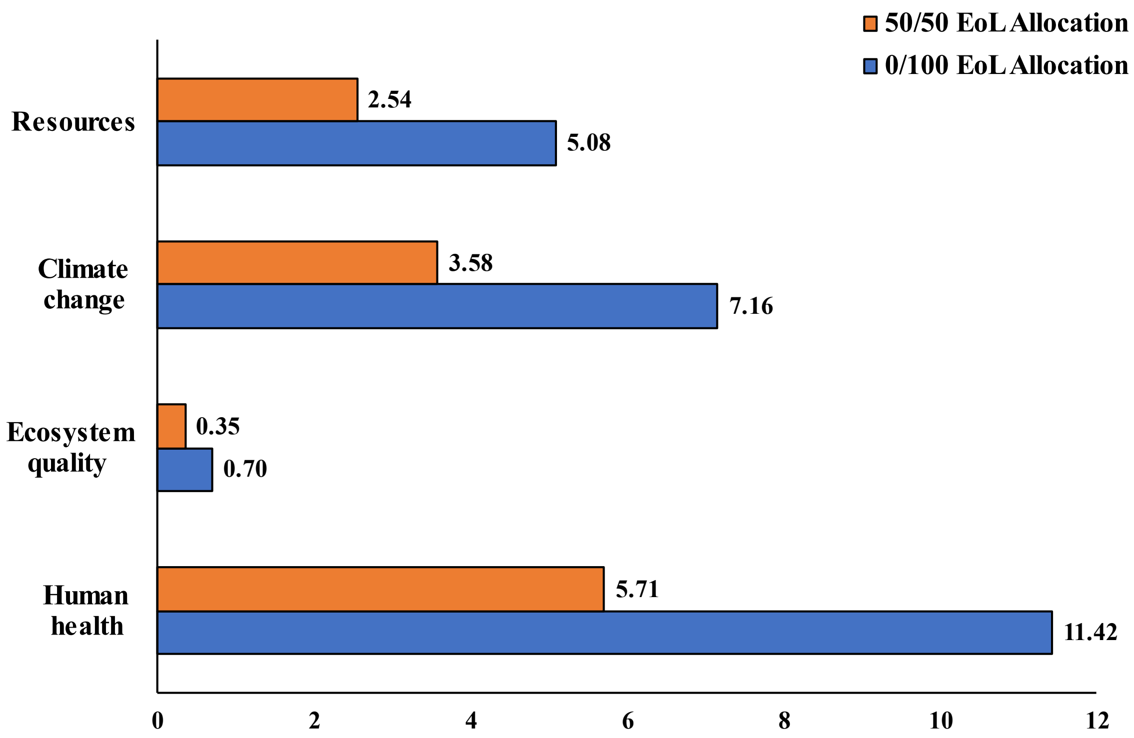


Fig. 6. Effects of EoL Allocation Approach on the lifecycle of the optimal scenario case slab

5. Conclusions

Measuring the adoption of circularity principles in product system design would require the consideration of methods or indicators which should be able to assess the environmental, technical, economic, social, functional, and systems dimensions of CE. Existing methods such as LCA, LCC, SLCA, and their derivatives have been adopted to evaluate the potential environmental, economic, and social impacts of circular products or processes. However, their usage for other dimensions of circularity is fraught with several challenges. In this study, the LCA system boundary was extended to C2C and combined with the PBSCI method to evaluate the environmental, systems, business, and retainable dimensions of different case scenarios of a modular steel slab of a residential building in China. Adopting this combined iterative methodological approach provided means for assessing the environmental and technical consequences of different scenarios of the product system and the ensuing impact potentials across the lifecycle and beyond the system boundary of the modular steel slab.

Three case scenarios were modeled and compared to the base scenario to illustrate this method. The recyclability plan, product utility, recycled content, and forecasted recyclability of the base scenario were obtained from the case company and fed into the PBSCI model to determine the recoverability/circularity potential of the case slab at EoL. It was identified that the product system adopted for the base scenario could lead to about 50.4% of the mass of the slab being recyclable at EoL. In comparison, 0%, 70.8%, and 38.8% of the slab's recyclable mass were recorded for the case slab's product system based on scenarios one to three, respectively. The rate of recoverability of the case slab was hugely influenced by the normalization factor, which is calculated from the adopted recyclability plan of the different scenarios of the product system. Also, the average product utility, the amount of recycled content in the processing of the slab, and the forecasted recyclability at EoL based on the scenarios of the product system design influence the recoverability indices of the whole product system. The effects of the case scenarios were also evaluated using LCA-C2C while considering the percentages of mass of the slab recyclable at EoL and including the impacts of the EoL reuse pathways in assessments. It was identified that the modular steel slab should induce 38.64 kg CO_2 / m^2 in climate change for the base scenario and 68.2, 28.28, and 44.95 kg CO_2 / m^2 for case scenarios one to three, respectively. Compared with the base scenario, scenario two's EoL waste management impact (the circular case) should save about 36.1% kg CO_2 eq. in climate change. In comparison, scenario one (the linear case) should induce about 97.125% kg CO_2 eq. in climate change.

To select the optimal product system to adopt for the modular steel slab, the simple additive weighting method was used by considering the environmental, technical, functional, and systems dimensions of the scenarios of the case slab. Scenario two was chosen as the optimal product system for the case slab, with a performance score of 1.25. Adopting this scenario for the case slab should positively impact the environment and enhance the circularity of the slab at EoL based on the key selected indicators under each of the assessed dimensions of CE. The use of this iterative integrative method for determining the impacts and recoverability potentials of products or product systems is not to provide system designers an absolute means of guiding decisions on which materials or scenarios to adopt for a product system but to present a more comprehensive method where several vital dimensions of CE could be considered in assessments.

Theoretically, this study contributed to product system performance evaluation literature by presenting a novel means of assessing both the environmental and recoverability impact potentials of different case scenarios of a product system. Practically, the study also presented an innovative approach to provide system designers with a consolidative method for making decisions between different materials, products, or systems which should provide analogous functions in product system design.

The key performance indicators provided under each building block of CE in this study are not exhaustive. They would require further research and expert judgment to enhance them to measure precisely the vital indicators that should influence a product's circularity system within the construction industry. Also, artificial intelligence models could be adopted to enhance the prediction of the forecasted recyclability of the case slab based on design rather than depending on expert judgment only. Moreover, sensitivity analysis could be done in the LCA-C2C to assess the influence of several input parameters on the result of the LCA-C2C, such as changes in traveling distances, use of different lifecycle impact assessment methods, and LCA databases. Further study could be done by combining LCSA with predictive building systemic circularity indicator to enhance the selection of the optimal product system beyond the dimensions considered in this study.

6. Acknowledgement

The authors would like to acknowledge the Research Grants Council of the Hong Kong Special Administrative Region Government for financially supporting this study through the Collaborative Research Fund (Grant No.: C7047-20GF). The paper also forms a part of a Ph.D. research project currently undertaken by the first author under the University Grants Committee's Hong Kong Ph.D. Fellowship Scheme (PF18-17313). Part of the work has been presented at the 45th Australasian Universities Building Education Association (AUBEA) conference.

7. References

1. Oluleye, B. I., Chan, D. W. M., Saka, A. B., & Olawumi, T. O. (2022). Circular economy research on building construction and demolition waste: A global review of current trends and future research directions. *Journal of Cleaner Production*, 131927. https://doi.org/10.1016/j.jclepro.2022.131927
2. Ellen MacArthur. (2015). Towards a circular economy: business rationale for an accelerated transition. *Greener Manag International*, *20*.
3. Antwi-Afari, P., Ng, S. T., & Hossain, M. U. (2021). A review of the circularity gap in the construction industry through scientometric analysis. *Journal of Cleaner Production*, *298*. https://doi.org/10.1016/j.jclepro.2021.126870
4. Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Van Acker, K., de Meester, S., & Dewulf, J. (2019). Circular economy indicators: What do they measure? *Resources, Conservation and Recycling*, *146*, 452-461. https://doi.org/10.1016/j.resconrec.2019.03.045

5. Hossain, M. U., Ng, S. T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction [Review]. *Renewable and Sustainable Energy Reviews*, *130*, Article 109948. https://doi.org/10.1016/j.rser.2020.109948
6. Antwi-Afari, P., Ng, S. T., & Chen, J. (2022a). Developing an integrative method and design guidelines for achieving systemic circularity in the construction industry. *Journal of Cleaner Production*, *354*, 131752. https://doi.org/10.1016/j.jclepro.2022.131752
7. Meglin, R., Kytzia, S., & Habert, G. (2022). Regional circular economy of building materials: Environmental and economic assessment combining Material Flow Analysis, Input-Output Analyses, and Life Cycle Assessment. *Journal of Industrial Ecology*, *26*(2), 562-576. https://doi.org/10.1111/jiec.13205
8. Janjua, S. Y., Sarker, P. K., & Biswas, W. K. (2021). Sustainability implications of service life on residential buildings–An application of life cycle sustainability assessment framework. *Environmental and Sustainability Indicators*, *10*, 100109. https://doi.org/10.1016/j.indic.2021.100109
9. Kamali, M., Hewage, K., & Sadiq, R. (2019). Conventional versus modular construction methods: A comparative cradle-to-gate LCA for residential buildings. *Energy and Buildings*, *204*, 109479. https://doi.org/10.1016/j.enbuild.2019.109479
10. McAvoy, S., Grant, T., Smith, C., & Bontinck, P. (2021). Combining Life Cycle Assessment and System Dynamics to improve impact assessment: A systematic review. *Journal of Cleaner Production*, *315*, 128060. https://doi.org/10.1016/j.jclepro.2021.128060
11. Verberne, J. (2016). Building Circularity Indicators—An Approach for Measuring Circularity of a Building. *Eindhoven Univ. Technol*.
12. Cottafava, D., & Ritzen, M. (2021). Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects. *Resources, Conservation and Recycling*, *164*, 105120. https://doi.org/10.1016/j.resconrec.2020.105120
13. Antwi-Afari, P., Ng, S. T., & Ji, C. (2022b). Determining the impacts and recovery potentials of a modular-designed residential building using the novel LCA-C2C-PBSCI method. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2022.134575
14. ISO (2006b). ISO 14040: ISO 14044 International Standard. Environmental management–Life Cycle Assessment. Requirements and Guidelines. International Organization for Standardization, Geneva.
15. Ansah, M.K., Chen, X., Yang, H., Lu, L. and Lam, P.T., 2021. Developing an automated BIM-based life cycle assessment approach for modularly designed high-rise buildings. *Environmental Impact Assessment Review*, *90*, p.106618. https://doi.org/10.1016/j.eiar.2021.106618
16. Vandervaeren, C., Galle, W., Stephan, A. and De Temmerman, N., 2022. More than the sum of its parts: Considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings. *Resources, Conservation and Recycling*, *177*, p.106001. https://doi.org/10.1016/j.resconrec.2021.106001
17. Zhang, X., Liu, K. and Zhang, Z., 2020. Life cycle carbon emissions of two residential buildings in China: Comparison and uncertainty analysis of different assessment methods. *Journal of cleaner production*, *266*, p.122037. https://doi.org/10.1016/j.jclepro.2020.122037
18. Hossain, M.U., Ng, S.T., Dong, Y. and Amor, B. (2021). Strategies for mitigating plastic wastes management problem: A lifecycle assessment study in Hong

Kong. *Waste Management*, *131*, pp.412-422. https://doi.org/10.1016/j.wasman.2021.06.030

19. Carvalho, J.P., Villaschi, F.S. and Bragança, L. (2021). Assessing life cycle environmental and economic impacts of building construction solutions with BIM. *Sustainability*, *13*(16), p.8914. https://doi.org/10.3390/su13168914
20. Zhan, J., Liu, W., Wu, F., Li, Z. and Wang, C., 2018. Life cycle energy consumption and greenhouse gas emissions of urban residential buildings in Guangzhou city. *Journal of cleaner production*, *194*, pp.318-326. https://doi.org/10.1016/j.jclepro.2018.05.124
21. Chen, C.X., Pierobon, F., Jones, S., Maples, I., Gong, Y. and Ganguly, I., 2021. Comparative life cycle assessment of mass timber and concrete residential buildings: a case study in China. Sustainability, 14(1), p.144. https://doi.org/10.3390/su14010144
22. Dauletbek, A. and Zhou, P. (2022). BIM-based LCA as a comprehensive method for the refurbishment of existing dwellings considering environmental compatibility, energy efficiency, and profitability: A case study in China. *Journal of Building Engineering*, *46*, p.103852. https://doi.org/10.1016/j.jobe.2021.103852
23. Francis, A. and Thomas, A. (2022). A framework for dynamic life cycle sustainability assessment and policy analysis of built environment through a system dynamics approach. *Sustainable Cities and Society*, *76*, p.103521. https://doi.org/10.1016/j.scs.2021.103521
24. Soust-Verdaguer, B., Galeana, I.B., Llatas, C., Montes, M.V., Hoxha, E. and Passer, A. (2022). How to conduct a consistent environmental, economic, and social assessment during the building design process. A BIM-based Life Cycle Sustainability Assessment method. *Journal of Building Engineering*, *45*, p.103516. https://doi.org/10.1016/j.jobe.2021.103516
25. Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production*, *207*, 542-559. https://doi.org/10.1016/j.jclepro.2018.10.014
26. Iacovidou, E., Velis, C. A., Purnell, P., Zwirner, O., Brown, A., Hahladakis, J., Millward-Hopkins, J., & Williams, P. T. (2017). Metrics for optimizing the multi-dimensional value of resources recovered from waste in a circular economy: A critical review. *Journal of Cleaner Production*, *166*, 910-938. https://doi.org/10.1016/j.jclepro.2017.07.100
27. Niero, M., & Kalbar, P. P. (2019). Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. *Resources, Conservation and Recycling*, *140*, 305-312. https://doi.org/10.1016/j.resconrec.2018.10.002
28. Magrini, C., Degli Esposti, A., De Marco, E., & Bonoli, A. (2021). A framework for sustainability assessment and prioritisation of urban waste prevention measures. *Science of The Total Environment*, *776*, 145773. https://doi.org/10.1016/j.scitotenv.2021.145773
29. Franklin-Johnson, E., Figge, F., & Canning, L. (2016). Resource duration as a managerial indicator for circular Economy performance. *Journal of Cleaner Production*, *133*, 589-598. https://doi.org/10.1016/j.jclepro.2016.05.023
30. Peralta, M. E., Alcalá, N., & Soltero, V. M. (2021). Weighting with life cycle assessment and cradle to cradle: A methodology for global sustainability design. *Applied Sciences*, *11*(19), 9042. https://doi.org/10.3390/app11199042
31. Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019). Comparing life cycle assessment modelling of linear vs. circular building components. *IOP Conference Series: Earth*

and Environmental Science, *225*, 012039. https://doi.org/10.1088/1755-1315/225/1/012039

32. Saade, M., Erradhouani, B., Pawlak, S., Appendino, F., Peuportier, B., & Roux, C. (2022). Combining circular and LCA indicators for the early design of urban projects. *The International Journal of Life Cycle Assessment*, *27*(1), 1-19. https://doi.org/10.1007/s11367-021-02007-8
33. ISO (2006a). ISO 14040: Environmental Management- Life Cycle Assessment. Principles and Guidelines, International Organization for Standardization, Geneva.
34. EN 15978 (2012). Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method (Brussels: CEN).
35. Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *The International Journal of Life Cycle Assessment*, *22*(9), 1441-1458. https://doi.org/10.1007/s11367-016-1244-0
36. Malabi Eberhardt, L.C., van Stijn, A., Nygaard Rasmussen, F., Birkved, M. and Birgisdottir, H., 2020. Development of a life cycle assessment allocation approach for circular economy in the built environment. Sustainability, 12(22), p.9579. https://doi.org/10.3390/su12229579
37. Ecoinvent (2013e). Heat production, at hard coal industrial furnace, Alloc Def, U. Ecoinvent System Processes. Swiss Centre for Life Cycle Inventories.
38. Ecoinvent (2013f). Market for iron ore, beneficiated, 65% Fe GLO. Ecoinvent System Processes. Swiss Centre for Life Cycle Inventories.
39. Ecoinvent (2013g). Polyethylene, high density, granulate production (RoW), Alloc Def, U. Ecoinvent System Processes. Swiss Centre for Life Cycle Inventories.
40. Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., & Rosenbaum, R. (2003). IMPACT 2002+: a new life cycle impact assessment methodology. *The International Journal of Life Cycle Assessment*, *8*(6), 324-330. https://doi.org/10.1007/BF02978505
41. Fishburn, P.C., 1967. Methods of estimating additive utilities. *Management science*, *13*(7), pp.435-453. https://doi.org/10.1287/mnsc.13.7.435
42. MacCrimmon, K.R., 1968. *Decision-making among multiple-attribute alternatives: a survey and consolidated approach*. Rand Corp Santa Monica Ca.
43. Hossain, M.U., Liu, J.C., Xuan, D., Ng, S.T., Ye, H. and Abdulla, S.J., 2022. Designing sustainable concrete mixes with potentially alternative binder systems: Multi-criteria decision-making process. *Journal of Building Engineering*, *45*, p.103587. https://doi.org/10.1016/j.jobe.2021.103587
44. Akbar, A. and Liew, K.M., 2021. Multi-criteria performance evaluation of fiber-reinforced cement composites: An environmental perspective. *Composites Part B: Engineering*, *218*, p.108937. https://doi.org/10.1016/j.compositesb.2021.108937
45. Broad Group (2022). Broad group drawings http://en.broad.com/ProductShow-111.aspx [assessed, 15/05/2022].
46. Hossain, M. U., Poon, C. S., Lo, I. M. C., & Cheng, J. C. P. (2017). Comparative LCA on using waste materials in the cement industry: A Hong Kong case study. *Resources, Conservation and Recycling*, *120*, 199-208. https://doi.org/10.1016/j.resconrec.2016.12.012
47. Figueiredo, K., Pierott, R., Hammad, A. W. A., & Haddad, A. (2021). Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP. *Building and Environment*, *196*, 107805. https://doi.org/10.1016/j.buildenv.2021.107805

48. Geldermans, R.J., 2016. Design for change and circularity–accommodating circular material & product flows in construction. *Energy Procedia*, *96*, pp.301-311. https://doi.org/10.1016/j.egypro.2016.09.153

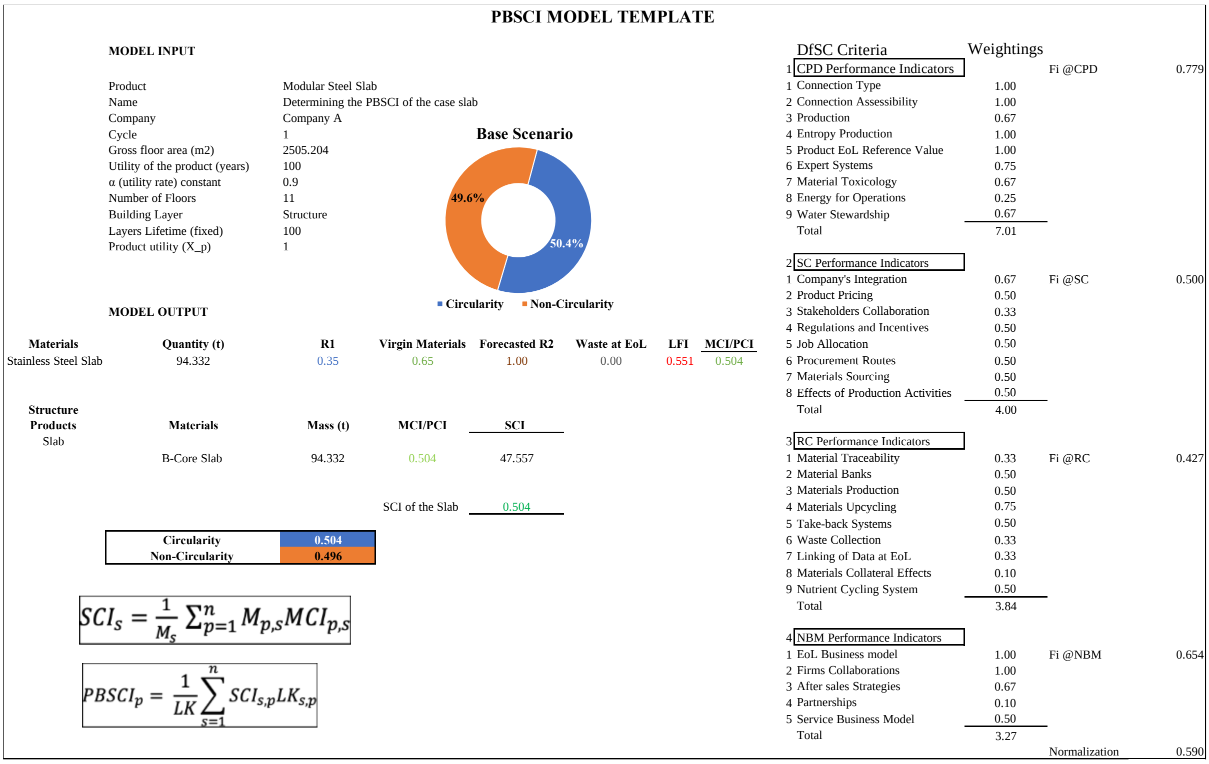
49. Favi, C., Germani, M., Luzi, A., Mandolini, M. and Marconi, M., 2017. A design for EoL approach and metrics to favour closed-loop scenarios for products. *International Journal of Sustainable Engineering*, *10*(3), pp.136-146. https://doi.org/10.1080/19397038.2016.1270369

50. Teng, Y. and Pan, W., 2020. Estimating and minimizing embodied carbon of prefabricated high-rise residential buildings considering parameter, scenario and model uncertainties. *Building and environment*, *180*, p.106951. https://doi.org/10.1016/j.buildenv.2020.106951

51. Balasbaneh, A.T., Sher, W., Yeoh, D. and Koushfar, K., 2022. LCA & LCC analysis of hybrid glued laminated Timber–Concrete composite floor slab system. *Journal of Building Engineering*, *49*, p.104005. https://doi.org/10.1016/j.jobe.2022.104005

8. Appendix A. Supplementary Information

9. Appendix B.



PBSCI MODEL TEMPLATE

MODEL INPUT

Product	Modular Steel Slab
Name	Determining the PBSCI of the case slab
Company	Company A
Cycle	1
Gross floor area (m2)	2505.204
Utility of the product (years)	100
α (utility rate) constant	0.9
Number of Floors	11
Building Layer	Structure
Layers Lifetime (fixed)	100
Product utility (X_p)	1

MODEL OUTPUT

Materials	Quantity (t)	R1	Virgin Materials	Forecasted R2	Waste at EoL	LFI	MCI/PCI
Stainless Steel Slab	94.332	0.35	0.65	1.00	0.00	0.551	0.504

Structure Products	Materials	Mass (t)	MCI/PCI	SCI
Slab				
	B-Core Slab	94.332	0.504	47.557
			SCI of the Slab	0.504

Circularity	**0.504**
Non-Circularity	**0.496**

$$SCI_s = \frac{1}{M_s} \sum_{p=1}^{n} M_{p,s} MCI_{p,s}$$

$$PBSCI_p = \frac{1}{LK} \sum_{s=1}^{n} SCI_{s,p} LK_{s,p}$$

	DfSC Criteria	Weightings		
1	CPD Performance Indicators		Fi @CPD	0.779
1	Connection Type	1.00		
2	Connection Assessibility	1.00		
3	Production	0.67		
4	Entropy Production	1.00		
5	Product EoL Reference Value	1.00		
6	Expert Systems	0.75		
7	Material Toxicology	0.67		
8	Energy for Operations	0.25		
9	Water Stewardship	0.67		
	Total	7.01		
2	SC Performance Indicators			
1	Company's Integration	0.67	Fi @SC	0.500
2	Product Pricing	0.50		
3	Stakeholders Collaboration	0.33		
4	Regulations and Incentives	0.50		
5	Job Allocation	0.50		
6	Procurement Routes	0.50		
7	Materials Sourcing	0.50		
8	Effects of Production Activities	0.50		
	Total	4.00		
3	RC Performance Indicators			
1	Material Traceability	0.33	Fi @RC	0.427
2	Material Banks	0.50		
3	Materials Production	0.50		
4	Materials Upcycling	0.75		
5	Take-back Systems	0.50		
6	Waste Collection	0.33		
7	Linking of Data at EoL	0.33		
8	Materials Collateral Effects	0.10		
9	Nutrient Cycling System	0.50		
	Total	3.84		
4	NBM Performance Indicators			
1	EoL Business model	1.00	Fi @NBM	0.654
2	Firms Collaborations	1.00		
3	After sales Strategies	0.67		
4	Partnerships	0.10		
5	Service Business Model	0.50		
	Total	3.27		
			Normalization	0.590