Implementing Circular Economy in the Construction Sector: Evaluating CE Strategies by Developing a Framework

Zahra Hosseini,[a,]* Bertrand Laratte,[b] and Pierre Blanchet [a]

Among various industries, the construction sector has one of the greatest impacts on the environment. Minimizing the resource use and the waste outputs in this sector could be fulfilled by applying circular economy (CE) strategies. Although research on CE in the construction sector has increased in recent years, there have not been remarkable adjustments by applying these strategies to the construction industry. The purpose of this study was to examine the impacts of using CE strategies in the construction sector. A framework was adapted to guide the application of different CE strategies at the end-of-life of buildings. The framework was assessed by a case study of a residential building in mass timber. This study evaluated the application of CE strategies from the environmental aspect with the life cycle assessment (LCA) method. The results confirmed that circular strategies can deliver lower environmental impacts.

DOI: 10.15376/biores.18.3.4699-4722

Keywords: Circular economy; Construction sector; Framework; End-of-life; Strategies; Life cycle assessment

Contact information: a: NSERC Industrial Research Chair on Eco-responsible Wood Construction (CIRCERB), Laval University, Department of Wood and Forest Sciences, 2425 De La Terrasse Street, Québec City, QC G1V 0A6, Canada; b: Arts et Métiers Institute of Technology, University of Bordeaux, CNRS, Bordeaux INP, INRAE, I2M Bordeaux, F-33400 Talence, France;
** Corresponding author: zahra.hosseini.1@ulaval.ca*

INTRODUCTION

Circular economy (CE) can be regarded as a recent concept that has emerged in the field of sustainability. The CE concept attempts to replace linear systems with circular ones and to separate economic growth from the consumption of non-renewable materials and environmental degradation (Masi *et al.* 2017). In contrast to the linear economy and the traditional take, make, dispose model (Eberhardt *et al.* 2019), CE seeks to keep materials in loops and thus, to reduce the amount of generated waste and resource usage. The concept of CE was first introduced in 1990 by Pearce and Turner (1990) and it was described when the environmental concepts were emerging in linear economy. According to Kirchherr *et al.* (2017), CE describes an economic system based on business models that replace the concept of end-of-life with reduction, alternative reuse, recycling, and recovery of materials in production and consumption stages. This definition indicates that there is no single CE practice to apply throughout the value chain, and that these strategies can vary among industries. To implement CE in an industry it is important to know how the system works. Therefore, the processes, business models, and the involved actors must be clearly identified. Transforming from a linear approach to a circular one is a challenging task because most organizations are used to their linear economy model. Changing toward circularity requires time and it can impose costs (Zhu *et al.* 2010) as organizations are required to redefine their supply chain (Kazancoglu *et al.* 2018) and establish communication among the actors along the chain.

CE concepts have also been put into practice in some governmental programs on national levels. In 1996 Germany became the first to implement CE principles as a part of Closed Substance Cycle and Waste Management Act (Su *et al.* 2013) and addressed the waste disposal. After Japan, which established a law to valorize recycling in 2002, the Circular Economy Promotion Law of the People's Republic of China was declared in 2008, which introduced three strategies as main activities for CE. The reduction of natural resource use and waste generation, the reuse of waste in the form of new products, and the recycling of wastes were announced as the activities, representing the 3R framework for CE (PRC 2008). By adding the recovery strategy to the 3R framework, the 4R framework of the circular economy was developed and became the core of the European Union's Waste Framework Directive (Kirchherr *et al.* 2017).

Table 1. 10R Circularity Strategies (adapted from Potting *et al.* (2017))

Category	Circularity level	Strategy	Definition
Smarter product use and manufacture	R0	Refuse	Abandoning a product’s function or offering the same function with different product to eliminate it
	R1	Rethink	Make product use more intensive
	R2	Reduce	Increase the efficiency of product manufacture by using fewer resources
Extend lifespan of product and its parts	R3	Reuse	Re-use product by another consumer in the original function
	R4	Repair	Repair a defective product to be used in its original function
	R5	Refurbish	Bring an old product up to date
	R6	Remanufacture	Use parts of discarded product in new products in their original function
	R7	Repurpose	Use parts of discarded product in new products in different functions
Useful application of materials	R8	Recycle	Process materials for obtaining the same or lower quality
	R9	Recovery	Incineration and energy production

Although the fundamental aspects of CE are the same, there are several schools of thought and researchers have proposed different descriptions for circular economy (Alkhuzaim *et al.* 2021). According to Goddin and Marshall (2019) CE can be defined by three main principles: eliminating pollution and waste generation, circulating the materials, and the regenerative processes of nature. In a more specific direction, the definition of CE in the province of Quebec, Canada, highlighted three main concepts of reducing the consumption, extending the life of a product, and finding an inventive way to use products (Pouliot 2021). These concepts imply the use of CE in an early stage, and especially in the design phase of a product. The existence of different definitions for CE in the literature shows that the definition of CE varies according to the sector of application.

CE can also be described through a series of strategies and frameworks. After the 3R and 4R lists, the 6R list was formed by adding re-design and remanufacturing activities to the 4R list (Sihvonen and Ritola 2015). These developments continued and provided the most comprehensive list so far, the 10R list, which was mentioned in Potting *et al.* (2017). In this list ten strategies are introduced for moving towards circularity. The steps are grouped into three main categories: practical application of materials, extending product life, and using products more efficiently. The strategies are ranked according to the level of circularity they impose on a system. The list of these strategies as well as their description are presented in Table 1.

As indicated in the categories, R0, R1, and R2 are the strategies that apply the highest level of circularity in the design stage of the products. Followed by the strategies that are applied to prolong the lifetime (R3 to R7), this list mentions the least circular strategies such as recycling (R8) and recovery (R9) that are applied at the end-of-life phase of a product to avoid landfilling.

Circular Economy in Construction Sector

The shift towards a circular economy is not easy (Pouliot 2021), and the need for this shift is crucial when the aim is to address environmental sustainability within sophisticated supply chains such as the construction sector (Alkhuzaim *et al.* 2021). The construction sector is responsible for extracting about 40% of the world's resources (Ness and Xing 2017), generating about a quarter of the solid waste in the world (Benachio *et al.* 2020), and producing a third of the global greenhouse gas emissions (Ness and Xing 2017). Using the linear economic models in the construction sector beside the growth in the population and increasing demands for constructions are the reasons for this destructive behavior (Jeffries 2021). Increasing concerns about the environment highlight the necessity of CE and its application in the building and construction sector (Ghufran *et al.* 2022). To ease the transition towards the application of CE in the construction sector some solutions are already proposed (Jeffries 2021); however, a full conversion to this model is still needed.

As indicated in Boza-Kiss and Bertoldi (2018), the building processes in the construction sector include material supply, product manufacturing, design and construction, use and maintenance phase, and the end-of-life phase. The application of CE strategies in the construction sector can be considered in any of these steps.

There has been a significant growth in the number of CE studies in the construction sector since 2017 (Hossain *et al.* 2020); however, there are few examples of applying CE in construction. The barriers for applying CE in this sector have been categorized in six groups (Osei-Tutu *et al.* 2022). These include the low cost of virgin materials and high prices of recycled materials (Ghisellini *et al.* 2018; Huang *et al.* 2018), the lack of a quality standard for materials to be used after their recycling process (Alberto López Ruiz *et al.* 2020), the low demand of recycled materials (Lockrey *et al.* 2016; Nußholz *et al.* 2019), the lack of regulations regarding construction and demolition waste management and environmental costs (Lockrey *et al.* 2016; Nußholz *et al.* 2019), and the low cost of landfilling waste (Ghisellini *et al.* 2018; Singhal *et al.* 2020).

Circularity paves the way to apply sustainability in the construction sector (Munaro *et al.* 2020), and applying CE is a prerequisite for having more sustainable and resistant construction results. Sustainability has been mostly described as involving three pillars: environmental, economic, and social (Anastasiades *et al.* 2020), which could also refer to three aspects that CE have impacts on (Corona *et al.* 2019). Kirchher *et al.* (2017) define sustainability as a goal to be achieved, and circular economy (CE) as the tool for reaching this goal. The increased attention towards sustainability and circularity reflects developing performance measures throughout the supply chain (Alkhuzaim *et al.* 2021).

This study is intended to facilitate the application of CE in the construction sector. By resolving one of the barriers in the literature, the goal of this study is to adapt and develop a framework to evaluate the utilization of CE in buildings and therefore to aid in the application of circular strategies at the end-of-life of buildings. By highlighting the importance of CE in the built and construction sector, at first a definition for CE will be proposed. Then, by having a methodological approach, a framework for evaluating CE will be developed. Later, tools and evaluation methods will be defined and finally the application of the framework will be evaluated from the environmental aspect.

Frameworks for Applying CE

The construction sector is currently in the early stages of implementing CE (Hossain and Ng 2018). To have a clearer perspective on how to use CE in the construction sector and to ease the transition to a circular approach, some frameworks have been proposed. Hossain *et al.* (2020) suggested a framework for implementing the CE in sustainable constructions. Their framework includes modular design, reuse, recycling initiatives, and repair techniques to recover the materials after deconstruction. This framework also considers the usage of waste as resources in different industries, by circulating materials in open loops. The framework created by López Ruiz *et al.* (2020) highlighted the use of CE for treating construction and demolition wastes (C&DW). This framework concentrated on the end-of-life of buildings and was based on the 3R CE principle in the construction and demolition waste management. This framework was then specialized in López Ruiz *et al.* (2022) for the application of CE for concrete wastes in the construction sector.

By putting up a framework, Hentges *et al.* (2022) discussed the possibilities of implementing circular economy in the Brazilian construction sector. Possibilities such as waste sorting, valorizing wastes, and incorporating wastes from other industries were depicted as some of the opportunities to apply circular economy in the construction industry. In the framework proposed by Rahla *et al.* (2021), deconstruction of the building and reuse, using recycled materials in the production stage, and repair concepts were suggested as activities to implement CE in the construction sector. Their proposed framework emphasized the importance of using CE in the design stage, as well as for waste generation to keep the materials in closed loops. Another framework by Lei *et al.* (2021), emphasized the use of LCA as a tool to evaluate CE application from the environmental aspect. This framework also valued the importance of having a proper definition for circularity and sustainability. In 2022, Charef (2022) proposed a theoretical framework to show how CE strategies could be applied in the construction sector. This comprehensive framework was designed for different phases of a construction: design, construction, use and end-of-life, in the context of Building Information Modelling (BIM). This framework considers the recycling, reusing, and recovery strategies, as well as the impacts of remanufacturing and refurbishment as the mentioned CE strategies.

Collaboration among the actors along the supply chain, from the designer and project managers to the suppliers, stakeholders, and the clients, is necessary for enhancing CE in the construction industry. The benefits of CE must be introduced to all actors in order to create an efficient collaboration for having a successful CE application (Hossain *et al.* 2020). Having all these frameworks, the application of CE in the built and construction sector has not evolved much yet and developing guidelines for employing CE in this sector is obscure (Hossain and Ng 2018). So far, the frameworks have studied limited CE strategies for the application of CE, while the most complete CE list contains 10R strategies. The theoretical concepts for CE that already exist need to be translated into a practical framework that can evaluate the various levels of circularity in constructions.

Methods for Evaluating CE in Construction Sector

As mentioned earlier, CE implementation can be evaluated from three different aspects. With the increasing complexity of supply chains, the concept of CE has gained significance in addressing environmental sustainability issues (Alkhuzaim *et al.* 2021). The literature offers a variety of methods to do this evaluation, most of which evaluate the environmental aspect of CE. Saidani *et al.* (2022) mentioned that CE evaluation methods could be categorized in different scopes and scales. This means that these methods can evaluate the performances under the effects of circular approaches in macro, micro, or the meso level, for different study boundaries. A list of the more frequently used methods for measuring the environmental aspect of CE in the literature is presented here:

- In Hossain *et al.* (2020), the Life Cycle Assessment (LCA) approach was introduced as the most used method in the construction sector for analyzing CE. This method evaluates the potential environmental impacts of processes in all the stages in the construction of a building (Perminova *et al.* 2016).
- Material Flow Analysis (MFA) and the Input-Output method (IO), which can aid in better regulating the usage of resources and waste generation (Alkhuzaim *et al.* 2021), were noted as other methods for CE evaluation by Hossain *et al.* (2020). In MFA the flow of materials in each direction is precise, which then can be evaluated from the economical aspect by the IO method. As MFA is considered as the foundation of resource conservation and the first step for LCA, it must be taken into consideration in conjunction with LCA (Brunner and Rechberger 2004).
- Life Cycle Costing assessment (LCCA) and Sustainability Performance Assessment are two other techniques for CE evaluation. LCCA is used to expresses environmental problems in financial values, while sustainability performance assessment can measure the supply chain sustainability as well as product development sustainability (Alkhuzaim *et al.* 2021).
- Emergy Analysis (EA) is a method which evaluates the energy use in a system. This approach also known as embodied energy, recognizes all sorts of energy inputs and by quantifying the effects of nature (wind, sun, *etc.*) as well as other energy sources, calculates them all in a single unit, solar emjoules (sej) (Alkhuzaim *et al.* 2021).

Each of these methods employs indicators to assess how well the method is applied. For instance, in LCA, environmental indicators such as global warming potential (GWP), acidification, ozone depletion, ecotoxicity, and fossil fuel depletion could be mentioned as the relevant indicators. In MFA the flow of materials in the system is named as a pertinent indicator and the emergy investment ratio which represents the degree of energy use was mentioned as an indicator for Emergy analysis (Ren *et al.* 2015). Choosing the relevant methods and indicators depends on the study and the scope of the evaluation.

Existing Limitations

Because the construction sector has major environmental implications, adopting CE in this sector could result in reducing these effects. There have been studies on how to implement CE principles on constructions, but the number of constructed buildings based on CE principles are few and it is still challenging for the building industry to fully adopt a circular approach (Rahla *et al.* 2021). As CE concepts are expanded in the construction sector, stakeholders are willing to adopt them in practice, but a paradigm is required to facilitate this shift and bring it into practice (Rahla *et al.* 2021). Previous studies have shown that CE can be defined in several ways, based on the industry and according to different objectives.

Among the proposed frameworks for applying CE, not having detailed instructions, limited end-of-life alternatives, and the consideration of CE in a closed loop system are acknowledged as the existing limitations. The most optimal solution is to extend the perspective and apply CE among all sectors and apply it in open loops. As Charef (2022) indicates, the literature lacks a framework that considers the lifecycle of the materials. It is therefore critical to develop a framework for applying CE strategies and their evaluation. Such a framework also can help in establishing guidelines for supply chain collaborative actor behavior, circular design, and material handling by taking into account all circularity levels.

EXPERIMENTAL

This study provides a framework to evaluate the application of CE strategies in buildings and to ease the shift towards circularity by mentioning the required steps to take. It is anticipated that the presented framework will be adopted by the architects in the design stage of the buildings, researchers, suppliers, and recyclers. Additionally, the framework could be advantageous at the end-of-life (EoL) stage of the buildings, as it presents the opportunities for the second use of the materials and building elements or for the building’s destruction. This framework can also be useful for comparative circularity analysis in future works. To achieve this goal, a research method was developed to do the literature review and to determine the necessary steps to take. Table 2 illustrates the workflow of this study.

Defining Research Scope

The literature review for this research was done among research articles and technical reports. The emphasis of this article was on the published articles in the last five years and between 2017 and 2022, since there was a significant growth in the number of studies on CE (Munaro *et al.* 2020) and CE in the construction sector recently (Hossain *et al.* 2020). The literature research of this study was conducted in accordance with the hermeneutic circle method proposed by Boell and Cecez-Kecmanovic (2010). The scope of this study was limited in order to use the CE framework for evaluating the application of CE strategies on a six-floor residential reference building, designed according to the Canadian regulations and in the context of Montreal in the province of Quebec (Canada).

Table 2. The Methodology of this Study

Step 1- Defining research scope
• Applying CE in construction sector.

Step 2- Literature review
• According to hermeneutic circle method: starting by reviewing articles to survey the general concepts of CE and evaluation methods. • Then restrict the literature to CE in the construction sector, to survey the frameworks and guidelines for CE application, and identify the involved actors.

Step 3- Identifying the gaps and research direction
• Lack of methods to evaluate CE and need for frameworks and directives in the construction sector and for buildings.

Step 4- Developing the solution
• Presenting an adapted definition for CE in this study. • Developing a framework for CE evaluation and according to the definition.

Step 5- Validating the framework
• Designing a reference building. • Evaluating the framework from the environmental aspect.

Literature Review

The research surveyed the existing CE definitions, evaluation methods for CE, proposed frameworks for applying CE, and the role of actors in applying CE in the sector, which were presented in previous sections. To narrow down the list of articles, keywords such as circular economy, circular economy AND building, circular economy AND construction, circular economy AND sustainability, circular economy AND evaluation method and circular economy AND framework were searched. Publications were selected from ScienceDirect and Google Scholar databases.

Reading review articles as the first step of conducting the research is important, since it can provide information on vocabulary use in the field and can bring a list of publications for subsequent literature searches from the cited papers (Boell and Cecez-Kecmanovic 2010). To avoid going back in time by only reading the cited publications in review articles, derivative works of an article were also read. Reading technical reports and governmental documents, participation in international conferences and webinars, as well as attending workshops, were used to identify challenges for the application of CE and identifying the problems.

Identifying the Gaps and Research Direction

Understanding the concepts of CE and its various definitions served as the foundation for this study. As it was concluded that the definition of CE is not exclusive, it was crucial to establish one for CE in the construction sector and within the scope of this study. For having a decent definition of CE, the goals that were going to be attained had to be determined and to be mentioned in the definition.

As the construction sector has a significant impact on the environment, the focus of studies on CE application in this sector has recently increased. Despite the willingness of stakeholders to move towards circularity, this concept has not been put into practice much. The literature review revealed the need for a framework to better lead the application of CE strategies in the construction sector, and by which this application can be evaluated. It is therefore important that the framework be developed for all CE strategies, while considering the impacts of these strategies on the sector. Therefore, identification of the gaps in previous studies led to the development of the proper research questions: how to evaluate the application of CE in the buildings and constructions?

Developing the Solution

To address the research question, it is important to first identify the most relevant CE concepts for the construction sector. Then, it is necessary to discuss the evaluation methodologies and to adapt a framework for evaluating CE.

Adapting a definition for CE in this study

In order to elaborate a definition for CE in this study, it was crucial to identify the most used concepts in the literature. The review of studies revealed that main concepts for CE in the building industry are minimizing the resource use and waste generation. The comprehensive list of CE strategies to date was the 10R list (Table 1). Based on this list and for the construction sector, the least circular method for treating the wastes is the recovery technique which gives value to wastes for generating energy and preventing landfilling. Recycling was the other strategy that was broadly taken into consideration for reducing waste generation at the end-of-life stage. In their study, strategies for prolonging the life of products were introduced as reusing, remanufacturing, and repurposing. Reusing the materials for the same purpose and after their first lifetime is the activity that imposes the highest degree of circularity in this category, as it prevents waste generation and avoids the need for any additional processes. When reusing the product is not applicable, remanufacturing new products from the discarded products for the same function or repurposing them for different functions should be considered. These activities impose additional processes for the second use of products, which is why they are considered as the next level of circularity. For the materials to have the required quality for second use, repairing and refurbishing strategies can play important roles.

The importance of the design strategies and defining proper business models for constructions in accordance with circular models were also noted among the CE strategies in the literature. Named as rethinking and refusing strategies, these strategies can represent implying new designs in constructions to move towards circularity and minimizing the construction of new buildings in the first place.

After characterizing the most common CE strategies in the construction sector, a CE definition for this study was developed. This definition was elaborated in accordance with the sustainability objectives and the aforementioned strategies. As a result, in this study circular economy in the construction sector is defined as a concept for optimizing the sustainability of buildings, conserving materials at their best quality, and minimizing the risks and uncertainties for their future use. These goals are achieved through a decent material selection and building design, and by having regular maintenance activities during the use phase of the building, which result in the reduction of resource use and the conservation of materials in loops while reducing the waste generation in the end-of-life phase of the building.

Developing a framework for evaluating CE in buildings

The proposed trans-scalar CE framework for constructions in Charef (2022), as well as the theoretical framework in Lopez Ruiz *et al.* (2020) were chosen as the bases for the developed framework in this study. The two mentioned frameworks were developed for the whole life cycle of constructions; however, in this study only the end-of-life stage was taken into account. While Lopez Ruiz *et al.* (2020) considered repair, refurbishment, and re-manufacturing strategies as parts of reusing, in this study they have been defined independently, as shown in Fig. 1.

The framework in Hossain *et al.* (2020) was also inspiring to acknowledge the impacts of CE strategies in an open loop system and to apply them to different industries. The developed framework in this study also shows the role of transportation and reveals the relationship among the CE strategies (R1 to R9 in Table 1) at the EoL stage of the building.

Creating a framework that can address the application of CE in the building and construction industry is necessary to facilitate the shift towards circularity in this sector. The proposed framework in this study was developed by linking several CE strategies according to the elaborated CE definition in the previous section and the 10R list. It was crucial that the framework could be assessed by various evaluation methods and therefore, different indicators.

The adaptation of the framework in this study was developed for the end-of-life phase of the buildings. As a result, at the beginning, this framework is questioning the disassembly and separation potential of the building elements. According to the framework, the demolition of a building system is applied only when disassembly is not possible. This framework can be shown in two sections. In section A, which is shown by orange arrows, the strategies are following the demolition of the building. The considered strategies in this section are the least circular ones (landfilling, incineration, and recycling) which result mainly in the elimination of the materials. The red bordered cells in the framework show the termination points; therefore, in section A only the recycling strategy can result in the preservation of materials. Section B on the other hand, which is shown in blue arrows, is considered only when the disassembly of the building is possible. Here, at first the possibility of reusing the products is questioned. When direct reuse is not possible, other circular strategies are considered, which try to preserve parts of a product. The framework was developed for an open-loop system therefore, the use of second-hand materials, different parts and products in the same or a different industry is considered. Section B of the framework will result in reducing the resource consumption and will provide second use of the products or an innovative way to use parts or products. In the framework, the word material is used when it is referred to a primary resource, the ensemble of materials is called a part, and several parts shape a product.

The impacts of applying circular strategies can also be useful in the use phase of buildings and in new designs. For instance, producing energy from the recovery strategy (incineration) can provide energy for the use phase of the buildings. Innovation in building designs by the application of a rethinking strategy can also lead to minimizing the resource consumption in the product stage of the buildings.

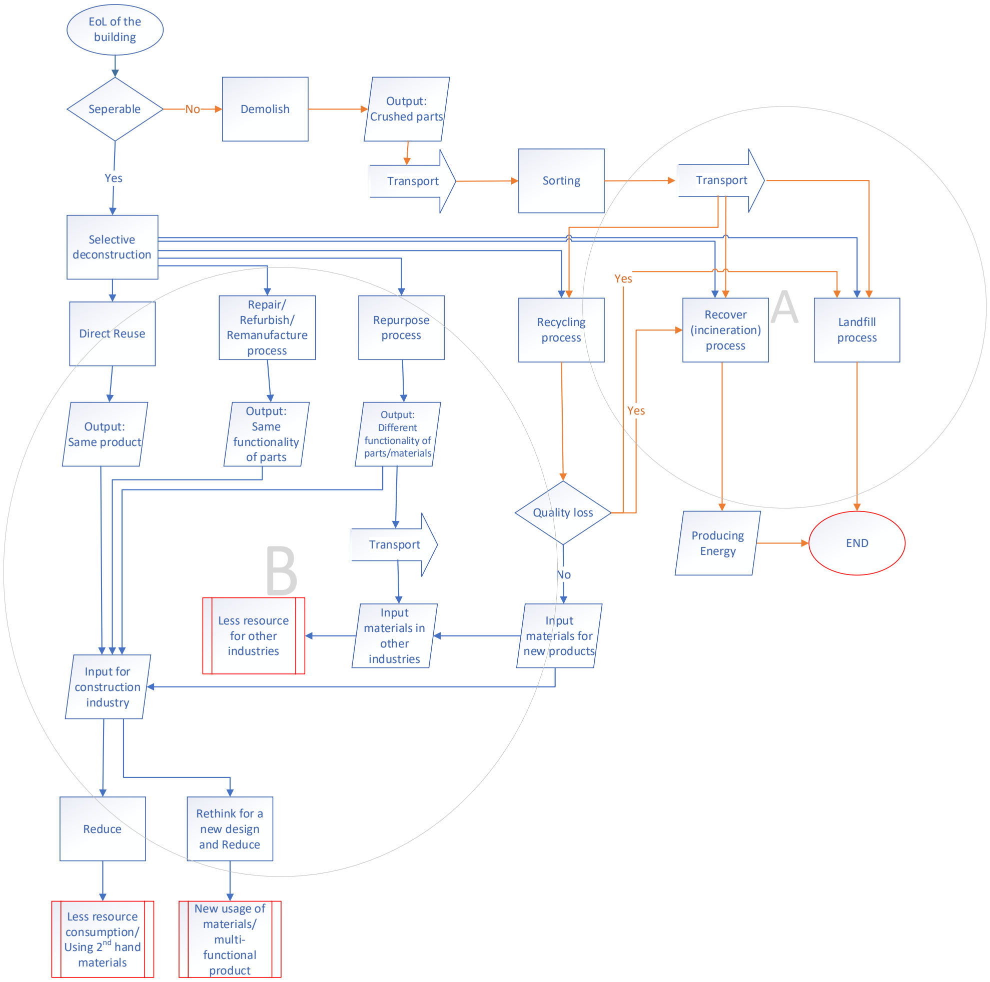

Fig. 1. Simplified framework for evaluating CE in the construction sector and for buildings

Validating the Framework

To evaluate the relevance of the simplified proposed framework in Fig. 1, the framework was applied in a case study. A reference building was designed, and three different scenarios were developed for the end-of-life of the building through the framework to assess its relevance. Mentioning the importance of CE environmental aspect in Alkhuzaim *et al*. (2021), the presented framework was decided to be evaluated from the environmental aspect. As Lei *et al.* (2021) and Hossain *et al.* (2020) emphasized the necessity of the LCA method for evaluating the environmental performances, the evaluation of the framework in this study was chosen to be done by the LCA method.

Description of the designed reference building

To design the reference building according to the regional aspect, it was decided to design a residential building. As stated in Statistics Canada website from 2018, residential buildings account the highest number in issued construction permits compared to commercial or industrial structures (though, the size of the buildings and the mass of the building materials are not considered in this comparison). This highlights the high number of residential building developments in Canada. To represent the local context, it was decided to design a reference building to be built Montreal in the province of Quebec, Canada. It was crucial from an architectural point of view that the building's typology reflects the real state context of the city. As a result, the building was designed as a six-story building with a total building area of 6,196 m^2 in mass timber (Laminated Veneer Lumber (LVL) and Cross Laminated Timber (CLT)). Figure 2 represents the designed reference building, and Table 3 provides the details on the quantity of the building materials.

Fig. 2. The designed residential building in mass timber

Evaluating the framework by LCA method

To better define the boundaries for the application of LCA in the construction sector, the EN 15978:2011 standard was used (Fig. 3). Based on this standard, four main stages are counted in the life cycle of a building and each of these stages are defined by a set of practices. In this standard, the impacts of recycling, reuse and recovery strategies are mentioned by a stage beyond the life cycle of the building.

Life Cycle of a Building																Benefits and Loads beyond the System Boundary
Product stage			Construction stage		Use stage							End-of-life stage				
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Resource extraction	Transport	Manufacture	Transport	Construction process	Use	Maintenance	Repair	Replace	Refurbish	Operational energy use	Operational water use	Deconstruction	Transport	Waste process	Disposal	Reuse/ Recovery/ Recycling potential

Fig. 3. Life cycle of the buildings according to the EN 15978:2011 standard (adapted from Lei *et al.* (2021) and EN 15978 (2011))

The simplified presented framework in Fig. 1 could be mentioned as a complementary step to this standard. For better explanation of the impacts of phase D of this standard, this framework can show the benefits of the circular strategies on the other phases of the life cycle of buildings, such as design, construction, or use phase.

In this study, as the focus of the presented framework was to evaluate the impacts of looping the materials between the end-of-life stage and the use of resources in the production stage of the buildings, the LCA method was applied by the consideration of A1, A2, A3, C2, C3, C4, and D stages (grey cells in Fig. 3). According to Quéheille *et al.* (2022), these stages are having the highest impacts on the environmental performances. Moreover, the energy usage for the maintenance (B2), repair (B3), replacement (B4), and refurbishment (B5) of the structural elements of the buildings are the same in three scenarios. Therefore, they are not considered as variables in the analysis as they do not affect the results. Consideration of stage D is possible by developing strategies, using the proposed framework.

As mentioned earlier, three scenarios were described for the reference building to evaluate the framework. The development of scenarios was according to the framework, as they involve different paths of the framework.

The first scenario in the case study is known as the worst-case scenario for all the materials. Scenario 1 only considers the demolishing of the buildings, where all materials are landfilled at their EoL (except for wood and bitumen sheet, which are incinerated). Representing section A of the framework, this scenario takes the orange paths through landfilling and recovery strategies and results in elimination of the materials. Scenario2 was developed for the recycling of materials, where a material with the potential of recycling is 100% recycled. The recycling of concrete, steel, wood, and brick were also considered in open loops. Taking the path through selective deconstruction and recycling strategy, this scenario entails impact reduction by means of resource usage in a second building. Finally, scenario3 is defined as the best-case scenario, considering the reuse potential of materials (wood and steel) and is developed through selective deconstruction and the direct reuse of parts of the framework. To evaluate the impacts of reuse and recycling strategies, it was necessary to apply the LCA for the functional unit (FU) of two buildings. In all three scenarios, the production of the materials for the first building was considered to be from virgin materials. In the second and the third scenarios, where a second life is given to the materials at the EoL of the first building, it is considered that there would be a reduction in resource use for the construction of the second building. This study only considers the materials used in the building envelope, building structure and the foundation. The considered strategies in the three elaborated scenarios are shown in detail in Table 3.

To evaluate the framework from the environmental aspect, LCA method was applied. OpenLCA software was used to do the LCA by using TRACI 2.1 impact assessment method, as this method was developed for the United States (Acero *et al.* 2015) and better represents the North American context (Larivière-Lajoie *et al.* 2022). The processes for the LCA model of the reference building were chosen from ecoinvent 3.6, Cut-Off database; however, some changes were made in the input data of electricity and heating processes to have relevant processes to represent processes in Quebec (Canada). Due to the limited number of available processes in the database, when the exact production process of a material did not exist, the most similar available process was chosen instead.

Table 3. Quantity of Materials in the Designed Building and the Considered Scenarios at the EoL of Each Material

Building Elements	**Materials**	**Quantity (kg)**	**Scenario1**		**Scenario2**		**Scenario3**	
			Building 1	**Building 2**	**Building 1**	**Building 2**	**Building 1**	**Building 2**
Interior and partition walls	Metal studs	31973.05	Landfilling	Landfilling	Recycling	Landfilling	Reusing	Recycling
	Insulation	9220.64	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Gypsum board	195125	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
Beams	LVL	47705.56	Incineration	Incineration	Recycling	Incineration	Reusing	Recycling
Columns	Concrete	61193.4	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	CLT	150394	Incineration	Incineration	Recycling	Incineration	Reusing	Recycling
	LVL	38436.72	Incineration	Incineration	Recycling	Incineration	Reusing	Recycling
Foundation	Concrete	683176	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Insulation	1762.5	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
Exterior walls	Brick	271707	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Insulation	8655.6	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Metal studs	8040.755	Landfilling	Landfilling	Recycling	Landfilling	Reusing	Recycling
	Gypsum board	25018.04	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
Floors	Concrete	855925.5	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	CLT	406974.4	Incineration	Incineration	Recycling	Incineration	Reusing	Recycling
	Lumber	2982.9616	Incineration	Incineration	Recycling	Incineration	Reusing	Recycling
	Insulation	4141.6	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Gypsum board	4761.2	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Bitumen sheet	494.4	Incineration	Incineration	Recycling	Incineration	Recycling	Incineration
	Steel	15700	Landfilling	Landfilling	Recycling	Landfilling	Reusing	Recycling
Roof	CLT	81987.64	Incineration	Incineration	Recycling	Incineration	Reusing	Recycling
	Insulation	11910	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Brick	2410.8	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Gypsum board	29933.46	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Bitumen sheet	5912	Incineration	Incineration	Recycling	Incineration	Recycling	Incineration
Parapets	Lumber and Plywood	1403.2821	Incineration	Incineration	Recycling	Incineration	Reusing	Recycling
	Brick	17441.4	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Insulation	1461.6	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Gypsum board	2618.56	Landfilling	Landfilling	Recycling	Landfilling	Recycling	Landfilling
	Steel	634	Landfilling	Landfilling	Recycling	Landfilling	Reusing	Recycling
	Bitumen sheet	659	Incineration	Incineration	Recycling	Incineration	Recycling	Incineration

RESULTS AND DISCUSSION

A relevant framework for evaluating CE in buildings must consider the type of the building, the building's elements and materials, and transportation (Hossain *et al.* 2020). In addition to the CE strategies, the framework must be tailored for buildings' elements and materials. The proposed framework in this study aims to evaluate the circularity in the building and construction sector and guides toward a circular approach. In this section, the framework is validated by being applied in the EoL stage of the designed building.

LCA Results and Discussion

In the construction of the designed mass timber building, eight elements were considered, as shown in Fig. 4. The elements in order of their contribution in the total weight of the building materials (kg) are floor and slabs, foundation, exterior walls, columns, interior and partition walls, roof, beams, and studs. The data for the construction of this building shows that concrete, CLT, gypsum, LVL, and steel account for 53%, 22%, 8%, 3%, and 2% of the total mass of materials, respectively.

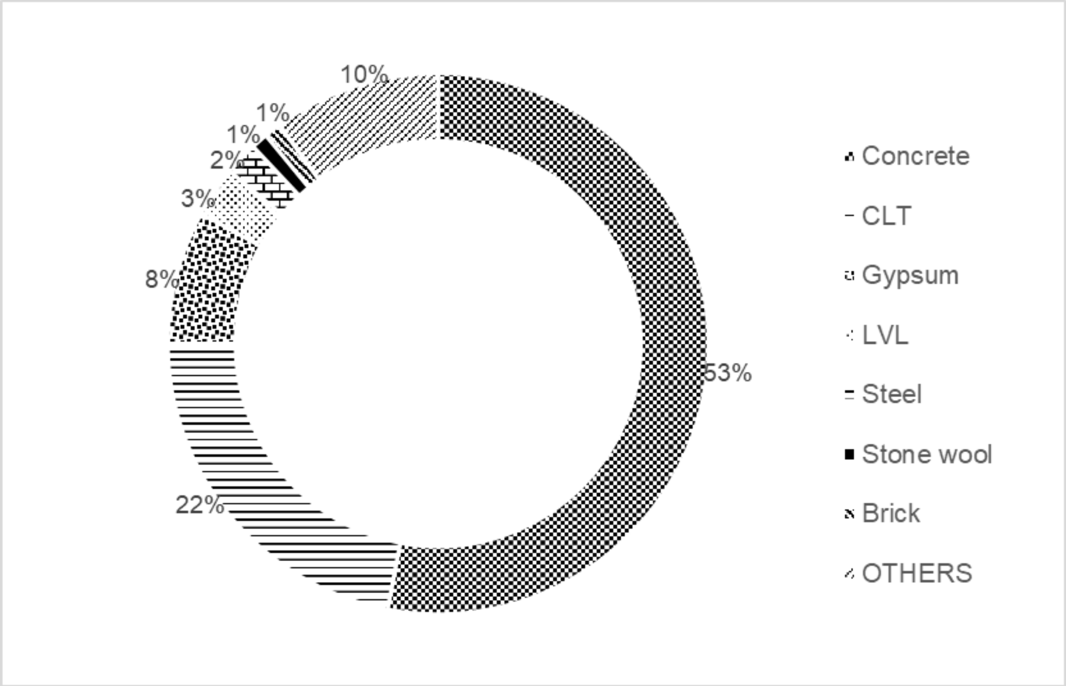

Fig. 4. The contribution of building materials in the modelled mass timber building

Obtaining the LCA results for scenario 1 shows the most impactful materials in each impact category (Fig. 5). Shaping the two highest contribution of materials, Fig. 5 shows that CLT and steel cause the highest impacts on most of the impact categories. This figure reveals that the weight of the materials does not necessarily represent the impact of them; yet the impacts are greatly influenced by the production processes.

By applying LCA for all three scenarios, the performance of each scenario was compared in the 10 different impact categories of the TRACI 2.1 assessment method, as shown in Fig. 6. To present the results in one graph, as the scales of the indicators in the impact categories are different, Fig. 6 considers the highest number in each impact category as 100%.

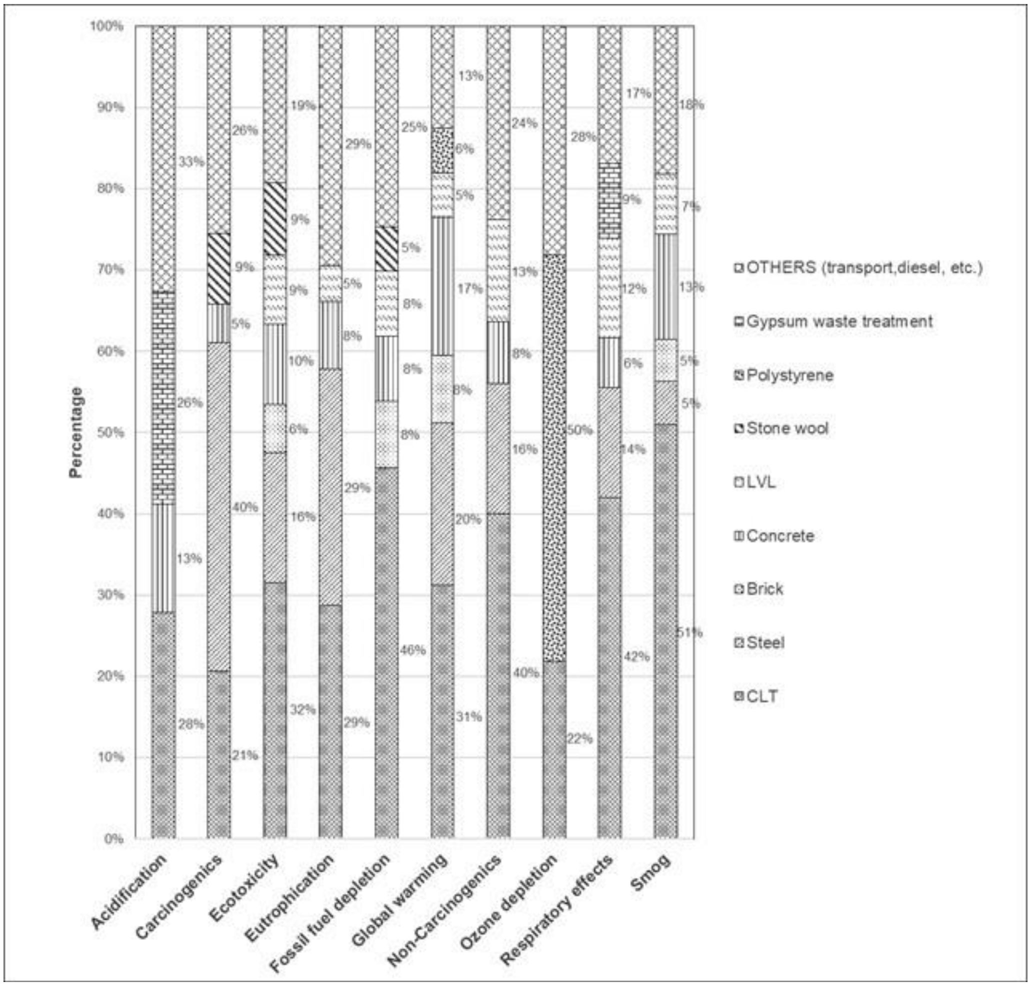

Fig. 5. Characterized LCA results for the production stage of the buildings in the FU

Figure 6 indicates that the consideration of CE strategies can enhance the environmental performances in all the impact categories, as the striped and dotted bars show a noticeable reduction in each impact category. As it is shown in Fig. 1, if recycling strategy does not cause a reduction in the quality, the recycled materials can be taken into account as the resources for products in open loops. As an example, in a recycling scenario, for implying the impacts of recycling wood, it was considered that the recycled wood replaces the wood chips in the production of particleboards. Following this assumption, the process of wood chips is eliminated from particleboard production. These impacts are applied as negative values to represent the benefits of the process of recycling wood in the LCA. As a result, this strategy has a direct impact in reducing the resource usage. Same for the repurposing strategy, the application of this strategy in this study is considered only when it is beneficial for material supply in other industries. Reuse strategy, on the other hand, impacts the supply of the final product and not only reduces the resource use, but also results in the elimination of the production processes. It relates to reusing the product in the construction industry with the same functionality, and its benefits are applied in the construction of the second building of the FU. For developing the reuse scenario, only the reuse of wood and steel (the two materials with the highest impacts in all impact categories) were considered. Therefore, it was assumed that only the wooden beams, columns, floors and the roof, as well as the used steel in walls and floors are reused. Same as the recycling scenario, the impacts of reuse strategies were applied by negative values. By eliminating the production process of building elements in the second building, reuse strategy directly affects the construction sector. In summary, as the recycling strategy would apply extra processing to the building system and only reduce the amount of resource use, its application cause fewer changes than reusing strategy where no extra process is applied to the system and a building element is considered to be entirely reused.

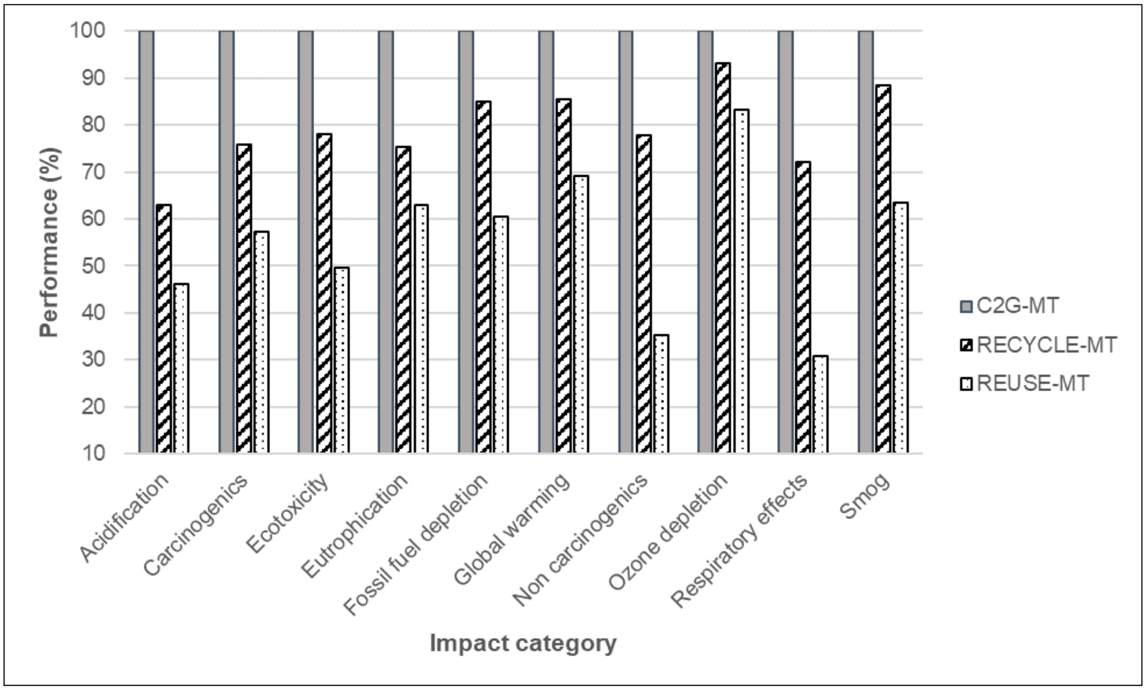

Fig. 6. The LCA results of three scenarios in ten different impact categories of TRACI 2.1: MT: mass timber building, C2G-MT: Scenario1, RECYCLE-MT: Scenario2, REUSE-MT: Scenario3

The detailed results of the LCA for each scenario in each impact category are presented in Table 4. This table also shows the difference among scenarios in a two-by-two comparison in percentages. The comparison among scenarios is possible through each impact category individually; however, the uncertainty of the impacts categories should be considered.

Although the circular strategies showed better performance in all impact categories in Fig. 6, it cannot be certainly claimed that they have better performance in all categories, as a minimum deviation has to be respected for comparing scenarios. Table 4 also represents the minimum deviation that is required for comparing two scenarios in each impact category, based on two different references. The attributed numbers to the uncertainties were done according to the qualitative definition by Jolliet *et al.* (2003) and the minimum deviations defined by Humbert *et al.* (2009). In these studies, the uncertainties were defined for the IMPACT 2002+ impact assessment method, which was then adapted for the TRACI 2.1 method in this study. As smog does not exist in IMPACT 2002+method, no deviation could be defined for it.

Table 4. LCA Results Obtained from OpenLCA Software for Each Scenario in Impact Categories, Difference among Scenarios and the Required Deviation for Comparison in Each Impact Category

Impact Category (Unit)	**Scenario 1 Landfilling**	**Scenario 2 Recycling**	**Scenario 3 Reuse**	**Benefits of Recycling *vs.* Landfilling**	**Benefits of Reuse *vs.* Landfilling**	**Benefits of Reuse *vs.* Recycling**	**Minimum required deviation** (adapted and adjusted from (Jolliet *et al.* 2003))	**Minimum required deviation** (Humbert *et al.* 2009)
Acidification (kg SO_2 eq)	1.50E+04	9.49E+03	6.94E+03	37%	54%	27%	30%	30%
Carcinogenics (CTUh)	1.77E-01	1.34E-01	1.01E-01	24%	43%	24%	90%	-
Ecotoxicity (CTUe)	2.65E+07	2.07E+07	1.32E+07	22%	50%	36%	90%	order of magnitude (factor 10)
Eutrophication (kg N eq)	6.00E+03	4.52E+03	3.78E+03	25%	37%	17%	30%	30%
Fossil fuel depletion (MJ surplus)	2.90E+06	2.46E+06	1.75E+06	15%	40%	29%	10%	10%
Global warming (kg CO_2 eq)	1.96E+06	1.67E+06	1.35E+06	15%	31%	19%	10%	10%
Non carcinogenics (CTUh)	6.11E-01	4.75E-01	2.16E-01	22%	65%	55%	90%	-
Ozone depletion (kg CFC-11 eq)	5.43E-01	5.05E-01	4.51E-01	7%	17%	11%	50%	-
Respiratory effects (kg PM2.5 eq)	2.57E+03	1.85E+03	7.94E+02	28%	69%	57%	50%	30%
Smog (kg O_3 eq)	2.20E+05	1.95E+05	1.40E+05	12%	37%	28%	-	-

The green cells in Table 4 show where it is possible to compare scenarios regarding their performance. In the acidification category, choosing either the recycling or the reuse strategy over landfilling results in better performance. Between recycling and reusing strategies, due to the uncertainties of the models and the minimum required deviation which is 30%, it cannot be decided which scenario can be chosen over the other, as the difference between performance of these two scenarios is only 27%. In the eutrophication category, it can certainly be claimed that reusing gives better results than landfilling strategy, but it cannot be said if it has better impacts than recycling, as the difference between the results are lower than the minimum required deviation. For fossil fuel depletion and global warming categories, considering a circular strategy at the EoL results in better performances. Among the circular strategies, reusing is chosen over recycling and brings more circularity. By respecting the minimum required deviation in the respiratory effects category, it can be concluded that the reuse strategy performs certainly better than recycling or landfilling. In the rest of the impact categories, as the difference among scenarios do not satisfy the minimum required deviation, no scenario can be chosen over others.

Following these interpretations, the detailed results based on the lifecycle stage of the building in the five impact categories of acidification, eutrophication, fossil fuel depletion, global warming, and respiratory effects are presented in Fig. 7. This figure represents the contribution of building life cycle stages for the three considered scenarios, on the environmental impacts. As indicated in this figure, the production stage has the most impact in all the impact categories for all scenarios. Considered the same among all three scenarios, the impacts of production stage can be reduced by the benefits of circular strategies. Figure 7 indicates that applying reuse and recycling strategies at the EoL stage of the building results in reducing the waste treatment impacts and provides a reduction in the total environmental impacts.

The main contribution of this study was the adaptation of a framework, which aids in evaluating different CE strategies at the EoL of the buildings. The developed CE scenarios were evaluated from the environmental aspect and then were compared. The results of this study demonstrate that the adoption of circular perspective, in accordance with the suggested framework in the construction sector, provides advantages from the environmental aspect for the designed building in mass timber. The consideration of CE strategies resulted in a reduction of impacts in all the studied impact categories. Similar results were presented in Coelho and de Brito (2012), Ram *et al*. (2020), and Mesa *et al*. (2021), where the consideration of recycling strategy provided improvements in environmental performance in constructions compared to landfilling. However, in this study the impacts of uncertainties of the LCA model were also considered, a perspective that was ignored in the mentioned studies. The consideration of uncertainties is important, as they may allow for rejection of a strategy if it does not provide enough environmental benefits.

The presented framework in this study can ease the tracking of the materials at the EoL of the building. The obtained results from the case study also show compatibility with the 10R list, which indicated the increasing rate of the circularity of the strategies. Despite all the studies on CE, the application of CE practices in real cases still must be progressed. As the first goal of CE was to reduce the resource use and waste generation as much as possible, this study focused on the possibilities for valorizing the materials at the EoL stage. However, it did not consider the reduction of the quality of the recycled materials. More scenarios can be defined through the framework as the future developments of this work. These strategies can be defined in more detail as the future developments of this work.

The presented framework in this study can also be used to compare the application of CE strategies on different building systems in the future. As the sustainable development occurs when all three environmental, economic, and social pillars of sustainability are achieved at the same time, as another future development, the relevance of the framework can be evaluated also from the economic and social aspects of CE.

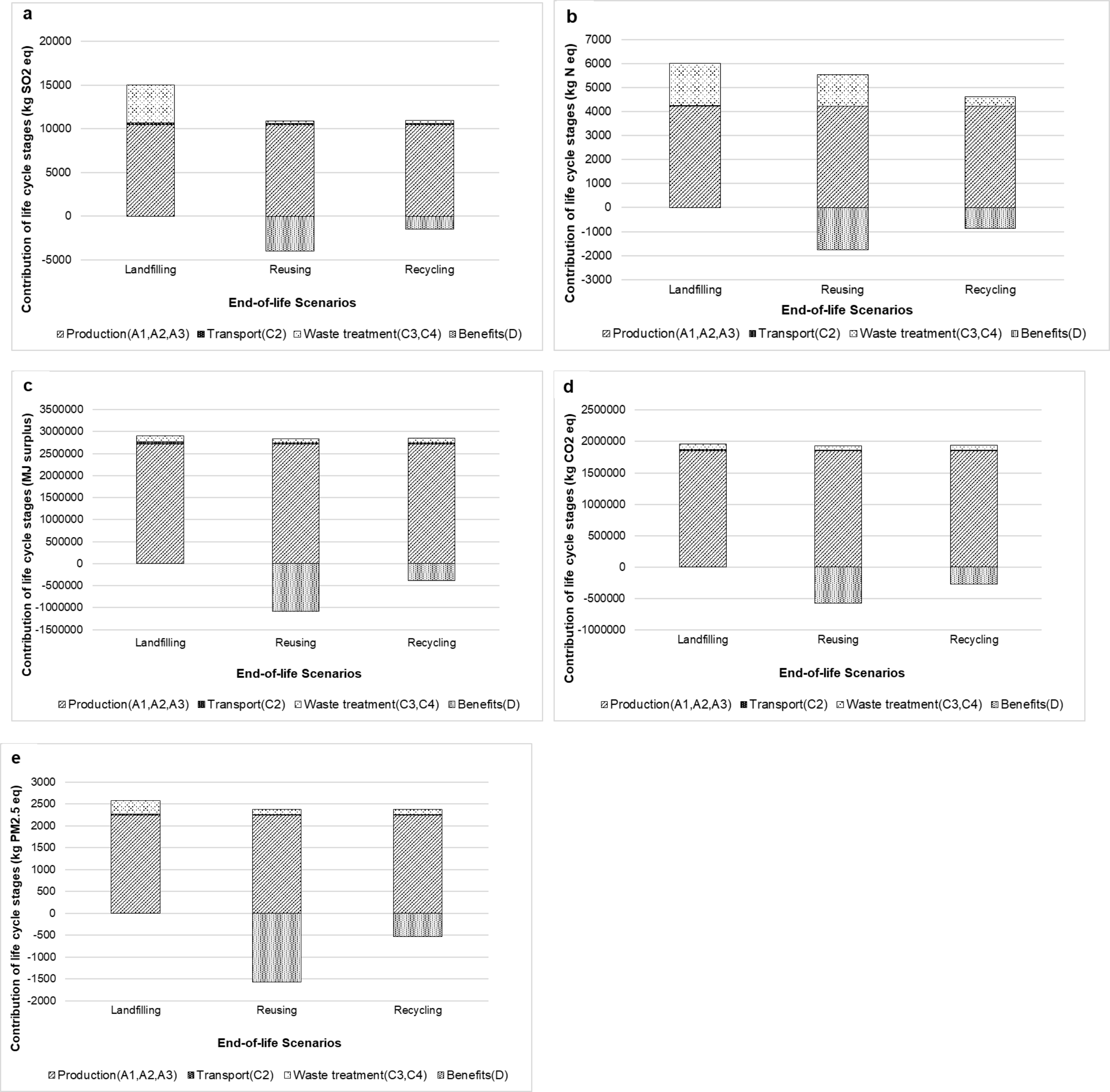

Fig. 7. LCA results based on lifecycle stage for different impact categories; a: Acidification, b: Eutrophication, c: Fossil fuel depletion, d: Global warming, e: Respiratory effects

CONCLUSIONS

1. This study has presented a framework to apply and evaluate the application of circular economy (CE) strategies in the construction sector. The presented framework is adapted to consider the CE strategies from the 10R list. By resolving an important gap in the existing literature, the framework in this study evaluates the impacts of applying CE strategies at the end-of-life of a building system as a case study.

2. The analysis of the results showed that the production stage of the materials is the phase having the most impact on the environment.
3. It is therefore important to reduce the impacts of the production phase by applying CE strategies at the end-of-life of the buildings, looping the materials between the end-of-life stage and the production stage, and therefore reducing the resource usage.
4. Results also revealed that only a reduction in the environmental performance of a CE strategy does not necessarily show the best scenario to choose, as there must be a minimum difference between the results of two scenarios to be able to compare them.
5. The life cycle assessment (LCA) model used in this study allows the comparison of various end of life (EoL) scenarios for building materials. The framework can also be served to guide architects in the design stage to be able to design a building, to specifically serve a circular scenario at its EoL stage.

ACKNOWLEDGMENTS

The authors are grateful to Natural Sciences and Engineering Research Council of Canada for the financial support through its IRC and CRD programs (IRCPJ 461745-18 and RDCPJ 524504-18) as well as the industrial partners of the NSERC industrial chair on eco-responsible wood construction (CIRCERB).

REFERENCES CITED

Acero, A. P., Rodríguez, C., and Ciroth, A. (2015, March 16). "LCIA methods impact assessment methods in Life Cycle Assessment and their impact categories," https://www.openlca.org/wp-content/uploads/2015/11/LCIA-METHODS-v.1.5.4.pdf

Alkhuzaim, L., Zhu, Q., and Sarkis, J. (2021). "Evaluating emergy analysis at the nexus of circular economy and sustainable supply chain management," *Sustainable Production and Consumption* 25, 413-424. DOI: 10.1016/j.spc.2020.11.022

Anastasiades, K., Blom, J., Buyle, M., and Audenaert, A. (2020). "Translating the circular economy to bridge construction: Lessons learnt from a critical literature review," *Renewable and Sustainable Energy Reviews* 117, article 109522. DOI: 10.1016/j.rser.2019.109522

Benachio, G. L. F., Freitas, M. do C. D., and Tavares, S. F. (2020). "Circular economy in the construction industry: A systematic literature review," *Journal of Cleaner Production* 260, article 121046. DOI: 10.1016/j.jclepro.2020.121046

Boell, S. K., and Cecez-Kecmanovic, D. (2010). "Literature reviews and the Hermeneutic circle," *Australian Academic and Research Libraries* 41(2), 129-144. DOI: 10.1080/00048623.2010.10721450

Boza-Kiss, B., and Bertoldi, P. (2018). "One-stop-shops for energy renovations of buildings," *JRC Science for Policy Report*.

Brunner, P. H., and Rechberger, H. (2004). "Practical handbook of material flow analysis," *The International Journal of Life Cycle Assessment* 9(5), article 5.

Charef, R. (2022). "Supporting construction stakeholders with the circular economy: A trans-scaler framework to understand the holistic approach," *Cleaner Engineering and Technology* 8, article 100454. DOI: 10.1016/j.clet.2022.100454

Coelho, A., and de Brito, J. (2012). "Influence of construction and demolition waste management on the environmental impact of buildings," *Waste Management* 32(3), 532-541. DOI: 10.1016/j.wasman.2011.11.011

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., and Worrell, E. (2019). "Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics," *Resources, Conservation and Recycling* 151, article 104498. DOI: 10.1016/j.resconrec.2019.104498

Eberhardt, L., Birgisdottir, H., and Birkved, M. (2019). "Comparing life cycle assessment modelling of linear vs. circular building components," IOP Conference Series: Earth and Environmental Science 225, article 012039. DOI: 10.1088/1755-1315/225/1/012039

EN 15978 (2011). 15978: 2011 Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method. CEN: Brussels, Belgium.

Ghisellini, P., Ji, X., Liu, G., and Ulgiati, S. (2018). "Evaluating the transition towards cleaner production in the construction and demolition sector of China: A review," *Journal of Cleaner Production* 195, 418-434. DOI: 10.1016/j.jclepro.2018.05.084

Ghufran, M., Khan, K. I. A., Ullah, F., Nasir, A. R., Al Alahmadi, A. A., Alzaed, A. N., and Alwetaishi, M. (2022). "Circular economy in the construction industry: A step towards sustainable development," *Buildings* 12(7), article 1004. DOI: 10.3390/buildings12071004

Goddin, J., and Marshall, K. (2019). "Circularity indicators: An approach to measuring circularity, methodology," *Methodology*. DOI: 10.13140/RG.2.2.29213.84962

Hentges, T. I., Machado da Motta, E. A., Valentin de Lima Fantin, T., Moraes, D., Fretta, M. A., Pinto, M. F., and Spiering Böes, J. (2022). "Circular economy in Brazilian construction industry: Current scenario, challenges and opportunities," *Waste Management and Research: The Journal for a Sustainable Circular Economy* 40(6), article 6. DOI: 10.1177/0734242X211045014

Hossain, M. U., and Ng, S. T. (2018). "Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review," *Journal of Cleaner Production* 205, 763-780.

Hossain, Md. U., Ng, S. T., Antwi-Afari, P., and Amor, B. (2020). "Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction," *Renewable and Sustainable Energy Reviews* 130, article l109948. DOI: 10.1016/j.rser.2020.109948

Huang, B., Wang, X., Kua, H., Geng, Y., Bleischwitz, R., and Ren, J. (2018). "Construction and demolition waste management in China through the 3R principle," *Resources, Conservation and Recycling* 129, 36-44. DOI: 10.1016/j.resconrec.2017.09.029

Humbert, S., Rossi, V., Margni, M., Jolliet, O., and Loerincik, Y. (2009). "Life cycle assessment of two baby food packaging alternatives: Glass jars *vs*. plastic pots," *The International Journal of Life Cycle Assessment* 14(2), 95-106. DOI: 10.1007/s11367-008-0052-6

Jeffries, N. (2021). *Building Lighthouses*. https://ellenmacarthurfoundation.org/articles/building-lighthouses

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., and Rosenbaum, R. (2003). "IMPACT 2002+: A new life cycle impact assessment methodology," *The International Journal of Life Cycle Assessment* 8(6), 324. DOI: 10.1007/BF02978505

Kazancoglu, Y., Kazancoglu, I., and Sagnak, M. (2018). "A new holistic conceptual framework for green supply chain management performance assessment based on circular economy," *Journal of Cleaner Production* 195, 1282-1299. DOI: 10.1016/j.jclepro.2018.06.015

Kirchherr, J., Reike, D., and Hekkert, M. (2017). "Conceptualizing the circular economy: An analysis of 114 definitions," *Resources, Conservation and Recycling* 127, 221-232. DOI: 10.1016/j.resconrec.2017.09.005

Larivière-Lajoie, R., Blanchet, P., and Amor, B. (2022). "Evaluating the importance of the embodied impacts of wall assemblies in the context of a low environmental impact energy mix," *Building and Environment* 207, article 108534. DOI: 10.1016/j.buildenv.2021.108534

Lei, H., Li, L., Yang, W., Bian, Y., and Li, C.-Q. (2021). "An analytical review on application of life cycle assessment in circular economy for built environment," *Journal of Building Engineering* 44, article 103374. DOI: 10.1016/j.jobe.2021.103374

Lockrey, S., Nguyen, H., Crossin, E., and Verghese, K. (2016). "Recycling the construction and demolition waste in Vietnam: Opportunities and challenges in practice," *Journal of Cleaner Production* 133, 757-766.

López Ruiz, L. A., Roca Ramón, X., and Gassó Domingo, S. (2020). "The circular economy in the construction and demolition waste sector – A review and an integrative model approach," *Journal of Cleaner Production* 248, article 119238. DOI: 10.1016/j.jclepro.2019.119238

López Ruiz, L. A., Roca Ramon, X., Melissa Lara Mercedes, C., and Gasso Domingo, S. (2022). "Multicriteria analysis of the environmental and economic performance of circularity strategies for concrete waste recycling in Spain," *Waste Management* 144, 387-400. DOI: 10.1016/j.wasman.2022.04.008

Masi, D., Day, S., and Godsell, J. (2017). "Supply chain configurations in the circular economy: A systematic literature review," *Sustainability* 9(9), article 9. DOI: 10.3390/su9091602

Mesa, J. A., Fúquene-Retamoso, C., and Maury-Ramírez, A. (2021). "Life cycle assessment on construction and demolition waste: A systematic literature review," *Sustainability* 13(14), 7676. DOI: 10.3390/su13147676

Munaro, M. R., Tavares, S. F., and Bragança, L. (2020). "Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment," *Journal of Cleaner Production* 260, article 121134. DOI: 10.1016/j.jclepro.2020.121134

Ness, D. A., and Xing, K. (2017). "Toward a resource-efficient built environment: A literature review and conceptual model," *Journal of Industrial Ecology* 21(3), article 3. DOI: 10.1111/jiec.12586

Nußholz, J. L. K., Nygaard Rasmussen, F., and Milios, L. (2019). "Circular building materials: Carbon saving potential and the role of business model innovation and public policy," *Resources, Conservation and Recycling* 141, 308-316. DOI: 10.1016/j.resconrec.2018.10.036

Osei-Tutu, S., Ayarkwa, J., Osei-Asibey, D., Nani, G., and Afful, A. E. (2022). "Barriers impeding circular economy (CE) uptake in the construction industry," *Smart and Sustainable Built Environment*. DOI: 10.1108/SASBE-03-2022-0049

Pearce, D. W., and Turner, R. K. (1990). *Economics of Natural Resources and the Environment*, Johns Hopkins University Press.

Perminova, T., Sirina, N., Laratte, B., Baranovskaya, N., and Rikhvanov, L. (2016). "Methods for land use impact assessment: A review," *Environmental Impact Assessment Review* 60, 64-74.

Potting, J., Hekkert, M., Worrell, E., and Hanemaaijer, A. (2017). *Circular Economy: Measuring Innovation in the Product Chain*, PBL Netherlands Assessment Agency.

Pouliot, E. (2021). "L'économie circulaire comme perspective d'avenir," https://www.portailconstructo.com/tendances_opportunites/l_economie_circulaire_comme_perspective_d_avenir

PRC. (2008). *The Circular Economy Promotion Law of the People's Republic of China* (V. Ebeling, Trans.). https://ppp.worldbank.org/public-private-partnership/sites/ppp.worldbank.org/files/documents/China_CircularEconomyLawEnglish.pdf

Quéheille, E., Ventura, A., Saiyouri, N., and Taillandier, F. (2022). "A life cycle assessment model of end-of-life scenarios for building deconstruction and waste management," *Journal of Cleaner Production* 339, article 130694. DOI: 10.1016/j.jclepro.2022.130694

Rahla, K., Mateus, R., and Bragança, L. (2021). "Implementing circular economy strategies in buildings—From theory to practice," *Applied System Innovation* 4(2), article 2. DOI: 10.3390/asi4020026

Ram, V. G., Kishore, K. C., and Kalidindi, S. N. (2020). "Environmental benefits of construction and demolition debris recycling: Evidence from an Indian case study using life cycle assessment," *Journal of Cleaner Production* 255, article 120258. DOI: 10.1016/j.jclepro.2020.120258

Ren, J., Tan, S., Yang, L., Goodsite, M. E., Pang, C., and Dong, L. (2015). "Optimization of emergy sustainability index for biodiesel supply network design," *Energy Conversion and Management* 92, 312-321. DOI: 10.1016/j.enconman.2014.12.066

Saidani, M., Kreuder, A., Babilonia, G., Benavides, P. T., Blume, N., Jackson, S., Koffler, C., Kumar, M., Minke, C., Richkus, J., Smith, C., and Wallace, M. (2022). "Clarify the nexus between life cycle assessment and circularity indicators: A SETAC/ACLCA interest group," *The International Journal of Life Cycle Assessment* 27(7), 916-925. DOI: 10.1007/s11367-022-02061-w

Sihvonen, S., and Ritola, T. (2015). "Conceptualizing ReX for aggregating end-of-life strategies in product development," *Procedia CIRP* 29, 639-644. DOI: 10.1016/j.procir.2015.01.026

Singhal, D., Tripathy, S., and Jena, S. K. (2020). "Remanufacturing for the circular economy: Study and evaluation of critical factors," *Resources, Conservation and Recycling* 156, article 104681. DOI: 10.1016/j.resconrec.2020.104681

Su, B., Heshmati, A., Geng, Y., and Yu, X. (2013). "A review of the circular economy in China: Moving from rhetoric to implementation," *Journal of Cleaner Production* 4, 215-227. DOI: 10.1016/j.jclepro.2012.11.020

Zhu, Q., Geng, Y., and Lai, K. (2010). "Circular economy practices among Chinese manufacturers varying in environmental-oriented supply chain cooperation and the performance implications," *Journal of Environmental Management* 91(6), article 6. DOI: 10.1016/j.jenvman.2010.02.013

Article submitted: February 10, 2023; Peer review completed: March 18, 2023; Revised version received and accepted: April 28, 2023; Published: May 18, 2023.
DOI: 10.15376/biores.18.3.4699-4722