School of Design and the Built Environment

Curtin University Sustainability Policy Institute

Circular Economy of Modular Buildings

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Doctor of Philosophy
of
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Author’s Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Roberto Minunno

31 May 2020

Statement of contributors

The research within this PhD and the hereafter proposed hybrid thesis was conceived and undertaken by me, Roberto Minunno. I also wrote gathered and analysed the data as reported in the produced manuscripts.

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Roberto Minunno

31 May 2020

Abstract

The building sector has a significant impact globally on the environment and includes depletion of natural resources, waste production causing pressure on landfills, greenhouse gas emissions resulting in global warming, embodiment of substantial amounts of energy. These environmental consequences are observed during the life cycle of buildings. During production, materials are extracted to be manufactured as building components. Post construction, building operation components are used to maintain or refurbish the buildings, until these are decommissioned. The materials and components that result from decommissioned buildings could either be disposed to landfill, or recycled, remanufactured and reused in their second life.

The circular economy approach aims to turn waste construction materials into new resources. This concept has been successfully applied to many industry sectors, but research reported for buildings and empirical studies have been relatively limited. To investigate possible solutions to this issue, this PhD mixes theory and practice by building a circular economy prototype as a case study, and exploring the related empirical implications.

Specifically, in this thesis, a literature review provided insight into the circular economy strategies that have been established in other industries, and to propose a model to create reusable, circular economy buildings. By applying these strategies to a modular building, a prototype of a disassemblable and reusable building, namely the Legacy Living Lab was manufactured. Further, a life cycle assessment method was adopted to calculate the environmental benefits of applying the circular economy to buildings. It was proved that, in so doing, up to 88% of greenhouse gas equivalent emissions could be avoided for Legacy Living Lab.

Through our research we have proposed a method to calculate an index, named D^3R, which could be used to calculate the degree of circularity of a building in its design stage. The D^3R index of the Legacy Living Lab demonstrates that this building is 69% circular, whereas a traditionally built modular building scores only a D^3R index of 37%.

Within this PhD a number of peer reviewed research papers are appended, and the research also concludes with the creation of the Curtin University asset, the Legacy Living Lab. This movable research facility is meant to be the breeding ground for further research on the circular economy of buildings. Its success depends on networking strategies between research institutes or universities, creating new knowledge; industry partners, pushing the boundaries of new product development; and society, influencing the market and policies.

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Finally, dear Greg and Tim, without your efforts the Legacy Living Lab would have remained just a sketch and a dream.

Dedication

To my family, to my friends.

Publications and submitted manuscripts included in the thesis

The following publications and manuscripts are the foundation of this thesis and are provided as appendices to the exegesis.

I. **Minunno, R.**, O'Grady, T., Morrison, G.M., Gruner, R.L., 2020. Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments. Submitted to *Renewable and Sustainable Energy Reviews.*

II. **Minunno, R.**, O'Grady, T., Morrison, G.M., Gruner, R.L. and Colling, M., 2018. Strategies for applying the circular economy to prefabricated buildings. *Buildings*, 8(9), p.125. doi.org/10.3390/buildings8090125.

III. **Minunno, R.**, O'Grady, T., Morrison, G.M., Gruner, R.L., 2020. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Resources, Conservation & Recycling*, vol. 160. doi.org/10.1016/j.resconrec.2020.104855.

IV. O'Grady, T., **Minunno, R.**, Chong, H.Y., Morrison, G.M., 2020. Design for disassembly, deconstruction and resilience in construction: A circular economy index. Submitted to *Journal of Cleaner Production.*

V. Cantu, C.L., Schepis, D., **Minunno, R.**, Morrison, G.M., 2020. The project network approach for Living Laboratories. Submitted to *Journal of Business and Industrial Marketing.*

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Publication I (manuscript)

I, Roberto Minunno, contributed 80% to the publication:

Minunno, R., O'Grady, T., Morrison, G.M., Gruner, R.L., 2020. Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments. Submitted to *Renewable and Sustainable Energy Reviews.*

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Glossary and acronyms explanation*

BoQ	Bill of Quantities	List of materials, components, machinery and labour involved in producing a building.
CE	Circular Economy	Theory according to which, if waste could be reused as a new resource, without external input of non-renewable energy or materials, that waste would have improved environmental and anthropogenic value.
D^{3}R	Design for disassembly, deconstruction and reuse	Method to quantify the level of disassemblability, reusability and recyclability of components.
GHG	Greenhouse Gas	Combination of gases which contributes to the greenhouse effect and related global warming.
L3	Legacy Living Lab	The modular building prototype that has been conceptualized and built within this PhD to test the CE of buildings.
LCA	Life Cycle Assessment	Method to quantify the environmental impact of products and services.
SLR	Systematic Literature Review	Method to collect and review literature in a structured way.

** To facilitate the reading of this thesis, these terms are re-explained the first time they are mentioned in each chapter.*

Chapter 1. **Introduction**

This research concerns the environmental sustainability of the construction sector with a focus on residential and commercial buildings. This PhD collates and integrates the findings of several published and submitted articles. In drawing on the literature concerning the environmental impact of buildings and the concept known as circular economy, i.e. turning waste into new resources, this PhD provides the underpinning for a full-scale circular economy modular building, the Legacy Living Lab. This introductory chapter explains the structure of this PhD, both in terms of research context and organization.

1.1 Research Context: The Environmental Impact of Buildings and their materials

The linear economy, or the practice of taking materials from the environment, manufacturing them into goods or fuel, using them and finally disposing them to landfill has its roots in the 1929's Great Depression (London, 1932). This concept, now believed to be unsustainable for the environment, is challenged by the circular economy framework (Benachio, Freitas, & Tavares, 2020). The circular economy theoretical framework suggests that, in making new resources out of waste, practitioners, firms and policy makers could implement a more sustainable, yet profitable, interaction with the environment (Morseletto, 2020).

However, challenging the linear *modus operandi* in favour of a novel, circular approach encounters many barriers. Some industry sectors overcame these barriers and succeeded in implementing circular economy strategies (see, for example, Apple deconstructs iPhones into their parts for an efficient recycling process; Toyota implemented the Just-in-Time management system to decrease waste production; Gaustad, Krystofik, Bustamante, and Badami (2018), Sarc et al. (2019)). Yet, many barriers hinder the application of the circular economy in the building context (Julian M. Allwood, 2014). As a result, the circular economy of the construction sector is still in its infancy. This chapter explores why this is paramount, how this PhD proposes to overcome these barriers, and the background studies that helped frame this research.

1.1.1 Background

Globally, 60% of raw materials are used in the building sector by mass (Hossain & Poon, 2018), which embodies 6% of global energy use and releases 11% of related CO_2 into the atmosphere (Dean, Dulac, Petrichenko, & Graham, 2016; Hu, 2019; Sedláková et al., 2020). Some of the construction materials that are mainly employed are concrete, steel, bricks, tiles, insulation, timber. Producing 1 kg of concrete, for example requires ~1.1 MJ and emits ~0.16 kg of greenhouse gas (expressed in CO_2 equivalent — the units of measures are defined in Section 3.4; (Sicignano, Di Ruocco, & Melella, 2019)). Similarly, producing 1 kg of steel requires ~21.5MJ and emits ~1.5 kg of greenhouse gas equivalent (Ahmed & Tsavdaridis, 2018).

An attempt to decrease the impact of the construction sector is through the application of the circular economy (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014; L. C. M. Eberhardt, H. Birgisdottir, & M. Birkved, 2019). The circular economy proposes the transformation of waste into a new resource (Walter R Stahel, 2016). This concept was first formulated by Kenneth Boulding in his work “The Economics of the Coming Spaceship Earth” (Boulding, 1966) and further explored in the seminal book Economics of Natural Resources and the Environment (Pearce & Turner, 1990), and during the last three decades has been successfully applied to a number of industry sectors. For example, in the electronics sector, the leading smartphone and computer company Apple implemented a take back policy, with disassembly of used smartphones and separation and recycling or reuse of their internal components (Sarc et al., 2019). Other companies in the textile sector such as Levi’s take-back used garments, clean and repair them before reintroducing them into the market (Co., 2015; Singh & Ordoñez, 2016). When it comes to the construction sector, however, these practices are hindered by three main barriers.

First, buildings are typically conceptualized as monoliths. That is due to two reasons: a technical reason and a user related reason. The technical reason is that building components are typically welded together to improve structural stability, joints are reinforced to recreate the material integrity (W. Salama, 2017). Joints built this way are therefore difficult to disassemble, and often inaccessible. Moreover, building components tend to be too heavy to be lifted by manpower alone (van den Berg, Voordijk, & Adriaanse, 2020). The combination of these characteristics makes disassemblability of buildings time consuming and economically unfeasible. Consequently, components that cannot be disassembled are crushed and stockpiled. If possible, and depending on countries’ regulations, these stockpiles could be sorted and divided by material, then recycled or landfilled (van den Berg et al., 2020). For reference, while in Australia 57% of construction and demolition waste is recycled (Senaratne, Lambrousis, Mirza, Tam, & Kang, 2017), in Sri Lanka this practice is yet to be mainstreamed (Kumanayake, Luo, & Paulusz, 2018).

Second, building components drastically differ in shape and mechanical characteristics. That is, because buildings are fabricated to satisfy architectural needs, which in most cases depend on factors such as customers’ specifications, site dimensions and the load bearing capacity of the soil (Julian M. Allwood, 2014). As a consequence, if the first barrier were to be overcome, and a few components could be disassembled, engineers would be unable to find a second use for them (Sanchez, Rausch, Haas, & Saari, 2020).

Third, a closed-loop supply chain of building materials is yet to be established. Building components that are disassembled from their previous construction might need to be recertified before being sold back into the market (Densley Tingley, Cooper, & Cullen, 2017). A closed-loop supply chain is needed to establish the circularity of building components. However, so far, and in some countries only small items, such as doors, windows and lighting fixtures are re-sold as used (Arora, Raspall, Cheah, & Silva, 2020).

These barriers are closely intertwined. For example, if buildings were built for disassembly and their measures standardized then this might help create economic value for reused building components, which, in turn, might foster the development of a related closed loop supply chain. This might help decrease the environmental pressure of construction materials, and at the same time improve the economic turnover of these materials and components (Chan, Bachmann, & Haas, 2020). Instead, the most researched practice of construction materials seems to be recycling (2 618 articles in environmental science mention the keywords “buildings and recycling” in their abstracts versus 1 171 only that mention “buildings and reuse”; source: Scopus, May 2020). Notwithstanding the benefits of recycling construction materials, recent literature seems to agree that further efforts should aim towards disassemblability and reuse of construction components (van den Berg et al., 2020). Indeed, through reuse, components would remain in the material loop as there are, without the need for the — often highly impacting and degrading — chemical and mechanical alterations linked to recycling (Adams, Osmani, Thorpe, & Thornback, 2017; Lederer, Trinkel, & Fellner, 2017).

Modular buildings, however, could be a perfect fit for disassemblability, standardization and therefore to establish a market of reusable materials. Modular buildings are composed of box-shaped structures, with dimensional similarity, built off-site in specialized and controlled facilities (T. Salama, Salah, Moselhi, & Al-Hussein, 2017). Once these structures are completed, sometimes including furniture and fittings, they are transported on site where, with the aid of cranes, they are lifted and assembled into the finished building (Srisangeerthanan, Hashemi, Rajeev, Gad, & Fernando, 2020). Modular building technology leads the market in Northern European countries (for example, 70% of buildings in Sweden are modular; see Ferdous, Bai, Ngo, Manalo, and Mendis (2019)). Yet, in other countries, such as Australia, this technology is still underdeveloped (Ferdous et al., 2019).

Although several advantages are related to employing modular building technology, such as their minimal site disruption, optimal thermal performance and their improved ease of construction, they could also help going some way towards the application of the circular economy to the construction sector (Akanbi et al., 2019). Against this backdrop, this PhD applies several theories, models and frameworks.

1.1.2 Theoretical framework

This PhD has its theoretical foundation in circular economy. Although many researchers have attempted to define this theory (see, for example Benachio et al. (2020) or Merli, Preziosi, and Acampora (2018)), the definition adopted in this PhD is a variation of that proposed by Kirchherr, Reike, and Hekkert (2017): a circular economy is a system in which thorough design choices of materials and practices help replace end-of-life operations with reduction, reuse or alternatively recycle operations. Whereas Kirchherr et al. (2017) had a broader focus on the three main pillars of sustainability – society, economy and environment – with the goal of defining the circular economy "creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations", the focus of this PhD is the environmental benefits of circular economy in the built environment. Specifically, in this PhD, the circular economy has been studied and applied to a full-scale building. Therefore, the scale of the circular economy application studied here is the micro scale (as opposed to the macro scale, which might be a city or portions of a city). The aim of this application was to prove the environmental benefits of a circular economy approach in a real-life setting.

A key concept often associated with the circular economy of buildings is design for disassembly and reuse (L. Eberhardt, H. Birgisdottir, & M. Birkved, 2019; Eckelman et al., 2018). This concept draws on circular economy theory, but it differs in one fundamental aspect. While the circular economy focuses on the end-of-life strategies, the design for disassembly concept tackles the idea of creating reusable components by focusing on the design phase of a building (Abuzied, Senbel, Awad, & Abbas, 2020). This change in focus has been a key aspect in developing this PhD. The design stage is when the structure and super-structure of a building are defined (Van den Berghe & Vos, 2019) although during the design stage, the end-of-life stage is often overlooked (Gangolells, Casals, Forcada, & Macarulla, 2014, p. 105).

Several scholars support the idea that policies could go a long way towards the application of a circular economy, in a top-down approach (Alaerts et al., 2019; Hartley, van Santen, & Kirchherr, 2020). However, the approach adopted in this research is a bottom-up approach. Specifically, the empirical approach adopted consists of three main steps. First, a comprehensive review of the literature of circular economy applications. Second, demonstrate the feasibility of applying the circular economy framework to the building context and prove the related benefits. Third, disseminate the results and engage with industry partners and society to foster further similar innovations.

To evaluate the impact of a product (in this case a building), it has to be modelled at its material level, its manufacturing and assembly level and its functional level. The material level consists of the elements, materials and components that have been manufactured and assembled to create the product (W. Salama, 2017). In the case of a building, this includes its bill of materials and the components that will need to be manufactured to refurbish and maintain the building over its life cycle and translates into the inflow and outflow of materials (Gontia, Thuvander, & Wallbaum, 2020). The manufacturing and assembly levels include the equipment required to assemble and disassemble the components and the means of transport adopted to move the materials from factories to the site (Yuan, Sun, & Wang, 2018). Finally, the functional level includes the features that the product (or building) fosters. Through a holistic approach, this PhD evaluates how the circular economy framework can be integrated in environmental aspects of each of these levels.

To have a better perspective of what has been researched and the eventual literature gaps, it is important to position this PhD research in the literature.

1.2 Research positioning

This research is positioned in knowledge validation through an objectivist epistemological approach. A first perspective draws from the juxtaposition of a case of linear economy model to a circular economy model, for example, allowing the investigation and comparison of the environmental impact of a circular economy building to a traditional, linear, building (see Fig. 1.1).

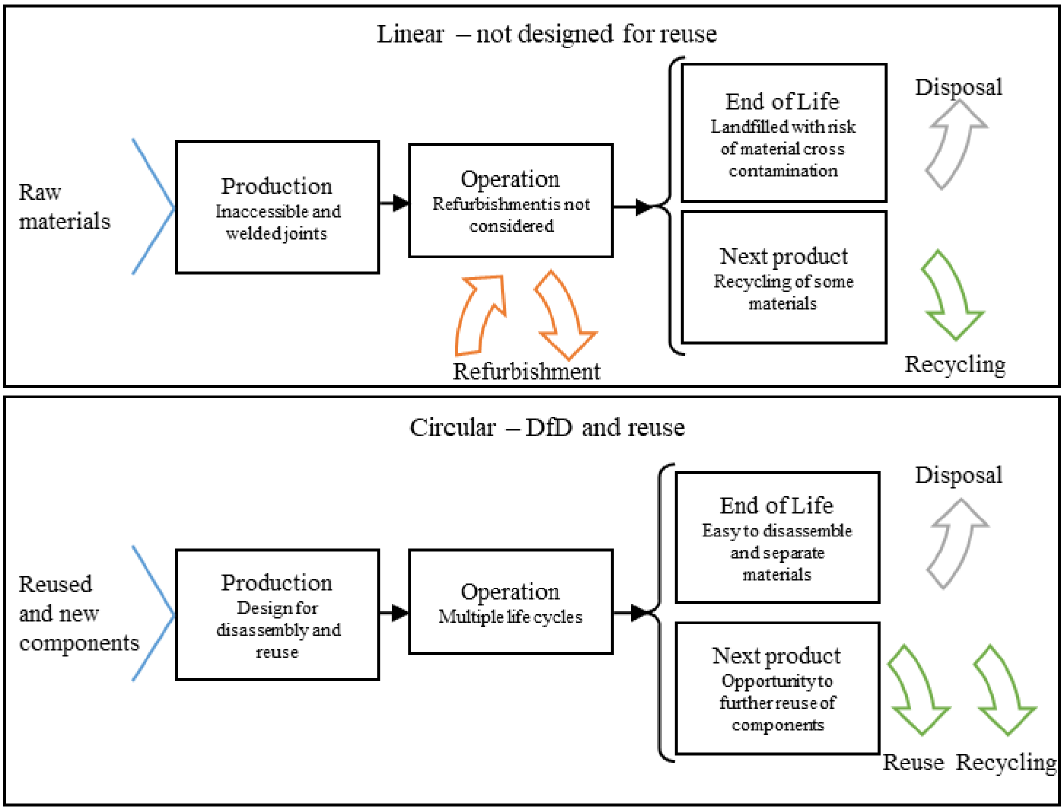

Fig. 1.1 – Juxtaposition of linear and circular building across its life cycle stages. The two building technologies differ in material inflow and outflow. Figure adapted from Publication III.

Additionally, as discussed in Sections 3.1 and 3.2, a second approach draws from a combination of a systematic and narrative literature review on circular economy theory.

These perspectives find their positioning in the interaction between the two overarching literatures: the literature on circular economy and related applications, and the literature on modular building technology. In turn, these literatures originate from academic disciplines such as business and management (linear economy and planned obsolescence), ecology, restoration and biological processes (circular economy), civil engineering and industrial manufacturing (modular building technology; see Fig. 1.2).

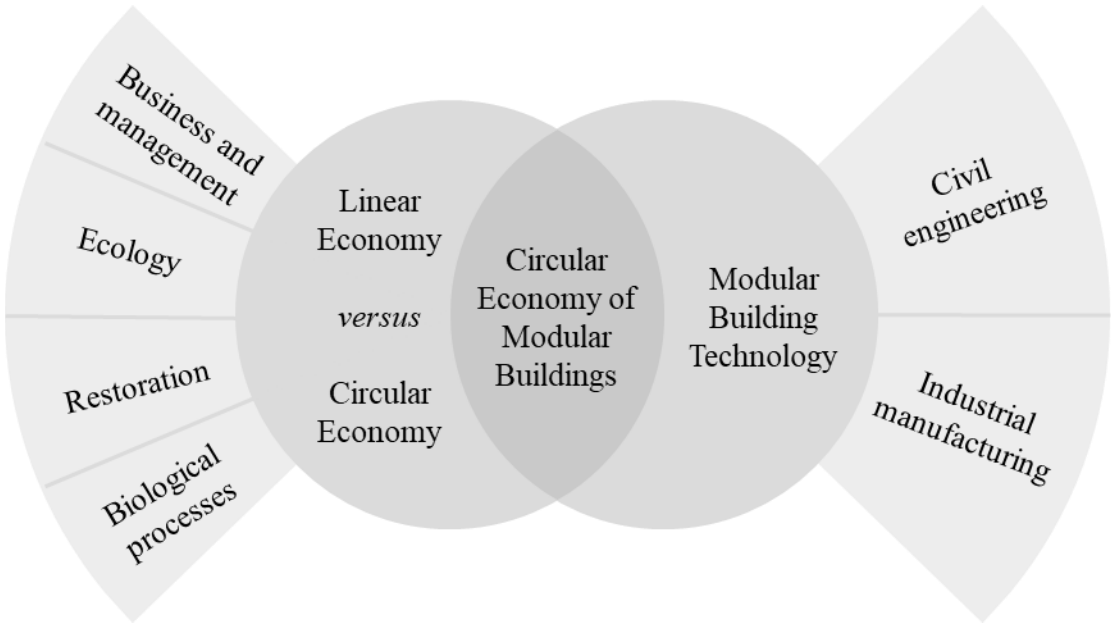

Fig. 1.2 – The research on circular economy of modular buildings is positioned in the intersection between the knowledge on linear versus circular economy and modular building technology. Such knowledge germinates from the economic academic disciplines, ecology and restoration, biological processes merging civil engineering and industrial manufacturing.

The purpose of this PhD is to expand the knowledge in the direction of solving barriers, implementing practices and measuring outcomes of the application of circular economy to buildings. Many scholars have framed this phenomenon previously, proposed possible solutions or highlighted important barriers. For example, Julian M. Allwood (2014) proposed a focus on reduction of material use through life extension, while Walter R. Stahel (1997) proposed a focus on sharing spaces.

Despite these applications producing a number of valuable works, a holistic approach to apply and quantify the outcomes of the applications of the circular economy to a case study is still missing.

From these literature gaps the following research questions arose.

1.3 Research questions, sub-questions & objectives

The circular economy theory posits that, if an economic system is governed by a circular flow of materials, it has less impact on the environment, society and economy. With focus on its environmental aspects, this research attempts to test this postulate in applying the circular economy to the building system. Indeed, as Julian M Allwood (2014) states, albeit not explicitly related to buildings, modular design can be key to foster the application of the circular economy to a variety of products. Further, modular building technology could represent a positive fit in relation to the 3R's framework (reduce, reuse and recycle). First, modular buildings must be transported and often craned on-site, operations that typically implies designing light-weight components and material optimization, which, in turn, produces reduction of materials used. Second, modular buildings are, by definition, assembled offsite, operation that could be reverse-engineered to foster disassemblability and ease reuse of the disassembled components. Third, often modular building structures are made out of steel, which, compared to traditional construction materials such as bricks or concrete, is recyclable (instead of down-cyclable). In so doing, the research endeavours to answer a simple research question:

What is the environmental benefit of applying the circular economy theory to the building system, and how can the circular economy be applied to modular buildings?

The resolution of this research question implies and requires further research sub-questions. In turn, the sub-questions are linked to methodological, empirical and practical barriers. These sub-questions can be summarized as follows:

1. What can be learnt by collecting and summarizing individual environmental impact studies of buildings to foster environmental impact reduction towards a circular economy?
2. What are the limits of environmental impact assessment tools and how can these limits be overcome?
3. What are the main strategies that have fostered the application of the circular economy, and how can these strategies be adapted to the building context?
4. What are the environmental advantages of applying the circular economy to a building purposely built following the circular economy strategies?
5. How can the circularity — disassemblability and reusability — of a building be measured?
6. How can the living laboratory network foster and project further innovation in the field of circular economy?

Within this PhD, I investigated these questions and attempted to resolve them in five published and submitted peer-reviewed articles. The related articles, objectives and research sub-questions are summarized in Table 1.1.

Table 1.1 – Summary of the produced articles and manuscripts, related research sub-questions and objectives.

Title	***Research sub-question***	***Objective***

I. Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments. *Manuscript submitted to a peer-review journal.*	What can be learnt by collecting and summarizing individual environmental impact studies of buildings to foster environmental impact reduction towards a circular economy?	Collect and summarize the existing data on environmental impact of buildings into a ranking benchmark.
	What are the limits of environmental impact assessment tools and how can these limits be overcome?	Create procedural guidelines to assist LCA practitioners in their LCAs.
II. Strategies for Applying the Circular Economy to Prefabricated Buildings. *Peer-reviewed article published.*	What are the main strategies that have fostered the application of the circular economy, and how can these strategies be adapted to the building context?	Review the circular economy strategies that have been applied in various industry sectors and formulate and adaptation for the construction sector
III. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Peer-reviewed article published.*	What are the environmental advantages of applying the circular economy to a building purposely built following the circular economy strategies?	Calculate the environmental impact of the circular economy building, the prototype L3. Compare the L3's impact to the impact of a similar linear economy building.
IV. Design for disassembly, deconstruction and resilience in construction: A circular economy index. *Manuscript submitted to a peer-reviewed journal.*	How can the circularity — disassemblability and reusability — of a building be measured?	Create and test a model to calculate the degree of disassemblability, reusability, and recyclability of any building.
V. The project network approach for Living Laboratories. *Manuscript accepted with revisions in a peer-reviewed journal.*	How can the living laboratory network foster and project further innovation in the field of circular economy?	Evaluate the critical aspects of living laboratory research method and create a framework to minimize these criticisms.

1.4 Thesis organization

This hybrid thesis provides a collation and integration of the five articles produced within this PhD (appendices I to V), all of which have been submitted to or have been published in high quality academic journals. Two articles have been published, one accepted with revisions two submitted for peer review.

The following chapters are organized as follows. Chapter 2 explains the methodologies adopted in the produced articles. A systematic review of the literature on end-of-life scenarios of building materials and a narrative literature review of circular economy strategies are presented in Chapter 3 (extracted from articles I and II). Chapter 4 summarizes the results that have been obtained and Chapter 5 discusses how these results contribute to create important knowledge on the studied topics. Chapter 6 provides conclusions and offers future research opportunities. Finally, the Post Scriptum Chapter addresses the issue of managing the complex inter-relationships that lie ahead in a living lab context.

Chapter 2. **Literature Review Summary**

In this chapter a review of the relevant literature is presented (Table 2.1). Section 2.1 outlines a comprehensive analysis of the literature on the environmental impact of construction materials and buildings. A bibliographic study of the emerging literature is also presented. One of the results of this preliminary literature review is that the circular economy (CE) of buildings is still in its infancy (Publication I – manuscript). To address this issue, in Section 2.2 I review the literature to understand how different industries have successfully applied the CE (Publication II). The literature on living laboratories (living labs) is presented in Chapter 7, and refers to Publication V (manuscript).

Table 2.1 – Literature reviewed in four of the produced articles and manuscripts.

Title of publication	***Literature reviewed***
I. Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments. *Manuscript submitted for peer-review journal.*	Comprehensive review of the literature on environmental impact of construction materials and buildings.
II. Strategies for Applying the Circular Economy to Prefabricated Buildings. *Peer-reviewed article published.*	Literature on applications of the circular economy to several industry sectors.
V. The project network approach for Living Laboratories. *Manuscript under revision in a peer-reviewed journal.*	Literature on the living laboratory research method.

2.1 Literature on the impact of buildings

Publication I (manuscript) is a systematic literature review (SLR) and meta-analysis of the environmental impact of construction materials and buildings. In systematically reviewing the literature on the LCA of buildings and construction materials, it emerged that research on the environmental impact of buildings is gaining traction. Indeed, the incremental number of articles produced each year follows a quasi-exponential trend, as shown in Fig. 2.1.

In this research, the terms environmental impact of construction materials must be distinguished from the impact of buildings. The first refers to the environmental impact due to produce construction materials such as concrete, steel, timber, bricks. The second refers to the environmental impact of the building as a whole, which includes a great number of construction materials, assembly, transport and construction and demolition waste management.

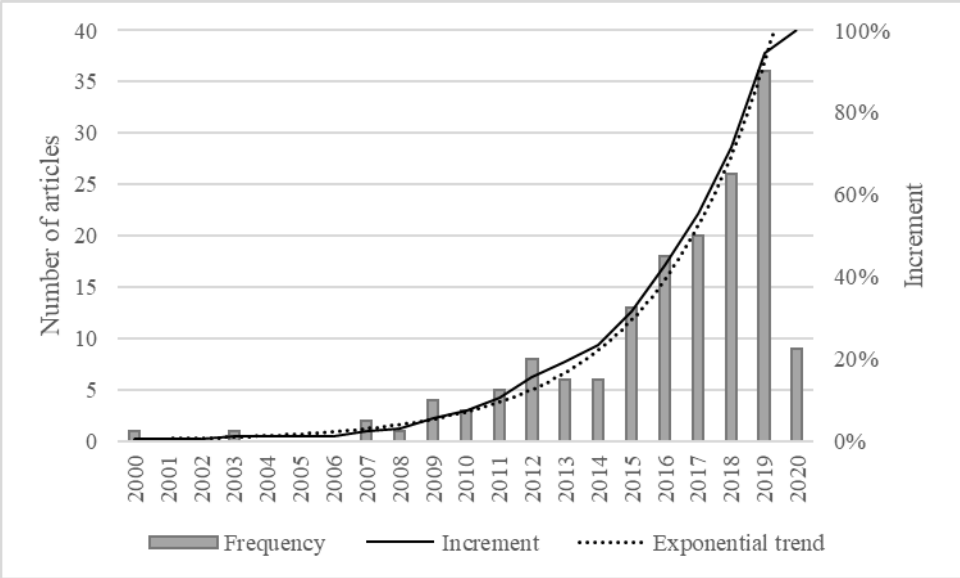

Fig. 2.1 – Distribution of the shortlisted articles across the years and comparison with the exponential trend. Extracted from Publication I (manuscript).

Further, more than 50% of the articles collected studied the environmental impact of either construction materials or overall buildings in Asia (Fig. 2.2).

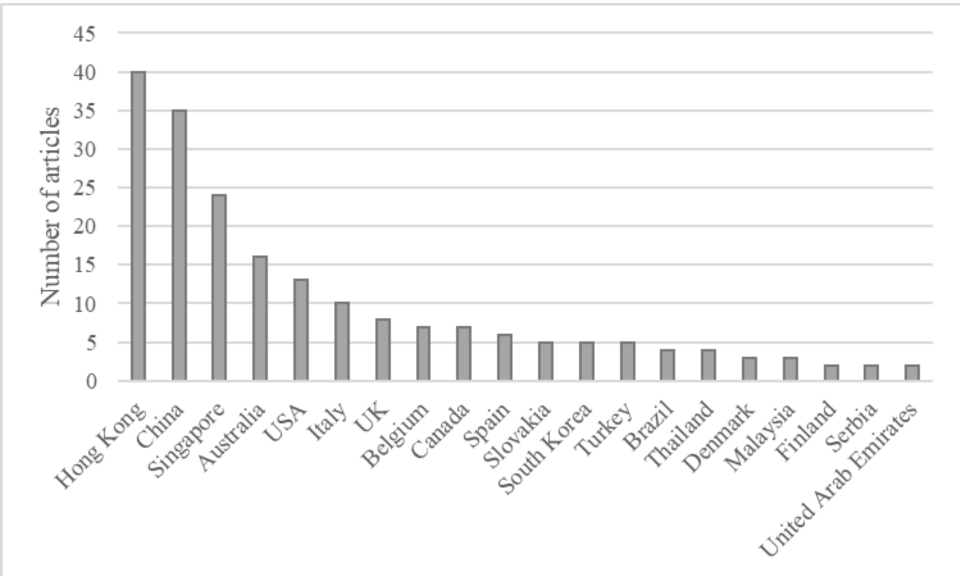

Fig. 2.2 – Distribution of the shortlisted articles across the countries. Extracted from Publication I (manuscript).

2.1.1 Environmental impact of construction materials

The SLR on the LCA of construction materials and buildings allowed the collection of information on eight construction materials (i.e. concrete, reinforcement bars, structural steel, timber, bricks, tiles, insulation (EPS) and plaster) and three building structures (i.e. concrete, timber and steel). More specifically, I extracted 338 LCA results for construction materials, and 292 LCA results for buildings, in terms of embodied energy (the sum of renewable and non-renewable energy required to extract, transport and manufacture these materials) and embodied carbon (the amount of greenhouse gas emitted to extract, transport and manufacture these materials). Most of the results extracted come from studies on concrete, both as construction material (as summarized in Fig. 2.3) and as building structure.

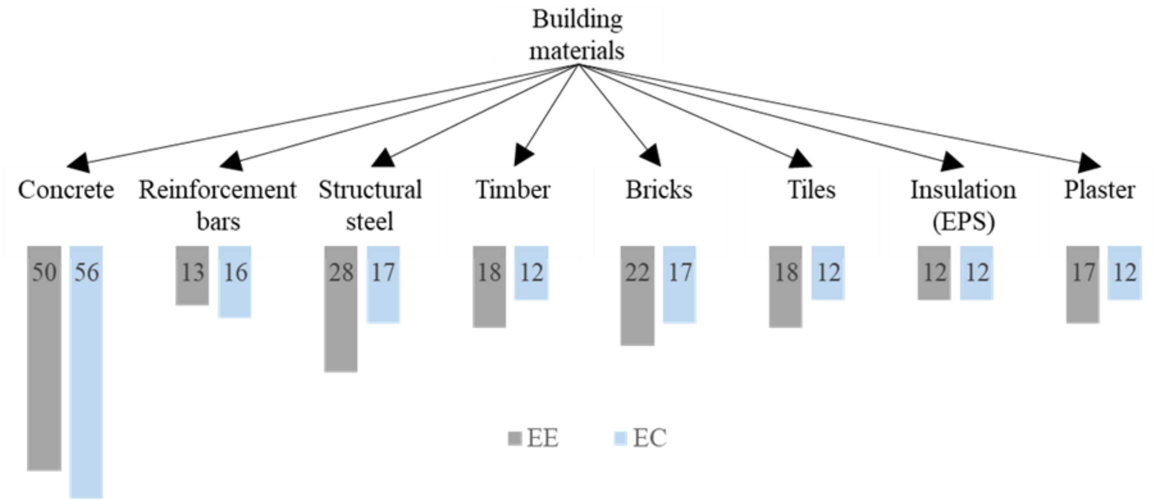

Fig. 2.3 – Number of articles categorized by building material. EPS = expanded polystyrene. Extracted from Publication I (manuscript).

Furthermore, the literature suggests that the most used LCA software is SimaPro (in various versions) and the most popular LCI database is Ecoinvent.

Statistical analysis enabled the creation of intervals of results from the collected individual datum points (see the box-whisker charts in Fig. 2.4 and Fig. 2.5). The environmental impact of these materials was measured in embodied energy and carbon to produce 1 kg of material, consistently in the literature. Among the construction materials, steel is the most impacting, as it embodies 25.5 MJ/kg and 2.2 kg CO_2 eq/kg as structural steel, and 18.0 MJ/kg and 1.5 kg CO_2 eq/kg as reinforcement bars (median values; in terms of embodied energy and carbon, respectively). The impact of timber follows, with 8.0 MJ/kg and 0.45 kg CO_2 eq/kg (in terms of embodied energy and carbon, respectively). Concrete, which is regarded as one of the most impacting construction materials (Gan, Cheng, & Lo, 2019), embodies only 1.11 MJ/kg of energy and 0.19 kg CO_2 eq/kg of CO_2. I will discuss these apparently conflicting findings and how they are affected by the functional units in the results section (see Section 5.3).

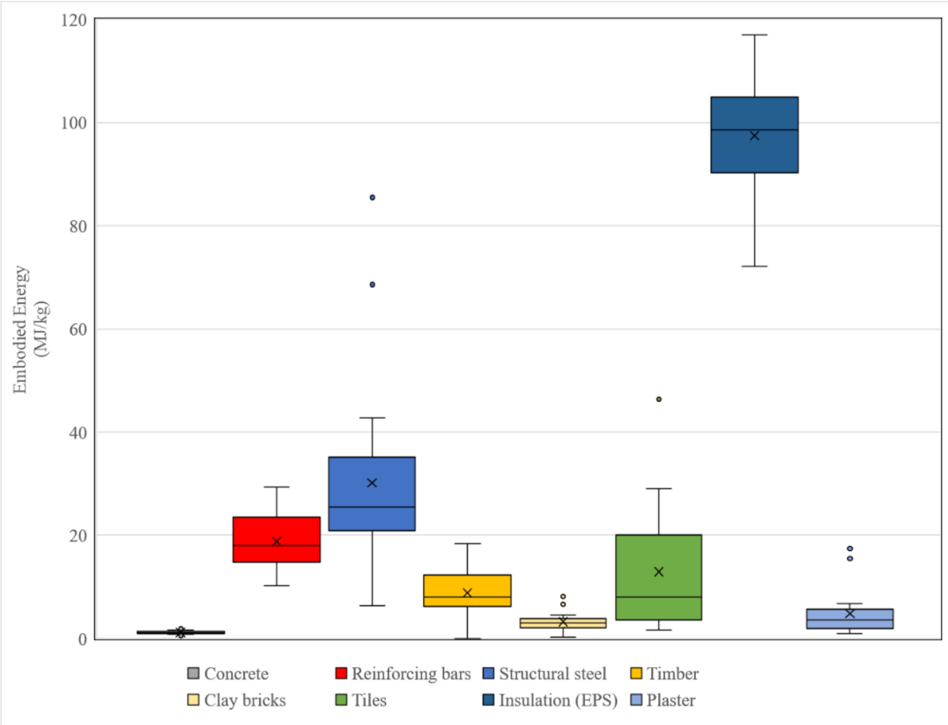

Fig. 2.4 – Environmental impact of the studied materials, in terms of embodied energy. Outliers are represented by dots outside the fences, and the crosses mark the mean values. Extracted from Publication I (manuscript).

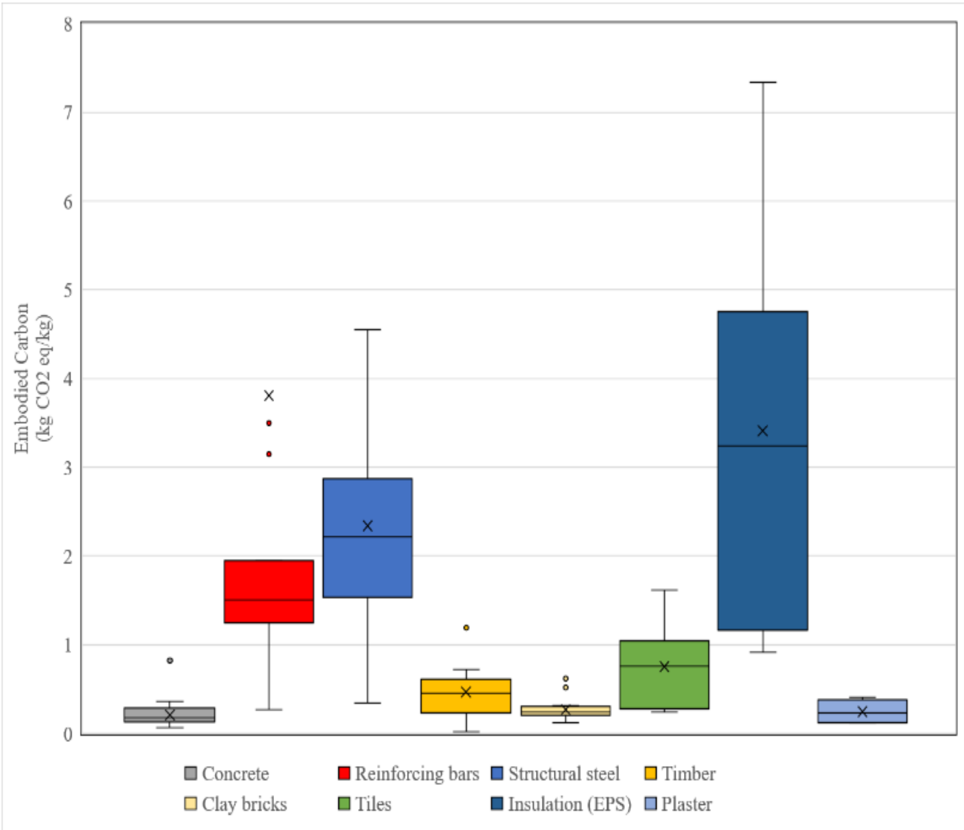

Fig. 2.5 – Environmental impact of the studied materials, in terms of embodied carbon. Outliers are represented by dots outside the fences, and the crosses mark the mean values. The reinforcing bar series shows its mean value outside of the interquartile range because of a top-outlier value that lies outside of the plot area. Extracted from Publication I (manuscript).

2.1.2 Environmental impact of buildings

Although the literature seems to suggest that the production of 1 kg of concrete is linked to a smaller environmental impact than the production of 1 kg of steel or timber (see Section 2.1.1), they are not taking into account the strength of the three structural materials. Further, those results are linked to the production stage alone and, thus, do not take into account the additional impact due to end-of-life operations. In analysing 116 LCAs of entire buildings, it is apparent that the timber structure is a preferable choice in regard to the environmental impacts of buildings. Buildings which use timber structures enable a saving of 43% in terms of embodied energy and 68% in terms of embodied carbon, over concrete structures (Fig. 2.6)

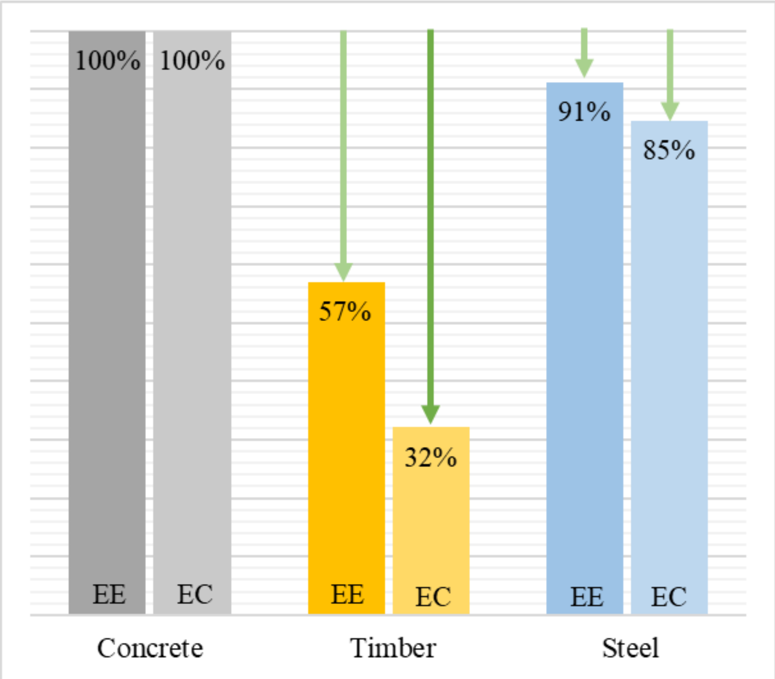

Fig. 2.6 – Medians of embodied energy and carbon of the timber and steel buildings relative to concrete buildings over the whole life cycle.EE= embodied energy, EC=embodied carbon. Extracted from Publication I (manuscript).

A fairer functional unit could be the element level. For example, instead of comparing the environmental impact of the production of 1 kg of concrete or steel, a functional unit that takes into consideration the actual element that is manufactured could be implemented. Such functional unit – construction element – would not only take into account the actual use of the component and its environmental impact, but would also pave the way to calculating the environmental saving due to components disassembly and reuse.

2.1.3 Environmental impact of transport

The life cycle assessment methodology is widely used to quantify the environmental impact of products and services (more in depth analysed in Section 3.4). Transport can represent a substantial portion of such impacts, especially in the construction sector. Indeed, transport of construction materials could increase both the embodied energy and carbon of up to 4% of the impact of the total building (see Y. Chang, Ries, and Lei (2012), H. Li, Deng, Zhang, Xia, and Skitmore (2019), Scheuer, Keoleian, and Reppe (2003), and Nässén, Holmberg, Wadeskog, and Nyman (2007)). The results that emerged from the analysed literature show that transport by truck impacts about 10 times more than transport by sea or train in terms of embodied energy, and 16 times more than transport by train in terms of embodied carbon (Table 2.2).

Table 2.2 – Embodied energy and carbon of transport by marine shipment, railway and road, including median values and sources. Results extracted from Publication I (manuscript).

	Embodied energy (MJ/t/km)	***Embodied carbon (kg CO_2 eq/t/km)***	***Source***
Marine shipment	0.20	0.0327	C. C. Chang, Shi, Mehta, and Dauwels (2019) Wang, Yu, and Pan (2018)
	0.16	0.0330	
Median	*0.18*	*0.0329*	
Mean	*0.17*	*0.0329*	
Railway	0.22	0.017	Gan, Chan, Tse, Lo, and Cheng (2017) Wang et al. (2018)
Road -truck	3.10	0.0833	C. C. Chang et al. (2019) Ghayeb, Razak, and Sulong (2020) Jia Wen, Chin Siong, and Noor (2015) H. Li et al. (2019) Liu, Guo, Sun, and Chang (2016) Monahan and Powell (2011) Paulsen and Sposto (2013) Peng (2016) Scheuer et al. (2003) Svajlenka and Kozlovska (2017) Wang et al. (2018) Wu, Yuan, Zhang, and Bi (2012) Yang, Hu, Wu, and Zhao (2018) Yang et al. (2018) Yu, Tan, and Ruan (2011)
	2.42	0.1281	
	2.30	0.1500	
	2.14	0.1286	
	1.62	0.1680	
	1.40	0.0942	
	1.09	1.2065	
Median	*2.14*	*0.1286*	
Mean	*2.01*	*0.2798*	

2.1.4 Circular economy applications

Despite the increasing interest and research on the LCA of buildings, the SLR undertaken in Publication I (manuscript) highlighted a lack of research on circular economy applications within the building sector. Specifically, only 17 results considered the reusability of building components (see, for example, Chau, Xu, Leung, and Ng (2017), Cruz Rios, Chong, and Grau (2019) and Nußholz, Nygaard Rasmussen, and Milios (2019)), while the majority of results adopted recycling as a circular economy strategy but did not consider the subsequent decreased quality of materials due to the recycling process (Zhao et al., 2020). Indeed, the term down-cycling should be used for materials such as concrete or timber (Ramage et al., 2017). That is because both concrete and timber are remanufactured as recycled materials characterized by lower structural quality: recycled concrete becomes aggregate (Xiao, Wang, Ding, & Akbarnezhad, 2018) which requires additional cement, sand and water to be remanufactured as concrete (Le & Bui, 2020); recycled timber is often recycled into MDF (medium density fibreboard; (Tam & Tam, 2006)) which, in turn, is ultimately often used for energy recovery (Cesprini et al., 2020).

Conversely, design for disassembly and reuse helps preserve the materials and components in their functional state (Munaro, Tavares, & Bragança, 2020). This practice, despite its substantial potential in terms of material saving and associated environmental impact, has been adopted only in a limited number of empirical works (Abuzied et al., 2020; L. C. M. Eberhardt et al., 2019; Kirchherr & van Santen, 2019). The lack of circular economy applications in the building sector was the reason why I researched how other industry sectors attempted to apply the circular economy. This issue was addressed in Publication II, whose literature review is summarized in the next section, 2.2.

2.2 Literature on Circular Economy Applications

To bridge the gap between CE and the building industry, I explored how the CE has been applied to other industry sectors – especially in the car industry – and adapted the related operations to the building context. In so doing, I proposed seven strategies that could be implemented into traditional buildings, but which have found their optimal applications when applied to modular buildings (Table 2.3). The proposed seven strategies are largely linked to the 3R's concept: CE implementations through reduce, reuse and recycle. The 3R's can be applied to each life cycle of a building.

Table 2.3 – Strategies and opportunities that arose, along with barriers and how they can be overcome with proposed solutions and link to the 3R's. BIM — Building Information Modelling. Adapted from Publication II.

	Strategy	*Opportunity*	*Barrier*	*Solution/link to the 3R's hierarchy*
1.	***Reduction of construction waste and the lean production chain***	Integrate a lean production in the prefabrication phase of building components.	Complexity and variability of traditional buildings.	Increase the use of prefabricated components. This strategies finds justification in the 'R' reduction: reduce waste production directly helps minimization of materials leakage from building system.
2.	***Integration of scrap, waste, and by-products into new components***	The use of concrete fosters the second life of by-products.	Strategy limited to the use of concrete, which, by itself, is highly carbon intensive.	Integrate by-products into concrete production. High potential in traditional buildings, where more concrete is typically used. By-product reintegration allows waste minimization, as it increases the value of such by-products making them more valuable in the production chain. The benefit is double: it avoids by-products from landfill and limits the need for new materials, as by-products are their substitutes.
3.	***Reuse of replacement parts or entire components***	Through reuse of parts, waste can be reduced, giving a second life to building components. Supply chain could be	Technological barrier of disassembling a monolithic building; economic barrier if components are not designed toward reuse.	Design for disassembly facilitates the reuse of components. Preferring visible joints, steel frames, and standard measures, components can be disassembled and reused, fostering the market of reused

		integrated in business planning.	Supply chain for reused components is yet to be developed in the building sector.	parts. This strategy is directly linked to the 'R' reuse.
4.	***Design toward adaptability (reduction through life extension) during operational stages***	Planning of flexible spaces and design of adaptable elements to reduce the waste due to modifications in the operational stage of buildings.	The degree of adaptability is proportional to the mobility degree of the building. Traditional buildings are built on-site to be permanent, and thus, are not adaptable.	Prefabricated building components could be designed to be movable, increasing the adaptability of both traditional and modular buildings. Adaptability helps reducing the need for new materials, spaces, products. It is linked to the 'R' reduce through life extension.
5.	***Design toward disassembly of goods into components to be reused***	The use of BIM in prefabrication allows for material tracking, identification, and cataloguing.	Cost effectiveness and technological feasibility hinder the practical application of disassembly.	BIM stores instructions on components and their relationship to the structure, enabling methodical deconstruction. In turn, deconstruction fosters second use of materials and components, linking to the 'R' material reuse. Also, a facilitated deconstruction helps decreasing material contamination, which, in turn, improves recyclability.
6.	***Design for recycling of construction materials***	Steel can be recycled, and concrete is commonly down-cycled. Building with steel would then increase the material saving.	Transport of recycling components and the recycling processes themselves are carbon-intensive for both concrete and steel.	Whenever possible, the use of recycled concrete and steel should be preferred. Steel in particular maintains its mechanical characteristics. Strategy 6 is directly linked to the 'R' recycle.
7.	***Systems to track materials and components within their supply chain***	Track materials and components throughout the life cycle of buildings.	Location of materials and time when those would become available.	Prefabricated buildings designed with BIM could allow the information to be shared on the upcoming deconstruction. This strategy could help creating a database of material and component stock, fostering a closed-loop of building materials towards reuse or recycle.

2.2.1 Strategy 1 – Reduction of production waste

During the production stage of a building, a large amount of waste is often generated in the form of reinforcement bar cut-offs, leakage from concrete elements, damaged materials and components such as bricks or tiles, and material lost during transport (Formoso Carlos, Soibelman, De Cesare, & Isatto Eduardo, 2002). Such waste could be diminished by improving the project management of the building production stage through management tools (Browning & Heath, 2009; Lin, Chang, & Chen, 2012). These tools include just-in-time manufacturing (i.e. ordering and receiving materials at the exact time when they are needed, as used in the car industry; Gaustad et al. (2018)), design for assembly (designing components that can easily be assembled without the need to fit-in and without producing cut-offs; (Aye, Ngo, Crawford, Gammampila, & Mendis, 2012)) or lean production chain (optimization of components' production to diminish waste generated; (Sacks, Radosavljevic, & Barak, 2010)).

Although this strategy could be applied to the broad construction sector, they find their optimal application within the narrower modular building industry (Goh & Goh, 2019). That is because modular buildings are built in controlled factories, where the optimization of management and production tools are facilitated (Heravi, Rostami, & Kebria, 2020).

2.2.2 Strategy 2 – By-products re-integration

The practice of using by-products, which also emerged from the SLR presented in Section 2.1 and will be later explained in detail in Section 4.1.2, attempts to reuse waste into a new product (Brown & Buranakarn, 2003). More specifically, waste from power-generating plants such as fly-ash could be used to substitute cement into concrete (Meyer, 2009). When 35% of fly-ash is employed in the concrete mix, up to 33% of both embodied energy and carbon can be saved, without endangering the final product (Gan, Cheng, Lo, & Chan, 2017).

2.2.3 Strategy 3 – Reuse of building components

Although the reuse of building components might be hindered by economic constraints, it is also regarded as the most promising CE strategy to diminish the environmental impact of buildings (Tumminia et al., 2018). At the same time, technological constraints limit disassemblability and reuse of building components (Rios, Chong, & Grau, 2015). If components are to be reusable, they must be lightweight, standard in measures, and their joints must be visible, reachable and easy to disassemble (Eckelman et al., 2018).

To overcome the technological and economic constraints, cars could be taken as an example. Cars represent an example of a disassemblable product, and modular building companies could draw from the approach of the car industry where joints and components are manufactured that can be feasibly disassembled or deconstructed (Hasibul, Gustav, & Malin, 2018).

2.2.4 Strategy 4 – Movability and adaptability

Buildings are typically static and monolithic (W. Salama, 2017). However, if buildings were designed to be movable, with adaptability of space, this would enable the reusability of the entire envelope to different locations and with different purposes (Sanchez et al., 2020). Relocation and adaptation could, in turn, diminish the amount of materials necessary to create a second building, and decrease the landfilled or recycled materials (Brambilla, Lavagna, Vasdravellis, & Castiglioni, 2019). Moreover, by saving time and labour to manufacture a new building, companies could retain the economic value of the first building and potentially increase their economic revenue (Morseletto, 2020).

Although some concrete components could be disassembled, movable buildings must be lightweight to be craned, and resilient to accidental impacts. Because modular constructions are built off-site and transported and assembled on-site (Alembagheri, Sharafi, Hajirezaei, & Tao, 2020), they represent the best application of the movability and adaptability strategy.

2.2.5 Strategy 5 – Disassembly as end-of-life practice

Similarly, design for disassembly is a fundamental CE approach to apply when buildings are decommissioned. This is based on the concept that materials and components might outlast the product of which they are a part (van den Berg et al., 2020). To disassemble building parts and exploit the remaining functionality of these valuable components, however, they must be designed with mechanical connections, rather than being welded or glued (L. C. M. Eberhardt et al., 2019). Building information modelling (BIM) also represents an accessible and useful tool to help practitioners in the design of buildings that can be disassembled once they reach their end-of-life stage (Basta, Serror, & Marzouk, 2020).

2.2.6 Strategy 6 – Design for recycling

Although reuse of components enables a near complete saving of materials and related emissions, design for disassembly and reuse is not always possible (Tingley & Davison, 2011). For this reason, designers should always plan buildings so that their materials are at least recyclable (Julian M. Allwood, 2014). Specifically, steel can be recycled infinite times without compromising its mechanical characteristics (Cao, Li, Zhu, & Zhang, 2015; Su, Li, Wang, & Zhu, 2016). Concrete, on the other hand, can be recycled into materials with lower quality and value, such as aggregates (Xiao et al., 2018). Regardless, material recycling is an important strategy that helps decrease environmental pressure and material depletion (Atsushi Takano et al., 2015).

2.2.7 Strategy 7 – Materials and components tracking

As highlighted in Section 1.1.1, a closed-loop supply chain of construction materials and components is under-developed (Densley Tingley et al., 2017). A database of components that are stocked in buildings, which includes their functional, architectural and mechanical characteristics could be implemented – a concept known as buildings as material banks (Benachio et al., 2020; Leising, Quist, & Bocken, 2018). Buildings as material banks could be further facilitated by the creation of a material passport, that is the information of building components attached through passive or active code systems (for example barcodes, QR codes or radio-frequency identification RFID system). Moreover, the attached code system could include information on the upcoming deconstruction. Although some studies show that component tracking could lead the way towards the implementation of a closed-loop supply chain of building materials, the material bank strategy has been applied only on a limited number of empirical studies Honic, Kovacic, and Rechberger (2019)). Despite the lack of applications, the integration of this strategy could be feasible in disassemblable and reusable buildings (Munaro et al., 2020).

The following Chapter explains the methodologies that I have adopted in this PhD to address the research questions listed in Section 1.3.

Chapter 3. **Methods**

Several methods have been applied to address the listed research question and sub-questions. First, a systematic literature review (SLR) method was applied to comprehensively review the relevant literature. A meta-analysis method was applied to the quantitative data, collected through the SLR, with extraction, coding and analysis, through descriptive and inferential statistical methods. In parallel, the SLR allowed the review of collected articles and extraction of the most researched end-of-life operations that have been applied to the building context.

The SLR and meta-analysis opened up new research opportunities. Most importantly, the under-researched applications of circular economy theory to buildings. To investigate this research area, a narrative review method was adopted. The literature review allowed the formulation of seven strategies that could foster the application of CE to buildings (Publication I).

The findings of the previously applied methods allowed the design and construction of a full-scale prototype of a circular economy building, the Legacy Living Lab (L3). Relevant data were collected during the design and production stage of the L3, for example a bill of quantities (BoQ), process to manufacture the materials.

A life cycle assessment (LCA) method was then applied to the L3 to calculate its environmental impact. Further, the L3's environmental impact was compared to the impact of a building designed with the same amount of materials, which differs from the L3 prototype as this linear version was virtually built without including the circular economy framework and the seven strategies previously developed.

The construction of the L3 opened up for two additional studies within this PhD. First, the proposal of a novel method, namely design for disassembly, deconstruction & resiliency (D^3R), which allows the calculation of the degree of circularity of a building. Second, the combination of a comparative case study and living laboratory methods to investigate how living laboratories maintain their efficiency in relation to their networks and actors.

This chapter presents the details of these methods, whose related articles are listed in Table 3.1.

Table 3.1 – Methods adopted in this research and related articles produced.

Title	***Methods applied or studied***	***Data analysed***
I. Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments.	- Systematic literature review. - Meta-analysis. - Life cycle assessment.	- Literature on life cycle assessments of buildings. - Construction materials and buildings' embodied energy and carbon.

Manuscript submitted for peer-review journal.		
II. Strategies for Applying the Circular Economy to Prefabricated Buildings. *Peer-reviewed article published.*	Narrative literature review and synthesis.	Literature on circular economy applications in several industry sectors.
III. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Peer-reviewed article published.*	Comparative life cycle assessment.	Data obtained from the Legacy Living Lab: - Bill of quantities. - Construction technologies. - Material inflow and outflow. - End-of-life and next product practices.
IV. Design for disassembly, deconstruction and resilience in construction: A circular economy index. *Manuscript submitted for peer-reviewed journal.*	Design for disassembly, deconstruction & resiliency (D^3R) — method proposition.	Data obtained from the Legacy Living Lab: - Bill of quantities. - Construction technologies. - Material inflow and outflow. - End-of-life and next product practices.
V. The project network approach for Living Laboratories. *Manuscript under revision in a peer-reviewed journal.*	- Comparative case study review. - Living laboratory research method.	Networks, objectives and value propositions of two case studies: - Sustainable Home Living Lab. - The Legacy Living Lab.

3.1 Systematic Literature Review & Meta-Analysis

3.1.1 The SLR Method

The SLR method allows the collection, coding and review, in a comprehensive way, of the available articles on a specific topic (Siddaway, Wood, & Hedges, 2019). While narrative reviews are characterized by a looser way of selecting the reviewed studies (Snyder, 2019), systematic reviews are less likely to be affected by biases, due to the structured methodology (Littell, Corcoran, & Pillai, 2008). Furthermore, when the methodology adopted in producing an SLR is transparently documented, the reviews is repeatable and updatable (Siddaway et al., 2019). Because of these characteristics, the SLR is considered the most rigorous literature review method (Sovacool, Axsen, & Sorrell, 2018). The SLR method adopted in the submitted Manuscript I was used to review the literature on LCA results of construction materials and buildings. The SLR method was adopted in addressing the research questions "What can be learnt by collecting and summarizing individual environmental impact studies of buildings to foster environmental impact reduction towards a circular economy?" and "What are the limits of the environmental impact assessment tools and how can these limits be overcome?". Additionally, the SLR also paved the way for the adoption of a meta-analysis approach to the quantitative data that was extracted from the selected literature (see details in Section 3.1). The SLR methodology was divided into four main steps. A summary of the four steps and related number of articles is provided in Fig. 3.1.

Step 1) Keywords and search string. Starting from the research questions that Manuscript I endeavoured to answer — What can be learnt by collecting and summarizing individual environmental impact studies

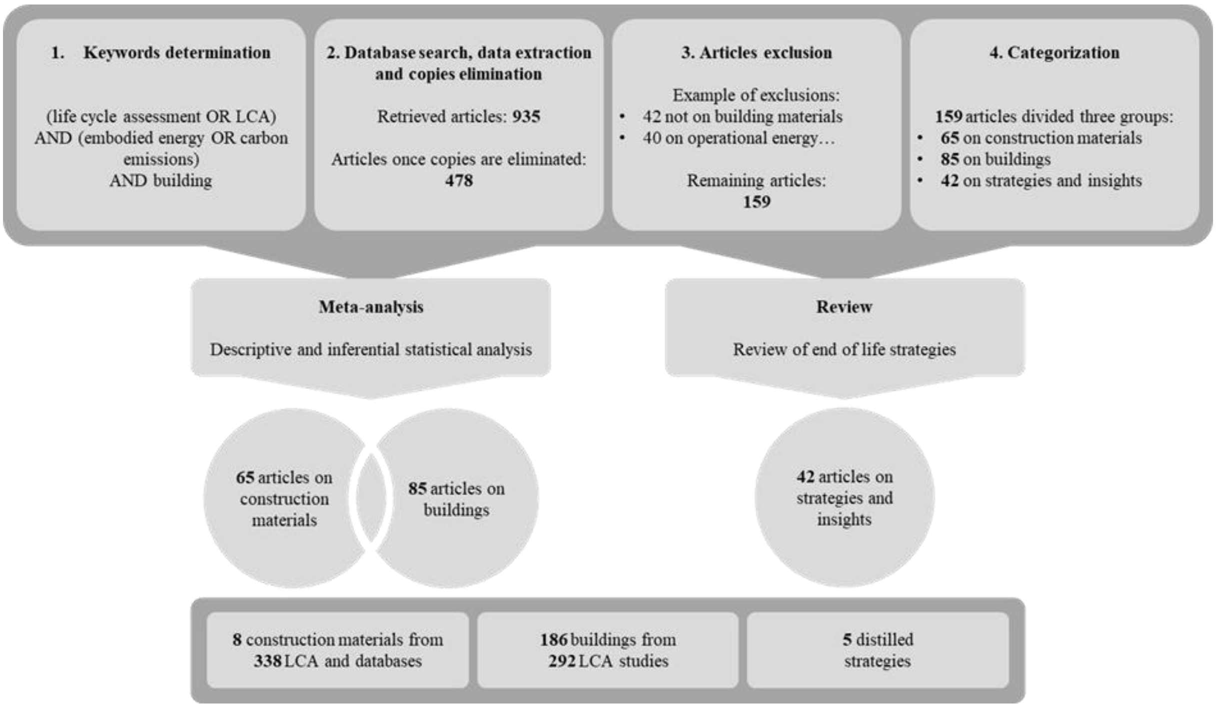

Fig. 3.1 – Overview of the systematic literature review and meta-analysis flow chart and results. Adapted from Publication I.

of buildings to foster environmental impact reduction towards a circular economy? What are the limits of the environmental impact assessment tools and how can these limits be overcome? — I selected the keywords that compose the Boolean search string (life cycle assessment OR lca) AND (embodied energy OR carbon emissions) AND building. Keywords composed of more than one word were retained by quotation marks, and the search engines automatically search for plural spelling of the same word.

Step 2) Database search, data extraction and copies elimination. The Boolean search string was applied to ScienceDirect, Scopus, ProQuest and Web of Science (search updated in April 2020). No year limit was applied, and only articles in English were retrieved. Further, to narrow down the findings to our research area, I filtered the results limiting the findings to environmental science only. The search resulted in 935 articles. Bibliographical meta-data was exported into EndNote X9 and Excel v.1908. Once the copies were eliminated, 487 articles remained.

Step 3) Shortlist creation. To limit the possibility of bias in selecting the articles that would compose the shortlist, I formulated a list of inclusion and exclusion criteria before working through the articles. Articles that were excluded were, for example, those which did not answer our research questions, did not provide detailed information or used incompatible functional units. To further limit bias, I used the statistical tool Cohen’s kappa to measure the level of agreement between the articles that I excluded, and the articles excluded by a co-author (Cohen, 1960). On a scale of 0-1, our Cohen’s kappa was 0.84, which is considered a high agreement. Once articles were excluded, the shortlist was reduced from 487 articles to 159.

Step 4) Categorization. I identified two overarching categories among the 159 articles: works on construction materials (65 articles), and results of the LCA of entire buildings (85 articles). Furthermore, another 42 articles were selected because of their focus on end-of-life and next product strategies.

The four steps of the SLR paved the way for applying a meta-analysis of the LCA results of the articles on construction materials and on entire buildings.

3.1.2 The Meta-Analysis Method

The objective of a meta-analysis study is to explore, from a collectiveness of individual data points that were extracted from selected articles, a comprehensive series of interval estimates. Additionally, a meta-analysis is a tool to recognise and investigate eventual patterns between individual quantitative results. To do so, I adapted descriptive and inferential statistical analysis tools to the quantitative data extracted from the literature that was previously selected through the SLR.

Descriptive statistical analysis. The quantitative data extracted was divided into two main categories: construction materials (i.e. concrete, reinforcement bars, structural steel, timber, bricks, tiles, insulation-expanded polystyrene, and plaster), and buildings (i.e. buildings with concrete, timber or steel structure). The means, medians, first and third quartiles, interquartile range and outliers of these data were identified, and the results were plotted on box-whisker charts.

Inferential statistical analysis. I studied the correlation of data through clutter plot charts and by calculating the relevant coefficient of determinations R^2, when the gathered data allowed (in some cases missing data did not allow the application of inferential tools). This fostered a deeper understanding of the relationship between, for example energy consumed to produce selected materials, related GHG emissions and countries where these results were calculated.

The 42 articles that were not included in the meta-analysis were employed to create procedural guidelines to integrate with the classical LCA method. The guidelines include a benchmark of LCA results, and a list of strategies to decrease the impact of buildings. Details are provided in Section 4.1.

The results and conclusions that arose from this SLR and meta-analysis research (Publication I) contributed to an understanding of the need for a more thorough theoretical application of the circular economy to buildings. Section 3.2 explains the methodology that this research applied to provide a theoretical understanding of how the circular economy could be applied to buildings.

3.2 Narrative Literature Review Method

Although the SLR and meta-analysis methods applied in Manuscript I enabled the formulation of a list of end-of-life strategies, these strategies were not necessarily related to a circular economy — they were the strategies that have been commonly applied in the building context. For this reason, the research question "What are the main strategies that have fostered the application of the circular economy, and how can these strategies be adapted to the building context?" was yet to be addressed. In addressing this research question, the literature review method was preferred, over the more rigorous SLR, because of the limited amount of literature available on the topic of practical applications on circular economy. Further, it was more beneficial for the purpose of creating a narrative spanning across different industry sectors (whereas the SLR is most appropriate when the literature is narrow around a focal topic/method). Finally, a narrative literature review method was preferred here as it helped merging and exploiting the expertise of one of Paper II co-authors. Indeed, with more than 10 years of experience in the construction sector, his experience was fundamental in analysing and synthesising the relevant studies that were found in the database search. Similarly to an SLR, this method is structured in four main steps (Fig. 3.2). In the first step the research question and related keywords were formulated. In the second step these keywords were applied to a number of selected databases, including ScienceDirect, Scopus,

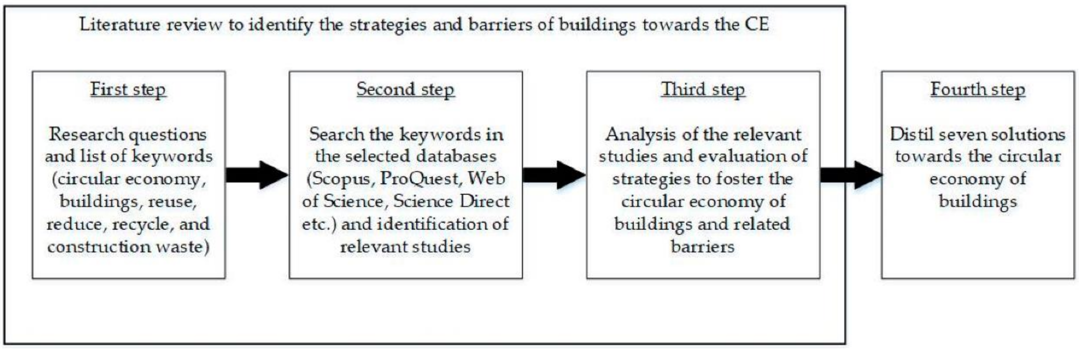

Fig. 3.2 – Steps of the narrative literature review method. Adapted from publication II.

ProQuest. This allowed the extraction of relevant studies that enabled the delineation of a narrative. Further, in the third step, from these studies I distilled the circular economy strategies that could be applied to the building industry. The fourth step is the formalization of these strategies.

The main outcome of this research (Publication II) was the result that the modular building technology could be fit-for-purpose for the application of the CE principles to building. Accordingly, Publication II provides a list of strategies that, applied to different life cycle stages of buildings could overcome the barriers of applying CE to the building context.

In applying these strategies to modular buildings, this research evolved into the practical application of conceptualizing and designing a disassemblable and reusable full-scale prototype of a circular economy modular building, the Legacy Living Lab.

3.3 The Legacy Living Lab

The Legacy Living Lab (L3; Fig. 3.3) is a modular building that has been conceptualized within this research to explore the practical barriers and implications of the CE of buildings. The CE strategies developed in Publication II have been applied to each life cycle stage of the L3, from its concept and space definition to its realization, so that most of its components are reused and reusable. Data collected during the creation of L3 is reported in Publications III and IV.

Fig. 3.3 – The Legacy Living Lab

The L3 was built in a modular construction factory in Perth, Western Australia. It is composed of eight steel frame modules. The 251 m^2 of internal floor area are distributed on two floors. Although the L3 internal spaces are organized into an open office area, a shared kitchenette, a commercial space and a café area for meetings and collaborative working sessions, the L3 has been designed for the adaptability of internal spaces. Space adaptability has been considered one of the aspects that might help to share spaces and reduce land and material consumption (see Julian M. Allwood (2014) and Walter R Stahel (2016); Fig. 3.4).

The L3 can be transported and relocated, built with minimal environmental impact (results provided in Section 4.2). Moreover, the L3 serves a number of purposes concerning the CE of buildings, fostering further research and innovation in the sectors of sustainability and buildings. The idea of building the prototype to apply and study the CE emerged from the results gathered in Publications I and II, which

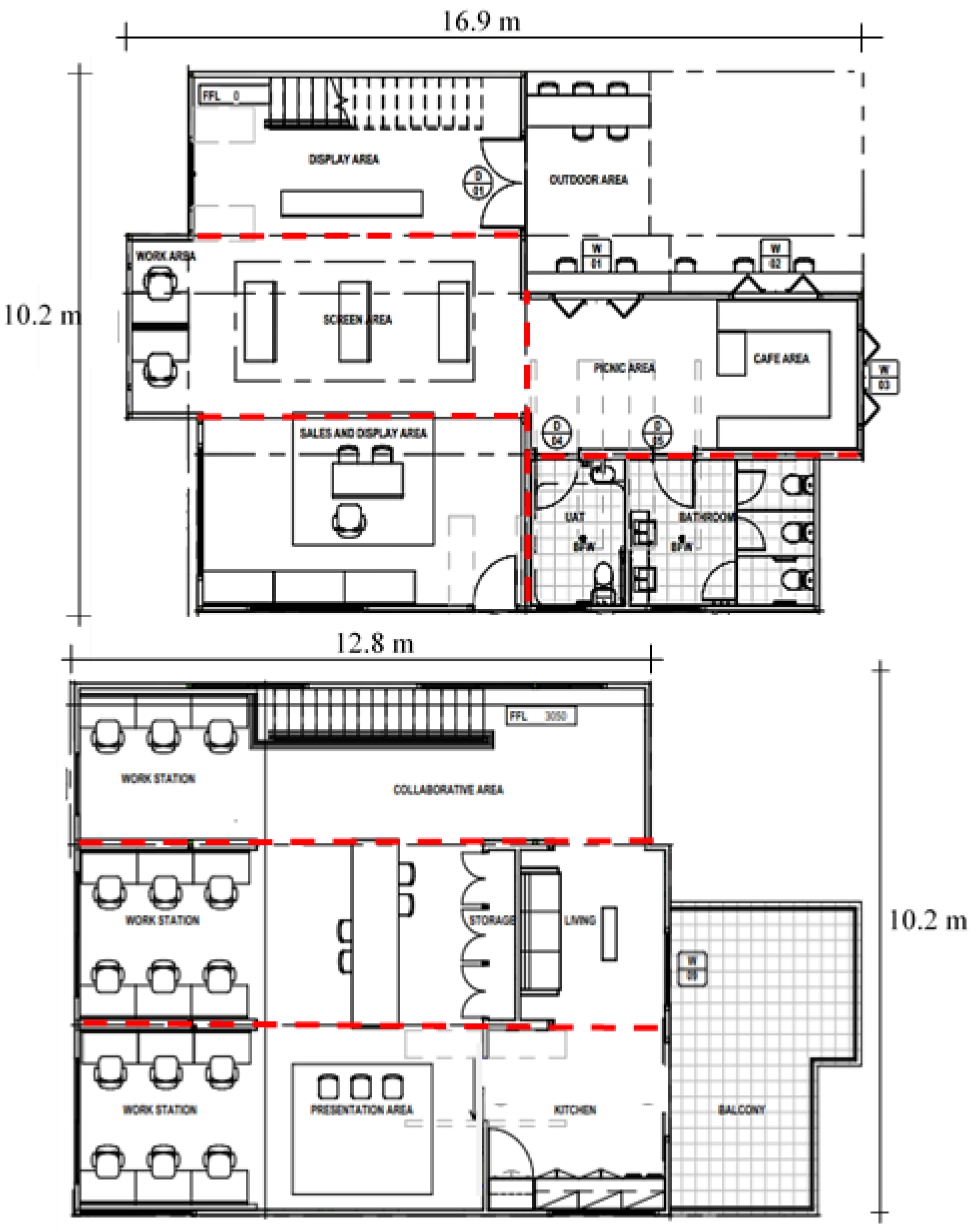

Fig. 3.4 – Plans of the prototype L3. The ground floor (top, 117m2) and the first floor (bottom, 129m2) were designed for adaptability of spaces. The red dashed lines highlight where the eight modules can be detached to disassemble the L3. Adapted from Publication III.

clarified that empirical and practical research are needed to create a deeper understanding of barriers to and implications of CE of buildings. More information on the L3 can be found in Publication III.

Several components and materials used in the L3 has been re-engineered and reused. Further, these components are reusable in next life cycles, once the building reaches its end-of-life. Structural steel, the timber stairway steps and the carpet tiles, for example had been sourced from a previous building.

Moreover, in line with the concept of reduction of highly impacting materials, no concrete was used in the entire building. A system of micro-pile foundations was employed to avoid the use of plinths. The floors are supported by reused steel chassis and particle board floors.

Fig. 3.5 – First floor of the prototype building L3. The wall and roof cladding are disassemblable, showing the frames granting access to insulation and systems. This feature allows low waste and low environmental impact during the operation stage of the L3. Adapted from Publication III.

To ensure adaptability of the structure, as well as internal disassemblability, the internal walls are clad with screwed plywood, avoiding plasterboard[1]. The screwed plywood panels allow the internal walls to be unscrewed, so that the electric and electronic systems can easily be modified and replaced (see details of disassembled walls in Fig. 3.5). One boundary of the present research is the exploration of the different joints employed in L3. Such boundary is due to the fact that several different types of joints have been employed in the complexity of L3 and exploring each one of them would require an additional effort out of the scope of this research.

3.4 Life Cycle Assessment

LCA is a method to quantify the environmental impact of products and services (Nwodo & Anumba, 2019). Therefore, LCA could be used in addressing the research question "What are the environmental advantages of applying the circular economy to a building purposely built following the circular economy strategies?". In so doing, I applied the LCA method in Manuscript III to calculate the environmental impact of the L3. Further, to understand the environmental benefits of adopting the CE in the building context, I compared these results with a case study modular building with the same dimensions and purpose but built without considering the CE strategies that were reported in Publication I and II. The software used in this LCA was SimaPro 9.0 and the database Ecoinvent 3.5. This

[1] With the exception of the kitchenette and bathrooms walls, which are clad with plasterboard for hygiene reasons.

comparative LCA unfolds in four modules that have been adapted from the European international standards 14040 and 14044 (Chomkhamsri, Wolf, & Pant, 2011).

Module 1) Goal and Scope Definition. The goal of this comparative LCA is to calculate and compare the results of the application of the CE strategies. Therefore, the system boundary of this LCA is the accounting of materials alone. That means that only the materials have been included in the calculations, and not fuel for transport or energy for energy and water for the building operations.

The functional unit, which describes the performance requirement that the building fulfills, in this calculation has been as the entire building, and this LCA follows an attributional method, which is designed to isolate the product, in this case L3, from the rest of the economic system (H. Baumann & Tillman, 2004, p. 84; Cabeza et al., 2014). In following the indications suggested by similar studies (GBCA, 2014; Khasreen, Banfill, & Menzies, 2009; Sharma, Saxena, Sethi, Shree, & Varun, 2011; Stocker et al., 2013; Yellishetty, Mudd, & Ranjith, 2011), I quantified the impact of the L3 according to six environmental impact indicators: global warming potential (GWP, measured in t CO_2 eq), ozone depletion potential (ODP, measured in kg CFC-11 eq $*10^4$), acidification potential (AP, measured in kg SO_2 eq), eutrophication potential (EP, measured in kg PO_4 eq), abiotic depletion of non-fossil resources (AD, measured in kg Sb eq $*10^2$), and abiotic depletion of fossil fuels (ADFF, measured in MJ$*10^2$).

The life cycle of the L3 is divided into its four life cycle stages (Table 3.2). In the production stage (A), the components are manufactured, and the building is assembled. Because of the purpose of this LCA I excluded from this study the transport of raw materials and transport of modules to site. In the operation stage (B), I included the materials needed to maintain the building in working condition and excluded operational energy and water. It is important to underline that, by applying the CE, the materials wasted during the operation stage of L3 are minimized. This was possible by a careful selection of materials such as plywood or steel cladding, which can be disassembled before moving the building, while conversely the plasterboards would be damaged before moving the building. In the end-of-life stage (C) I accounted the materials which will be sent to landfill and the impact of disposing these materials but excluded the consequences of transporting waste to landfill. Finally, the next product system stage (D) accounts for the materials that can be reused or recycled.

Table 3.2 – Life cycle stages of the L3 included and excluded from this study. Adapted from Manuscript III.

	LCA stage	***Process***	***Code***	***Included***
Material input	Production (A)	Raw materials input	A1	Yes
		Transport of raw materials	A2	No
		Production	A3	Yes
		Transport of modules to site	A4	No
		Craning	A5	Yes
	Operation (B)	Refurbishment/repair	B1	Yes

Material output		Energy and water consumption for operation	B2	No
	End-of-life (C)	Deconstruction/demolition	C1	Yes
		Transport to landfill	C2	No
		Waste recovery	C3	Yes
		Landfill disposal	C4	Yes
	Next product system (D)	Reuse, recovery or recycle	D	Yes

Module 2) Life Cycle Inventory Analysis. The data collected during the L3 design and building operations include the detailed amounts of materials of the L3 and the comparative case study, its linear version (Table 3.3). All the steel used in the L3 is recyclable, however, as suggested in the CE strategies, an effort should be made to reuse the components. According to this suggestion, 16 139 kg of steel are reused in the circular version of the L3. The strategies also suggest minimizing non-reusable or recyclable materials. In assuming that concrete is a down-cyclable material, the 19 848 kg of concrete was avoided by using steel foundations.

Table 3.3 – Life cycle inventory, materials input to produce the L3. Adapted from Manuscript III.

Material	***Description***	***Amount (kg)***
Steel	Chassis and load bearing structure, internal walls structure, and external cladding.	21 335
Timber	Stairway steps, cladding plywood, flooring pressed timber and external cladding pressed timber.	9 406
Concrete foundations	Concrete foundations composed of concrete discs and footings[1].	19 848
Steel foundations	Pile driven lightweight steel foundations[2].	735
Plasterboard	Plasterboard cladding, used in kitchen/bathroom areas and ground floor ceiling.	140
Others (carpet, vinyl and insulation)	Floor covering and insulation.	3 413
Openings	Aluminium windows and glazed doors, and internal timber doors.	63 (m^2)

[1] Concrete foundations are only used in the linear version.
[2] Steel foundations are included as an alternative design choice in the prototype only.

It is important to recognise that, because the amounts of materials calculated during the life cycle inventory analysis were measured as primary data, a sensitivity analysis of the LCA was not necessary (see Toniolo, Mazzi, Pieretto, and Scipioni (2017), Wei et al. (2015)). Indeed, sensitivity — or uncertainty — analyses are used in LCAs when some of the data cannot be precisely calculated. Some examples include the adoption of sensitivity analysis to calculate the impact of different transport scenarios (for example see Hossain, Poon, Lo, and Cheng (2016) and Brambilla et al. (2019)).

Module 3) Life Cycle Impact Assessment and Module 4) Results interpretation. These two modules are explained and discussed in detail in Section 4.2.

3.5 Building Circularity Index (D^3R)

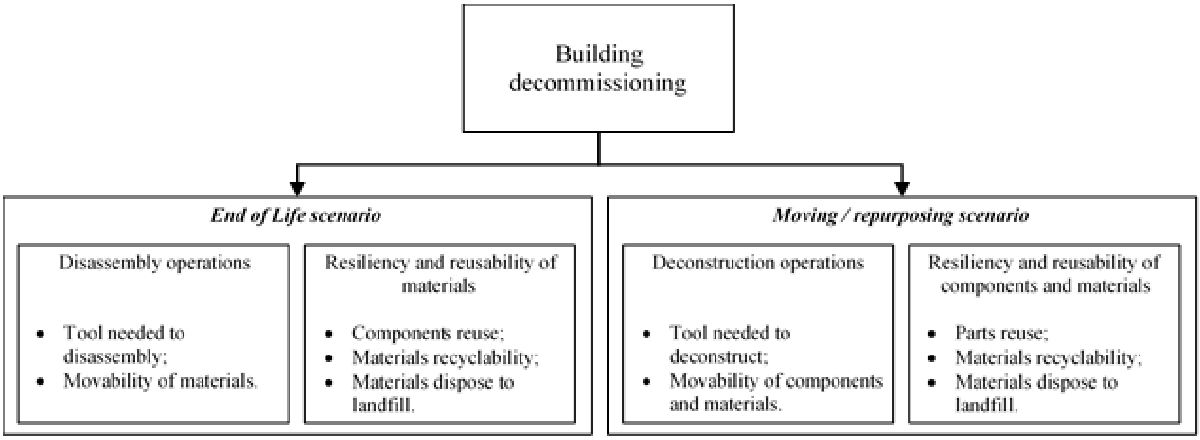

Fig. 3.6 – End of life and moving / repurposing scenarios in the circular economy context. Adapted from Publication IV.

The literature on the environmental sustainability of buildings agree that the impact of buildings and construction materals depends largely on their waste management. A noticeable gap in the literature is a method to calculate the level of disassemblability and reusability of building materials and components (Mesa, González-Quiroga, & Maury, 2020; Munaro et al., 2020). To fill this gap, Publication IV (manuscript) proposes a comprehensive method, namely design for disassembly, deconstruction and resilience (D^3R). This method is derived from the idea that, with an increasing number of buildings being disassemblable, and their components reusable, the concept of building decommissioning must be divided into two scenarios (Fig. 3.6). The first scenario, end of life, includes the operations to disassemble the decommissioned building, the tools needed for disassembly and move the materials. The second scenario, moving/repurposing, includes deconstruction operations and takes into account the resiliency and reusability of components and materials. Both scenarios account the necessity of tools to take buildings apart, but they differ in the portion of materials that are disassembled and demolished, and the portion disassembled for further reuse.

The D^3R method proposes the quantification of the D^3R normalized index as the sum of degree of disassembly (DI), deconstruction (DE) and resiliency (R) (equation 1):

1. $$D^3R = DI \times a + DE \times b + R \times c$$

The two extremes of the D^3R index are zero and one. If a building has $D^3R = 0$, its structure and components are fully linear, the building cannot be disassembled, reused or recycled. Conversely, if $D^3R = 1$, the building is fully disassemblable and all its components can be reused multiple times.

The parametric influences give the practitioner freedom to decide which of the three linked aspects is more relevant. Specifically, a, b and c account for the relevance of these operations in relation to the end-of-life scenario or moving/repurposing scenario. For example, if the analysed building reaches its end-of-life scenario, as defined in Fig. 3.6, the building will be disassembled. Conversely, if the building can be moved or repurposed, it is assumed fully deconstructed. Therefore $b = 0$ in the former case, and $a = 0$ in the latter. The sum of the remaining variables (a and c in the first scenario, b and c in the second) is in both cases one. Although we suggest assigning a value of 0.5 to the two non-zero variables, the user can decide to change them to increase the weight of disassembly/deconstruction over resiliency, thereby emphasizing the importance of one or the other aspect. The three other values in equation 1 are identified in equations 2, 3 and 4:

2. $$DI = \sum_{i=1}^{n} (DIt_i \times DIm_i \times w_i) \times \frac{1}{w_T}$$

3. $$DE = \sum_{j=1}^{m} \left(DEt_j \times DEm_j \times w_j\right) \times \frac{1}{w_T}$$

4. $$R = \sum_{k=1}^{t} (Re_k \times w_k) \times \frac{1}{w_T}$$

The variables of these equations calculate the influence that disassembly, deconstruction and resiliency of a specific building have when the building is decommissioned. Their values are explained in detail below. These parameters have a value when the related practice is closer to a circular economy (e.g., disassembly without power tools, or reusability infinite times) and zero to the practice that is considered less circular (e.g., dispose to landfill). These variables depend on the experience accumulated during the production operations of the L3 and the relevant literature on CE and reusability of materials and components.

Disassembly: equation 2. The level of disassemblability of a building at the end of its life depends on the tools required to disassemble the specific component i (Machado, de Souza, & Verissimo, 2018). This value is represented by the variable DIt_i. The variable DIm_i accounts for people or machines needed to move the components and materials (this includes only moving on-site, as accounting for transportation would be too broad and unpredictable) (Ganiron Jr & Almarwae, 2014; Musa, Yusof, Mohammad, & Samsudin, 2016) (Table 3.4). The parameter w_i represents the weight of the i component, while w_T is the total weight of the building. n is the total number of the building's components.

Table 3.4 – Values of the variables DIt and DIm used in equation 2, that define the degree of disassemblability of a building. Adapted from Manuscript IV.

	Operation & tools required		***Value***
DIt	Parameter that depends on the availability of tools, dimensions, manual, power tool etc.	No tool	1
		Hand tool	0.9
		Power tool	0.8
		Gas/pneumatic tool	0.5
		Hydraulic plant	0.2
DIm	Possibility of being disassembled and moved in	1 person < 25kg	1
		2 people < 42kg	0.9

	up to two people, more than two people, need for a fork-lift or a crane.	Hand trolley < 50kg	0.7
		Fork-lift < 2000 kg	0.4
		Crane > 2000kg	0.1

Deconstruction: equation 3. Similarly, the amount of materials and the components that can be deconstructed when a building is decommissioned depend on the tools required to deconstruct the part (parts can be entire modules or panels or materials) or components *j*, distilled in the variable DEt_j, and the people or machines needed to move the parts, components or materials on-site, distilled in the variable DEm_j (Table 3.5). The symbol w_j represents the weight of the *j* component. w_T is the total weight of the building. *m* represents the last component of the building.

Table 3.5 – Values of the variables DEt and DEm used in equation 3, that define the degree of deconstructability of a building. Adapted from Manuscript IV.

	Description		***Value***
DEt	Parameter that depends on the availability of tools, dimensions, manual, power tool etc.	No tool	1
		Hand tool	0.9
		Power tool	0.8
		Gas/pneumatic tool	0.5
		Hydraulic plant	0.2
DEm	Possibility of being disassembled and moved in up to two people, more than two people, need for a fork-lift or a crane.	1 person < 25kg	1
		2 people < 42kg	0.9
		Hand trolley < 50kg	0.7
		Fork-lift < 2000 kg	0.4
		Crane > 2000kg	0.1

Resiliency: equation 4. Once the parts, components and materials are taken apart, they could either be reusable infinite times, reusable a limited number of times, recyclable (or down-cyclable) or disposed to landfill (Cuellar-Franca & Azapagic, 2012). The symbol R_k takes this variability into account (Table 3.6). The symbol w_k represents the weight of the *k* component. w_T is the total weight of the building. *t* represents the last component of the building.

Table 3.6 – Values of the variable Re used in equation 4 that define the degree of resiliency of a part, component or material. Adapted from Manuscript IV.

Description	***Value of Re***
Reusable infinite times	1
Reusable up to 3 times	0.9
Reusable only once	0.7
Recyclable	0.6
Down-cyclable	0.2
Disposable	0

To validate this method, I applied it to the L3, in both its built circular and in its virtual linear version, and explain the results in the result chapter, Section 4.3.

3.6 Case Study Method

The last research question that this PhD addresses is "How can the living laboratory network foster and project further innovation in the field of circular economy?". The methodology adopted to address this question in Publication V (manuscript) is a case study method. The case study method is specifically effective to address the sixth research question of this thesis because it helps formulating new valuable insights from practical knowledge, being based on the experience that key actors have gained in building and managing the two investigated living laboratories (Flyvbjerg, 2006). More specifically, the case study method was designed to analyse qualitative data regarding complex changing contexts (Yin, 2011). However, in living laboratories a dichotomy between project goals and actors' goals might emerge (Leminen, Nyström, Westerlund, & Kortelainen, 2016). This dichotomy might, in the long run, harm the workflow of living labs and undermine their effectiveness. In addressing this issue, the scope of the research undertaken in Publication V (manuscript) was to investigate the alignment of living laboratories' goals during their operation and management stage. Specifically, two living laboratories were selected and examined in Publication V (manuscript): Sustainable Home Living Lab and the Legacy Living Lab. A juxtaposition of the two living laboratories' design aspects and management operations allowed the investigation of living laboratories goals' definition and alignment.

3.6.1 The Living Lab Goals

Living laboratories (living labs) provide innovation and prototyping places and spaces where researchers, industry and society work together to co-create and optimize products towards a central goal (Rosado, Hagy, Kalmykova, Morrison, & Ostermeyer, 2015; Veeckman, Schuurman, Leminen, & Westerlund, 2013). The goal of living laboratories is defined in their project design stage, and it inspires and affects all three features of living labs: research, business and society's involvement. A specific central goal of a living lab allows the orchestration and harmonization of operations of these three features. Conversely, a vague or undefined central goal might cause the living lab itself to be inefficient in producing research or in developing new products, and eventually result in the failure of the project. Similarly, the misalignment between the living lab's goal and the actor's goals might create tensions between the actors, which in turn might impair the quality of the living laboratory's operations.

3.6.2 Case studies and method design

To understand the complex inter-relations between living laboratories' actors, two case studies were selected, namely the Sustainable Home Living Lab and the L3 (as designed and built in this research). These two living labs were specifically selected because there was a related sequence in their designs: two of the researchers were involved in the design and studies of both living labs (myself and another co-author of Publication V, manuscript). This involvement allowed a direct observation of the conceptualization and practical implementation of the various activities of both living labs. To maintain an unbiased perspective, the two other authors of Publication V (manuscript) interviewed other involved stakeholders and users of the living labs. More than 30 meetings were held between industry partners and users, which, once arranged temporally, foster an understanding of the dynamics between living lab stakeholders and actors and how these dynamics might affect the centrality of the project goal. We then studied their relationships and roles by adopting the research approach of Nyström, Leminen, Westerlund, and Kortelainen (2014), in which several key actors are identified. The roles of key actors as defined by Nyström et al. (2014) helped in framing and understanding how the two case studies' actors are intertwined, and how eventually their goals might be misaligned with the project's goal. Further, the actors' roles might shift during the life cycle stages of a living lab (e.g. the actor that ideates the living lab in the conceptualization stage might become the planner in the project development stage).

The research undertaken in Publication V (manuscript) — discussed in Chapter 7 — helped to define how roles' shifts that necessarily occur during the living labs' production and management is linked to central goal misalignment.

Chapter 4. **Results**

This chapter summarizes the results obtained across the five publications and manuscripts produced within this PhD (Table 4.1). First, the systematic literature review (SLR) carried out in Publication I (manuscript) resulted in a proposal for procedural guidelines that can be integrated with the established life cycle assessment (LCA) method. Second, the strategies that emerged from the literature on the circular economy (CE) of buildings (Publication II, summarized in Section 2.2) guided the creation of the Legacy Living Lab (L3; the L3 has been outlined in Section 3.3). The data gathered from the L3 were modelled into an LCA. In so doing, the second result is the quantification of the environmental impact of a CE building, and its comparison with a linear case study (results published in Publication III). The third result is the validation of the D^3R method (explained in Section 3.5 above) which was developed by calculating the D^3R index of the L3 and through a comparison with a linear case study. Finally, the fourth result is the proposal for a transdisciplinary coach that emerged from the investigation of management in two Living Lab's. The transdisciplinary coach represents the central managerial role appointed to reduce conflicts and tensions in the future operations of Legacy Living Lab (this result will be discussed in Chapter 7).

Table 4.1 – Main results obtained in the five publications and manuscripts summarized in this thesis.

Title	***Results***
I. Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments. *Manuscript submitted for peer-review journal.*	Procedural guidelines to integrate with the LCA method.
II. Strategies for Applying the Circular Economy to Prefabricated Buildings. *Peer-reviewed article published.*	Seven strategies to apply the circular economy to buildings. *Results explained in Section 2.2.*
III. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Peer-reviewed article published.*	Quantification of the environmental impact of a circular economy building and comparison with a linear case study.
IV. Design for disassembly, deconstruction and resilience in construction: A circular economy index. *Manuscript submitted for peer-reviewed journal.*	Validation of the design for deconstruction, disassembly and resilience method.
	Calculation of the D^3R index of the Legacy Living Lab and comparison with a linear case study.

4.1 LCA procedural guidelines

The SLR and meta-analysis undertaken in Publication I (manuscript) resulted in a procedural guideline that, if integrated in the established LCA of construction materials and buildings, can assist LCA practitioners to rank their results in a proposed benchmark, and reduce the environmental impact of their studied buildings. Traditionally, LCAs are iterative (or recursive) methods following four steps: goal and scope definition, life cycle inventory, life cycle impact assessment and results interpretation. The procedural guideline that I am proposing unfolds in two additional steps: result ranking and project

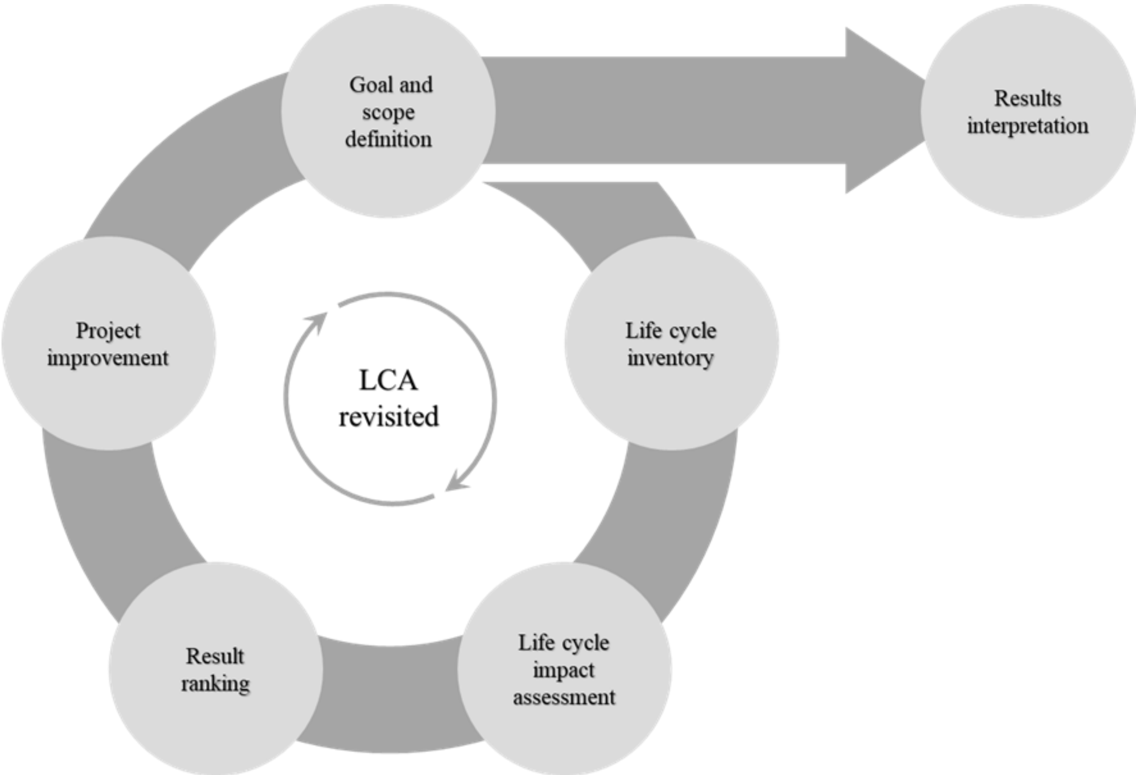

Fig. 4.1 – LCA revisited with the integration of the two-step procedural guideline: result ranking step and project improvement step. Extracted from Publication I (manuscript)

improvement (Fig. 4.1).

4.1.1 Result ranking

The historical LCA's of construction materials and buildings, in terms of embodied energy and embodied carbon were collated. I categorized the results depending on the material structure of the building, i.e. concrete, timber or steel, and summarized the collection of these results in box-whisker plots. These plots can be used to rank the results of the LCA of any building, as long as the functional unit is normalized to 1 m^2 of floor area, and the environmental indicators used are embodied energy (expressed in GJ/m^2) or embodied carbon (expressed in kg CO_2 eq/m^2). The LCA practitioner can use the charts presented in Fig. 4.2.

The results of the LCAs can fall into one of the six possible sections (a through f) as summarized in the guide represented in Fig. 4.3.

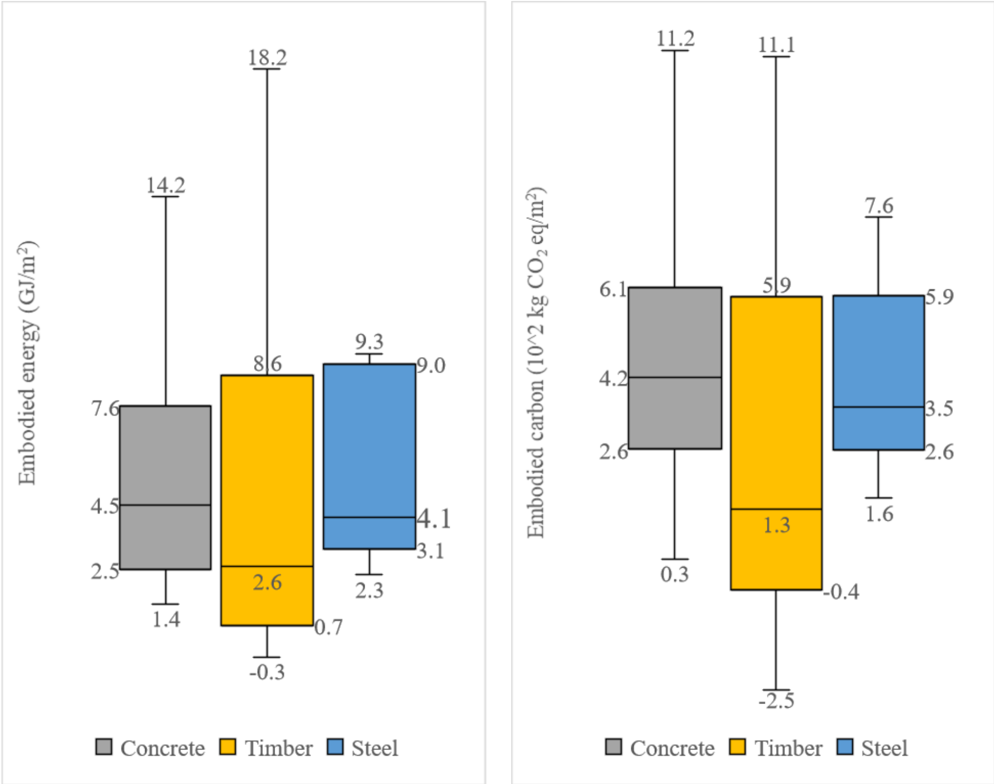

Fig. 4.2 – Box-whisker plots of embodied energy (left) and embodied carbon (right) of the LCA results collected and categorized depending on three structural materials: concrete, timber and steel. Plots extracted form Publication I (manuscript).

a) The results in this section are substantially higher than the average and median values and are therefore classified as top outliers. Although there could be mistakes in the LCA, or data could be incorrect, results in section a) could also be highly impacting buildings. It is strongly recommended that the following steps of the guidelines (project improvement) are followed to improve the LCA results and decrease the impact of the studied building.

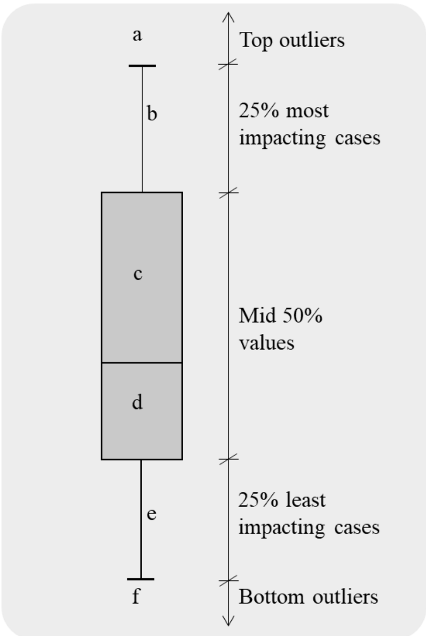

Fig. 4.3 – Box-whisker plot guide: six different scenarios of building impact ranking.

b) Buildings whose results fall in this section are amongst the 24% most impacting buildings. Although the sourced data and related results might be correct, it is strongly recommended that the practitioner follows the project improvement step in order to decrease the environmental impact of the studied building.

c) & d) Results in these sections are the most common, and buildings whose impacts are within these groups are considered average, however, improvements are recommended.

e) In this section the lowest 25% of results of LCA of buildings are situated. That means that the practitioners might have already considered a wide range of improvements to reduce the impact of the studied buildings. Nevertheless, the project improvement step could be followed to further reduce the embodied energy or carbon related to the building.

f) This section includes the lowest impacting outliers. That might be due to mistakes that occurred in applying the LCA method, in gathering and analysing the data. However, it could also mean that the studied building is exceptionally well designed, and its impact was low. It is unlikely that these results can be improved by applying the following step (project improvement).

4.1.2 Project improvement

In this step the practitioners are asked to apply one or more of five strategies, in an attempt to reduce the environmental impact of the studied building. Table 4.2 summarizes the strategies, the range of savings that can be expected in terms of embodied energy and carbon, and relevant sources. For a detailed explanation of the strategies see Section 4.2.2 of Publication I (manuscript).

Table 4.2 – Strategies to decrease the embodied energy and carbon of the studied buildings, and their percentual savings. Extracted from Publication I (manuscript).

Strategy	***Saving of EE (%)***	***Saving of EC (%)***	***Notes***	***Sources***
1. Material substitution				
Timber in place of concrete	43	68	Results calculated for a mix of CLT and timber studs, joists and trusses structures. Timber structure usually involve substantial amount of concrete. End of life and next product stages not included.	Ajayi, Oyedele, Jaiyeoba, Kadiri, and David (2016) Ajayi, Oyedele, and Ilori (2019) Å vajlenka, Kozlovská, and Spišáková (2017)
Steel in place of concrete	9	15	Steel structure usually involves a substantial amount of concrete. End of life and next product stages not included.	Azzouz, Borchers, Moreira, and Mavrogianni (2017) Cornaro, Zanella, Robazza, Belloni, and Buratti (2020) Guo et al. (2017) Svajlenka and Kozlovska (2017) A. Takano, Hughes, and Winter (2014) Tavares, Lacerda, and Freire (2019)

2. Recycle				
Concrete	-5÷29	6÷18	Recycling concrete is related to a negative saving, meaning that this operation has an adverse environmental impact. Further, although the literature refers to recycling of concrete, concrete is usually down-cycled into aggregates.	Blengini (2009) C. C. Chang et al. (2019) Chau, Hui, Ng, and Powell (2012) Gan, Cheng, et al. (2017) Gao, Ariyama, Ojima, and Meier (2001) S. Li and Altan (2012) Liu et al. (2016) Yan, Shen, Fan, Wang, and Zhang (2010) Thormark (2002)
Timber	7÷22	15÷200	Recyclability of timber products varies substantially between countries and regulations. Some studies considered energy and carbon recovery using timber as fuel as a recycling strategy.	
Steel	40÷45	22÷60	Up to 80% of steel is typically recycled into new material, which maintain the structural characteristics of virgin steel.	
3. By-product integration and cement substitution	16÷33	21÷63	Results related to the substitution of different amounts of by-products (i.e. Bayer liquor[b], fly ash, volcanic ash, ground granulated blast-furnace slag) instead of cement into concrete. Cement's EC is 248 higher than graphene nanoplatelets' EC, which is a safe substitution in concrete.	Jamieson, McLellan, van Riessen, and Nikraz (2015) Gan, Cheng, et al. (2017) Kupwade-Patil et al. (2018) Papanikolaou, Arena, and Al-Tabbaa (2019) Teh, Wiedmann, Castel, and de Burgh (2017)
4. Design for disassembly and reuse	81	18÷70	Although the literature suggests that concrete structures can be reused multiple times, specific regulations could depend on counties.	Aye et al. (2012) Cruz Rios et al. (2019) Dara, Hachem-Vermette, and Assefa (2019) L. C. M. Eberhardt et al. (2019)

[a] Recycling concrete yields a negative saving, meaning that this operation has an adverse environmental impact in terms of EC. Further, although the literature refers to recycling of concrete, concrete is usually down-cycled into aggregates.
[b] Bayer liquor is by-product derived from processing of bauxite to alumina.

4.2 The Environmental Savings of Applying Circular Economy to Buildings

In Publication III I undertook an LCA of the CE prototype building that I helped design and build during my PhD, the L3. As introduced in Section 3.3, the L3 is a modular, disassemblable and transportable research facility. The materials that compose the L3 have been selected to be reusable, and/or already reused and, when reusability was not possible, materials are recyclable. For example, most of the steel that composes its structure has been salvaged from a previous project and adapted to be reused. Further, disassemblability of the L3's components, including finishes such as cladding or tiles, allow the building to be maintained throughout its life cycle with close to zero waste production.

For the evaluation of the environmental benefits of applying the circular economy strategies to buildings, I carried out a comparison between the LCA results of the L3 and the LCA results of a similar modular building (i.e. a building built with the same architectural characteristics and dimensions), but built without considering the CE strategies. In this comparison, the L3 was defined as the circular building, and related results are labelled with the subscript C. Conversely, results of the comparative case study were labelled with the subscript L for the linear economy building. The life cycle stages[2] of the circular L3 are characterized by:

- $\boldsymbol{A_C}$: reused materials, addition of some raw materials, and assembly of the building.
- $\boldsymbol{B_C}$: refurbishment and renewal of internal and external finishes. This LCA stage has minimal impact in the circular L3, as all glued and welded connections were replaced by bolted (nut and bolt) or screw connections, making walls and ceilings accessible without having to destroy or cut wall finishes.
- $\boldsymbol{C_C}$: disposal of the materials that are not reusable or recyclable.
- $\boldsymbol{D_C}$: discount of CO_2 equivalent emissions attributed to reuse and recycle of components (e.g. steel components, aluminium, plasterboard).

Similarly, the life cycle stages of the linear version (L) are characterized by:

- $\boldsymbol{A_L}$: entirely new components, and assembly of the building.
- $\boldsymbol{B_L}$: refurbishment and renewal of internal and external finishes.
- $\boldsymbol{C_L}$: disposal of the materials that are not recyclable.
- $\boldsymbol{D_L}$: discount of CO_2 equivalent emissions due to recycling of materials (e.g. steel, aluminium, plasterboard).

The results of the LCA reported in Publication III were expressed through six environmental indicators: embodied carbon (expressed in global warming potential; GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), abiotic depletion (AP) and embodied energy (expressed in abiotic depletion of fossil fuels; ADFF). In carrying out the comparative LCA of the L3 for Publication III, I decided to adopt the entire building as the functional unit.

The results show that the total impact of the L3 over its life cycles offsets the impact of the comparative linear case study according to all the environmental indicators included in this study. For example, in terms of embodied carbon, the L3 emits 5.4 t CO_2 eq, while the linear L3 emits 44.5 t CO_2 eq, representing a saving of 88% of embodied carbon (Fig. 4.4 and Table 4.3). A more detailed explanation of the LCA results is presented in Publication III.

[2] The life cycle stages of a building are defined as production (A), operation (B), end-of-life (C) and next product system (D). A detailed explanation is provided in Section 3.4 and Table 3.2.

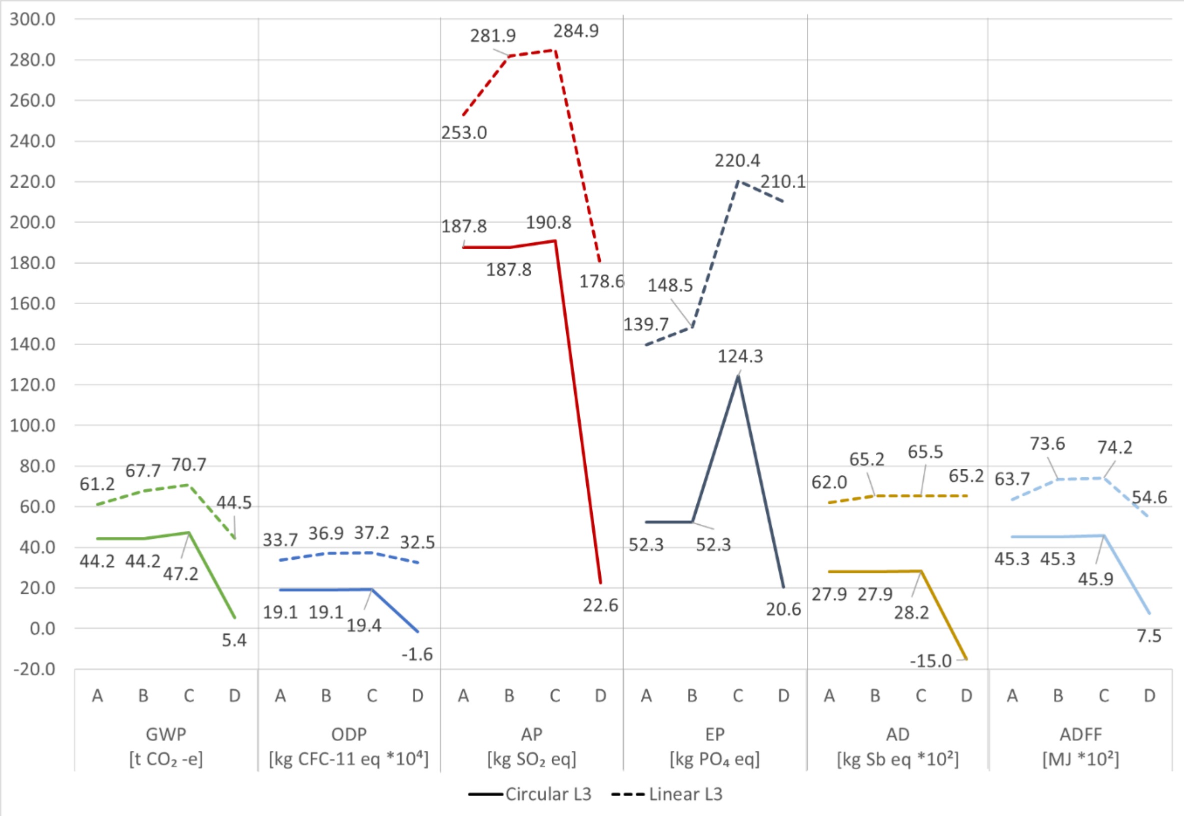

Fig. 4.4 – Comparison of the LCA of the circular and the linear versions of the L3. Continuous lines represent the circular L3, dashed lines represent the linear L3. Extracted from Publication III.

Table 4.3 – Life cycle impact assessment of the circular, design for disassembly and reuse L3 (C) and its linear version (L), divided in the four LCA stages: A, production; B, operation (refurbishment); C, end of life; D next product system.

	EE (GJ/m^2)	***GWP (10^2 kg CO_2 eq/m^2)***	***ODP (10 kg CFC-11 eq/m^2)***	***AP (10^{-1}kg SO_2 eq/m^2)***	***EP (10^{-2}kg PO_4 eq/m^2)***	***AD (kg Sb eq/m^2)***
A_C	44.2	19.1	187.8	52.3	27.9	45.3
B_C	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0
C_C	3.0	0.3	3.0	72.0	0.2	0.6
D_C	-41.9	-21.0	-168.2	-103.7	-43.1	-38.4
TOTAL	***5.4***	***-1.6***	***22.6***	***20.6***	***-15.0***	***7.5***
A_L	61.2	33.7	253.0	139.7	62.0	63.7
B_L	6.6	3.2	28.9	8.7	3.2	10.0
C_L	3.0	0.3	3.0	72.0	0.2	0.6
D_L	-26.2	-4.8	-106.3	-10.4	-0.3	-19.6
TOTAL	***44.5***	***32.5***	***178.6***	***210.1***	***65.2***	***54.6***

4.3 The D^3R index

In Section 3.5 I explained the D^3R method proposed in Publication IV (manuscript). The D^3R method takes into consideration factors, such as the machinery needed to disassemble or deconstruct a structure, the reusability or recyclability and weight of its components. The method applies equations 2, 3 and 4 to calculate the D^3R index as proposed in equation 1 (introduced above in Section 3.5, page 31). The D^3R index measures the level of deconstructability or disassemblability, and resiliency of a building, in a range from zero (which means that the building is entirely demolished and landfilled) to one (which means that every component is easy to disassemble and reusable infinite times). To validate the D^3R method, I applied the equations to calculate the D^3R index of the L3 modular building (called circular prototype, C), and compared the results with the D^3R index of a traditionally built modular building (called linear case study, L).

4.3.1 *D^3R of the circular L3*

To calculate the D^3R index of the L3 it is important to consider that the circular L3 is a disassemblable structure. Therefore, the parameter *b* of equation 1 equals zero. Further, the remaining parameters *a* and *c* are arbitrarily chosen as being equal to 0.5 (equation 5). That means that the disassemblability of the L3 and the reusability of its components are considered of equal relevance. In considering these parameters, equation 1 becomes:

5. $$D^3R = DI \times 0.5 + DE \times 0 + R \times 0.5$$

To calculate the values of DI and R I used the parameters listed in Table 4.4 (these values had been previously introduced in Section 3.5, Table 3.4 and Table 3.6), which depend on the mass of the components of the circular L3, and the tools needed to disassemble and transport them.

Table 4.4 – Values of the parameters DIt, DIm and Ri of the circular L3. Adapted from Publication IV (manuscript).

Description	*Mass (kg)*	*DI tools needed*	*DIt*	*DI moving tool description*	*DIm*	*Resiliency description*	*Ri*
Steel chassis and load bearing structure.	16 138.9	Gas/pneumatic tool	0.5	Fork-lift	0.4	Reusable infinite times	1
Salvaged timber composing the stairway steps.	164.0	Power tool	0.8	Fork-lift	0.4	Reusable up to 3 times	0.9
Plywood covering internal walls and the first floor's ceiling.	3 328.0	Power tool	0.8	2 people > 25kg	0.9	Reusable up to 3 times	0.9
Carpet covering 193m2 of internal floors.	183.4	No tool	1	1 person < 25kg	1	Reusable up to 3 times	0.9
Stairway steel structure.	422.8	Gas/pneumatic tool	0.5	Fork-lift	0.4	Recyclable	0.6

Lightweight steel structure, internal walls.	3 590.3	Power tool	0.8	2 people > 25kg	0.9	Reusable infinite times	1
Pressed timber used as ground floor external cladding.	1 811.7	Power tool	0.8	1 person < 25kg	1	Reusable up to 3 times	0.9
Steel sheets used at the first floor for external cladding.	652.1	Power tool	0.8	2 people > 25kg	0.9	Reusable infinite times	1
Steel sheets used for roof covering.	531.3	Power tool	0.8	2 people > 25kg	0.9	Reusable infinite times	1
Vinyl covering floors in wet areas.	714.0	No power tool	1	1 person < 25kg	1	Reusable 1 time	0.7
Aluminium windows and glazed doors.	744.0	Hand tool	0.9	2 people > 25kg	0.9	Reusable up to 3 times	0.9
Internal timber doors.	138.0	Power tool	0.8	1 person < 25kg	1	Reusable infinite times	1
Magnetic felt ceiling	333.7	No tool	1	1 person < 25kg	1	Reusable up to 3 times	0.7
Plasterboard cladding, used in kitchen/bathroom areas and ground floor ceiling.	140.2	Power tool	0.8	1 person < 25kg	1	Disposable	0
Pressed fibre particle board used as floor structure.	4 102.6	Power tool	0.8	2 people > 25kg	0.9	Down-cyclable	0.2
Insulation	2 516.0	No tool	1	1 person < 25kg	1	Recyclable	0.6
Screw pile lightweight steel foundations.	735	Hydraulic plant	0.2	1 person < 25kg	1	Recyclable	0.6

These parameters allow the calculation of the values of DI_C and R_C of the circular L3. $DI_C = 0.52$, and $R_C = 0.86$. Therefore, the D^3R_C of the circular L3 is calculated through equation 6.

6. $$D^3R_C = 0.5 \times 0.52 + 0.5 \times 0.86 = 0.69$$

This means that, in considering the joints that form the building, the level of reusability and recyclability of its components, the tools and machineries necessary to disassemble and transport them, 69% of the mass of the L3 has been designed following the CE framework.

4.3.2 *D^3R of the linear case study*

The same procedure can be adopted to calculate the D^3R index of a linear building — built without considering the CE framework in its design stage. To be able to compare the D^3R index of the linear building with the D^3R index of the circular L3, I assume that this linear building is similarly a steel-framed modular building, whose joints are welded, panels are glued and with a concrete foundation. Additionally, a traditionally built modular building would employ a concrete foundation. In considering these features of the linear building, Table 4.5 summarizes the *DIt*, *Dim* and *Ri* values of the components of the linear version of the L3.

Table 4.5 – Values of the parameters DIt, DIm and Ri of the linear version of the L3. Adapted from Publication IV (manuscript).

Description	***Mass (kg)***	***DI tools needed***	***DIt***	***DI moving tool description***	***DIm***	***Resiliency description***	***Ri***
Steel chassis and load bearing structure.	16 138.9	Large power tool	0.3	Fork-lift	0.4	Recyclable	0.6
Salvaged timber composing the stairway steps.	164.0	Small power tool	0.8	Fork-lift	0.4	Reusable up to 3 times	0.9
Plywood covering internal walls and the first floor's ceiling.	3 328.0	Small power tool	0.8	2 people > 25kg	0.9	Down-cyclable	0.2
Carpet covering 193m2 of internal floors.	183.4	No power tool	1	1 person < 25kg	1	Reusable up to 3 times	0.9
Stairway steel structure.	422.8	Large power tool	0.3	Fork-lift	0.4	Recyclable	0.6
Lightweight steel structure, internal walls.	3 590.3	Small power tool	0.8	2 people > 25kg	0.9	Recyclable	0.6
Pressed timber used as ground floor external cladding.	1 811.7	Small power tool	0.8	1 person < 25kg	1	Down-cyclable	0.2
Steel sheets used at the first floor for external cladding.	652.1	Small power tool	0.8	2 people > 25kg	0.9	Recyclable	0.6
Steel sheets used for roof covering.	531.3	Small power tool	0.8	2 people > 25kg	0.9	Recyclable	0.6
Vinyl covering floors in wet areas.	714.0	No power tool	1	1 person < 25kg	1	Reusable 1 time	0.7
Aluminium windows and glazed doors.	744.0	Small power tool	0.8	2 people > 25kg	0.9	Disposable	0
Internal timber doors.	138.0	Small power tool	0.8	1 person < 25kg	1	Disposable	0
Glued felt ceiling	333.7	Hand tool	0.9	1 person < 25kg	1	Recyclable	0.6
Plasterboard cladding, used in kitchen/bathroom areas and ground floor ceiling.	140.2	Small power tool	0.8	1 person < 25kg	1	Disposable	0
Pressed fibre particle board used as floor structure.	4 102.6	Small power tool	0.8	2 people > 25kg	0.9	Down-cyclable	0.2
Insulation	2 516.0	No power tool	1	1 person < 25kg	1	Recyclable	0.6
Concrete foundations composed by concrete discs and footings.	19 848.0	Large power tool	0.3	Fork-lift	0.4	Down-cyclable	0.2

These parameters allow the calculation of the values of DI_L and R_L for the linear version of the L3. This results in values for $DI_L = 0.35$, and $R_L = 0.38$. Therefore, the D^3R_L of the circular L3 is:

7. $$D^3R_L = 0.5 \times 0.35 + 0.5 \times 0.38 = 0.37$$

That means that, in considering that the joints that form the building are mainly welded, most components are not reusable, but are recyclable, the tools and machineries necessary to disassemble and transport them, 37% of the mass of the linear version of the L3 has been designed following the CE framework.

4.3.3 Comparison of the results

The calculation of the D^3R index allows an evaluation of the degree to which the CE framework has been applied in designing a building. Also, using a table template such as Table 4.4 or Table 4.5 allows the designer to evaluate which components are granting an increased D^3R index. For example, despite the efforts made to design the L3 by following the CE strategies and framework, the use of disposable or down-cyclable materials such as plasterboard or particle board, or the necessity of large power tools or fork-lift machineries contribute to reducing the D^3R index of the circular L3. When considering the linear version of the L3, it appears clear from Table 4.5 that the reason why its D^3R index is low is the impossibility of reusing components such as steel frames, which will instead be recycled, or the use of concrete foundations, which require large power tools to be crushed and down-cycled.

It follows that the same building that has been designed by following the CE framework has an D^3R = 0.69, while a building which is built with similar materials, but without applying the CE framework in its design stage has a D^3R = 0.37. The comparison between the two indices, one calculated for the disassemblable building, and the other calculated for the recyclable building, demonstrates that the D^3R index can effectively be employed to calculate the circularity level of a building.

Chapter 5. **Discussion**

Scholars have studied in depth the environmental impact of construction materials and buildings. In so doing, they discovered that the actual *modus operandi*, i.e. taking, using and disposing building materials, has a major impact on the environment. To limit these consequences, recycling operations have been proposed and thoroughly studied.

In contrast, the hypothesis of this PhD is that, although recycling is beneficial in saving material waste, a circular economy approach might yield far better environmental savings. Specifically, by designing for disassembly and reuse, building components can be re-integrated in the material loop, thus maintaining their qualities without creating material waste, increasing GHG emissions or further endangering the environment.

Therefore, this PhD proposes to expand the knowledge on environmental sustainability of buildings by answering the research question; What is the environmental benefit of applying the circular economy theory to the building system, and how can the circular economy be applied to modular buildings?

Many barriers stood in the way of answering this research question. For example, to reuse building components, buildings should be designed so that they can be easily disassemblable, but traditional buildings are built with chemical connections that do not allow conservative disassemblability. Further, to advance the knowledge on such a practical matter, a prototype case study was needed to understand the complexities of taking a building apart in a practical context. Additionally, the tools to measure the environmental impact of buildings have not been designed considering components' reuse and products' further life cycles.

In addressing these and other issues, this PhD contributes to expanding the knowledge of the environmental sustainability of the construction sector. In so doing, I proposed the results obtained in the five publications and submitted manuscripts. While some of these results confirm what has been theorized in the existing literature, other results contrast with previous findings which, in turn, leads to significant practical and theoretical implications.

5.1 Contextualization of the Findings

The established method to calculate the environmental impact of products and services is the LCA (Sharma et al., 2011). LCAs allow the quantification of several environmental indicators (e.g. embodied energy, embodied carbon, ozone depletion potential; (GBCA, 2014; Khasreen et al., 2009; Sharma et al., 2011; Stocker et al., 2013; Yellishetty et al., 2011)). Although the LCA method has been used for more than 40 years, its formulation did not evolve radically during these decades (Sharma et al., 2011). Consistently with their first proposition, LCAs allow the quantification of the environmental impact of a product over and beyond its life cycle (H. a. Baumann, 2004). Despite several applications in the context of buildings, scholars and practitioners call for a new, simple tool that enables not only the quantification of the impact of their case studies, but a comparison of their results (Björklund, 2002, p. 71). In answering this issue, in Publication I (manuscript), I proposed a two-step procedural guideline which can assist practitioners in ranking their LCA results. Indeed, the first step, *result ranking*, consists of a method to benchmark the embodied energy or carbon of a building. The second step, *project improvement*, helps the improvement of the building through a series of simple suggestions extracted from the literature.

The improvement options that I could collect and summarize in Publication I (manuscript) were however limited by the body of literature that I analysed: the existing literature on LCA of buildings (see, for example, Aye et al. (2012), Sovacool et al. (2018)). To overcome that limit, I studied the literature of other industry sectors (cars, for example; Gaustad et al. (2018), Sarc et al. (2019)), to explore how the circular economy (CE) has been applied in different industries beyond the building sector. Publication II resulted in a series of strategies to specifically apply the CE to the construction sector. Some of these strategies further consolidate the work of Kalmykova, Sadagopan, and Rosado (2018). These proposed strategies, in junction with the procedural guidelines proposed in Publication I (manuscript) set the theoretical background for the application of the CE framework to buildings.

However, the issue of the CE of building is both theoretical and practical (Kirchherr & van Santen, 2019; Tingley, Cooper, & Cullen, 2017). In addressing the need for a practical case study, the L3 was manufactured within this PhD to explore the practical implications of a CE modular building. The data collected whilst designing and manufacturing the L3 were used to quantify the environmental impact of a CE building across its life cycle, including end of life and next product stage. Further, to address the research question of this PhD, in Publication III I compared the LCA’s results with the results of a recyclable building (i.e. made primarily of steel and recyclable materials). The results of Publication III indicate that, compared to recycling, designing for reuse of building components offsets greenhouse gas emissions by 88%, while also benefiting other environmental indicators. The results obtained in Publication III confirm the hypothesis posited by Julian M. Allwood (2014), Kirchherr et al. (2017) and Walter R Stahel (2016) that reuse yields better environmental savings when compared to recycling.

Given the limited research on the CE of buildings highlighted in Publication I (manuscript), it is not surprising that a tool to measure the circularity of a building was missing. Although the Ellen McArthur Foundation proposed a tool that allows the quantification of the material circularity indicator (MCI; Lonca, Muggéo, Imbeault-Tétreault, Bernard, and Margni (2018), Haas, Krausmann, Wiedenhofer, and Heinz (2015) and MacArthur (2013)), the MCI is considered complex and data intensive. Further, it has not specifically been designed for buildings, it does not take into account the complexities of disassembling heavy components. Conversely, the D^3R method proposed in Publication IV (manuscript) requires the same data used in a typical LCA (i.e. BoQ and operations to manufacture, maintain and decommission a building; (Atmaca, 2016; Garcez, Abrahão Bernardo, & Luis Gabriel Graupner de, 2018; Serrano & Alvarez, 2016)), and results in the D^3R index, which can be used to calculate the circularity of a building. Specifically, high values of D^3R index mean higher levels of disassemblability and reusability of the building, and low levels of D^3R index mean that most components of the building are not disassemblable or resilient enough to be reused in other buildings. Results of applying the D^3R to the circular and linear versions of the L3 validate the hypothesis that a disassemblable building has a higher D^3R index when compared to a linear design (Publication IV, manuscript), at least for L3.

The combination of the results obtained in Publication III (LCA of the L3) and in Publication IV (manuscript on the D^3R method and D^3R index of the L3) further consolidate the hypothesis of this PhD, being that the applications of the circular economy strategies to the building context help decrease the environmental impact of buildings and increase material saving (Kalmykova et al., 2018; Kirchherr et al., 2017; Munaro et al., 2020).

5.2 Results Interpretation

The concept that underlies this PhD can be expressed with the words of Julian M. Allwood (2014): “recycling is neither “green” nor free of impacts.” Walter R Stahel (2016) echoes that concept, and further suggests that the primary objective of a closed-loop economy should focus on reuse and recycle what cannot be reused. In contrast, findings from Publications I (manuscript) and II demonstrate that the literature on CE and buildings focuses primarily on the recyclability of construction materials. The lack of research and applications of reusability of buildings could be the due to several, interconnected factors. First, reuse could be more expensive than demolition and recycling (Dantata, Touran, & Wang, 2005). That is because to reuse building components, the building has to be disassembled in parts, which is a labour-intensive operation (da Rocha & Sattler, 2009). Further, disassembly of a building requires transporting and storing the salvaged components, which increases the cost of disassembly and reuse (Tingley et al., 2017). Conversely, demolishing is a fast and established method, and recycling of demolished materials requires material separation to avoid contamination (Sormunen & Kärki, 2019). The remaining demolished materials that cannot be recycled, are sent to landfill (Hölzle, 2019). Second, because buildings are not typically designed for disassembly, their joints are often inaccessible or irreversible (Tingley & Davison, 2011). Joints between concrete components, for example, are irreversible because detaching components from each other without affecting their structural stability is not feasible (Suwaed & Karavasilis, 2020). Steel and timber could be combined in structures so that their joints could be disassemblable, by employing, for example dry joints such as bolted connections (bolt and nut) or screws when compatible with the structural stability of the building (Akanbi et al., 2019). Other barriers include the time-intensive operations of disassembly the complexity of recertification of used building components and the lack of demand for used components (Tingley et al., 2017). Despite these barriers, there are many recognized advantages of reuse of building components (Hosseini, Rameezdeen, Chileshe, & Lehmann, 2015). Among the advantages, the improved brand image of companies that include sustainability related goals in their management (Saghafi & Teshnizi, 2011) and meeting the new, and increasingly more stringent legislative requirements that, depending on the country, impose optimal waste management (Mulder, de Jong, & Feenstra, 2007). Against this backdrop, the creation of the L3 and the results I found in Publications III demonstrate that, not only building a movable, disassemblable and reusable building is an economic and technically feasible practice, but that the environmental benefits largely offset the benefits of recycling, in accordance with the CE theory. Further, the popularity of CE-centred Living Labs among manufacturers proves the social benefits in terms of branding image and reputation of targeting sustainability oriented goals, as proposed by Gorgolewski (2008).

5.3 Life Cycle Assessments' Functional Units Choice

The literature on LCAs agrees in calculating the environmental impact of construction materials by selecting constructions' mass or volume as functional unit (see, for example Gan, Cheng, et al. (2017), Teh et al. (2017)). Choosing such functional units might seem obvious, concrete, timber, steel and other construction materials are typically commercialized according to their mass (Balasbaneh, Bin Marsono, & Gohari, 2019). Indeed, the functional units used throughout all of the 65 articles selected in my SLR were only mass or volume (Publication I, manuscript). Although that choice might seem practical, comparing the emissions related to producing 1 kg construction materials might produce confusing results. For example, the energy embodied to produce 1 kg of concrete is, in median terms, 1.1 MJ/kg, and its embodied carbon is 0.19 kg CO_2 eq. In comparison, the energy embodied to produce 1 kg of timber is 8.0 MJ/kg, and its embodied carbon is 0.45 kg CO_2 eq. These results seem to contrast with the concept that timber is a material associated with low environmental impact (Liu et al., 2016). The reason for this contrast is that these results do not take into account the functional strength of the assessed materials, measurable, for example in specific strength, in kN m/kg. Indeed, if the functional unit of a construction material does not take into account its structural strength, the information related to material use in building is neglected. When shifting the functional unit from mass to specific strength, the embodied energy of concrete becomes 75.4 MJ/kN m, and the embodied energy of timber is 45% lower. Similarly, the embodied carbon of concrete becomes 13.71 kg CO_2 eq/kN m, whereas the embodied carbon of timber is 83% lower (more information is provided in Publication I, manuscript, Section 4.1). The conversion between the two examined functional units consolidates the concept that structures in timber produce lower environmental impact when compared to concrete structures (Guo et al., 2017; Liu et al., 2016).

Although the functional unit of similar categories of products, in this case construction materials, should be homogeneous among the literature, a thorough choice of a functional unit should be made considering the function of the materials, rather than commercial parameters, such as materials' mass or volume. Alternatively, two functional units could be considered in parallel in the same research, providing a transparent description of their choice and reciprocal conversion index. LCA scholars and practitioners could chose the two functional units based on the similar results that have been already published, and in considering the actual functionality of the examined product. Another functional unit that takes into account the component level (e.g. internal wall, floor structure) could be implemented.

5.4 Theoretical and Practical Implications

The theoretical framework of this PhD is the CE framework. The CE framework proposes to replace the end-of-life practice of disposing of construction materials with reduction of waste or material use, reintegration and reuse of components into the material loop, or alternatively by recycling the materials (Govindan, Soleimani, & Kannan, 2015). The results obtained in the five publications and manuscripts that I produced during this PhD confirm that, by applying the CE to the construction sector, the environmental impact of buildings can be drastically reduced. More specifically, I test this theoretical framework by applying the reduce, reuse and recycle operations to a prototyped case study built employing the modular building technology. Traditionally, modular buildings are built with recyclable materials, such as steel, but chemical and irreversible joints make reuse of their components impractical (Suwaed & Karavasilis, 2020). The findings proposed in Publication III confirm that, by applying the CE strategies identified in the literature in Publications I (manuscript) and Publication II, buildings could yield a saving of up to 88% of GHG while also benefitting several other tested environmental indicators (e.g. ozone depletion potential and abiotic depletion).

During the thorough practical and theoretical study of the CE of buildings undertaken in this PhD, I found no evidence that proves that the application of the CE to modular buildings could produce adverse environmental impact. It is acknowledged, however, that in many other instances the CE could, overall, produce negative effects, specifically, when considered the complex intertwined interaction of socioeconomics. Because the undertaken PhD was focussing solely on environmental aspects, these effects were not examined in this thesis. One prominent example is the issue know as rebound effect, which, among other reasons, posits that often secondary materials can be irrecoverable (Zink & Geyer, 2017). Another example dictates that neglecting opportunity cost might affect the market of reusable products (Figge & Thorpe, 2019).

This PhD has four practical implications. First, by applying CE practices, it challenges the traditional (linear) construction industry *modus operandi*, where recycling and integrating by-products in construction materials is the most common operation to diminish the adverse environmental impact of buildings. Second, by proving the feasibility of building a high quality disassemblable building, the L3, this PhD raises interest among the many industry partners (see Acknowledgments section). The interest generated through this PhD, and the results obtained, could further foster the establishment of reuse practices within construction firms. Third, the procedural guideline proposed in Publication I (manuscript) helps LCA practitioners to benchmark the environmental impact of their case studies and provides indications and guidance on how simple choices can help reduce the resulting impacts. Although the LCA method has been proposed in the 1970s (Guinée et al., 2011), a simple tool to benchmark the results against was lacking. The procedural guidelines that I propose bridge this methodological gap. Fourth, by exploring situational conflicts that might be generated in operating a living lab, Publication V (manuscript) assists living lab managers to establish a central, neutral actor that helps solving such conflicts, and maintain the optimal functionality of the living lab.

Chapter 6. Conclusions and Further Research

Circular economy (CE) theory posits that a system in which design choices replace the end-of-life operations with reduction, reuse or recycle operations should provide a reduction of environmental impact as well as benefits for both economic and society. With focus on its environmental benefits, I tested this posit by applying CE to the building context.

The CE has been applied in several industry sectors. For example, in the fashion industry, companies have implemented a take back policy to receive old garments and re-sell them once sanitized; (Urbinati, Chiaroni, & Chiesa, 2017)). CE applications can be further fostered by design for products' disassemblability, standardized components, or by implementation of closed-loop supply chains. However, many barriers hinder the application of a circular economy (Kirchherr et al., 2018), which can be divided between cultural, market, political and technological barriers. The analysed modular building, L3, was designed to study and overcome mainly the technical barriers of applying reuse practices to buildings. Of these barriers, the first is that buildings are conceptualized as un-movable monoliths, which limits the disassemblability of their components. Second, buildings' dimensions vary greatly between buildings, as their components are typically bespoke. In turn, components often cannot be passed on from one decommissioned building to another. Third, a closed-loop supply chain of building components is still under-developed. Scholars believe that modular buildings could partially solve these barriers. Indeed, modular buildings are designed in controlled facilities, manufactured offsite, and transported on-site. Consequently, modular buildings are designed for movability, as opposite to traditional, monolithic buildings. Further, modules have similar dimensions, as they have to be transported on roads.

In this PhD I first employed systematic literature review and meta-analysis methods to identify the environmental impact of building materials. This resulted in an empirically informed procedural guideline. The proposed guideline might help LCA practitioners to benchmark the results of their LCAs, and to reduce the impact of their buildings. Moreover, to understand the empirical implications of implementing the CE framework to buildings, within this PhD I conceptualized (helped design and built) a movable, disassemblable and reusable high-quality modular building, the Legacy Living Lab (L3). The L3 was assembled by combining reused components such as steel frames, carpet tiles and staircase, with recycled and recyclable materials such as steel roofing or pressed timber cladding. Further, the L3 is entirely disassemblable and transportable. This practical application of CE operations was essential to move on from theory and understand how far the CE can be implemented in a real-life case study. The environmental benefits of such practical applications were then quantified through an LCA method. The LCA demonstrated that the L3 enables a saving of 88% of greenhouse gas equivalent emissions, while also benefiting several other tested indicators. In granting a substantial environmental benefit, the results obtained during this PhD confirm the tested theory. Further, the environmental savings obtained can inform policy makers and practitioners of the validity of the CE framework.

Although LCA is an established tool for calculating the environmental savings of products, to my knowledge a tool to calculate the circularity of buildings was a noticeable literature gap, with the exception of the material circularity indicator (Haas et al., 2015; MacArthur, 2013), which however does not focus on buildings' operations. To bridge this gap, this research proposes the design for disassembly, deconstruction and reuse (D^3R) method, which guides practitioners in calculating the D^3R index. The D^3R index allows the quantification of any building. The D^3R index is decoupled from environmental impacts and therefore has the potential to give a perspective on buildings' circularity separated from their environmental saving (Linder, Boyer, Dahllöf, Vanacore, & Hunka, 2020).

The D^3R index varies between 0 and 1, with higher values associated with a higher level of circularity. To test the D^3R method, this was applied to the materials, assembly and disassembly operations of the L3, obtaining a $D^3R = 0.69$. When the same index was calculated for the L3 version built as a traditional modular building (i.e. not designed for circularity disassembly, but with most of its materials recyclable), the D^3R index was 0.37. Therefore, the results show that a building designed by following the CE framework can be related to a higher values of a D^3R index.

Beyond the environmental savings, however, this project also resonated with the construction industry. 23 industry partners provided support and sponsorship through their most sustainable products and came together to collaborate and provide ideas to make the L3 project reality. For example, one of the industrial partners donated a set of glazed doors and engineered the hinge system to transform the doors into windows: a strategy that demonstrates the adaptability of components, which in turns enables further reusability (i.e. a door can easily become a window in another life cycle). This type of response from our industry partners indicates that companies value the applications of the CE framework and are ready to make an effort to work towards decreasing their products' environmental impact. The industry partners that participated in the creation of the L3 have further access to the building and can, during its operation, benefit from the facility and its living lab features.

The participation of industries in the operations of the L3 is considered a fundamental aspect in the intrinsic definition of Living Labs (Linder et al., 2020). Indeed, Living Labs are defined as spaces for co-creation and innovation through collaboration between industries, research institutes or universities, and society (Rosado et al., 2015). Such a definition entails the collaboration of a substantial number of actors and partners. On the one hand, collaboration can lead to benefits such as wider networks, wider reach, more competencies connected in the same space. However, on the other hand, a complex association of different partners means different goals, as each partner might have different agendas. To optimize the collaboration of the Living Lab partners, a final study undertaken within this PhD results in proposing a central actor, a coach, needed to limit the tensions that might arise during the Living Lab's operations.

The research undertaken and reported within this PhD has resulted in a deeper understanding of the theoretical and empirical implications of applying the CE to modular buildings. Moreover, it opens up a number of future research opportunities.

6.1 Future research

Five main future research opportunities arise from this research.

First, this study addresses the environmental implications of applying the CE framework to buildings. That is, the environmental benefits of manufacturing a disassemblable and reusable building. However, future research could foster the practical application of a closed-loop supply chain of construction components. Such research could, for example, apply the concept known as the material passport to building components. The material passport is the digitalization of the physical characteristics of products, including their geographical location. The material passport might be integrated into on-line platforms, providing information on when and where components could be reintegrated into the market, and their physical characteristics. Therefore, construction firms interested in sourcing reused components would be able to retrieve them when needed. The application of the material passport to building components could be key in fostering the implementation of a closed-loop supply chain of buildings.

The second research opportunity addresses the economic benefits of reusing building components. Beyond being feasible, and environmentally beneficial, the disassembly of buildings is more time consuming than demolition operations. Moreover, in order to reuse these components, they must be re-certified. The time and labour-intensive practice of disassembling a building and re-certifying its components will increase the price of reused components. Further knowledge is required to solve the issue of marketing of reused components. To this extent, education and technical guidance could drastically change the operations of disassembly and re-certification of building components (Tingley et al., 2017), which, in turn, could decrease their price and make the reusability of building components a viable option.

Third, the D^3R method proposed in this PhD was validated by calculating the D^3R index of the L3 building. The D^3R method is a simple and efficient tool to calculate the level of circularity of a building. The level of circularity thus calculated have values that span from 0 to 1, implying that higher values are related to a higher level of circularity. In turn, higher levels of circularity mean reduced environmental impact (as the CE theory posits, and as confirmed in this PhD). However, more research is required to further consolidate this method and its relation to the environmental saving of the case studied.

Fourth, this PhD addressed the environmental benefits of material reuse, but did not consider how the CE could be employed to reduce buildings’ operational energy and water consumption. Therefore, further research should empirically assess the benefits of strategies to reduce energy and water use. The issue of operational energy and water consumption is complicated by the socio-technical dynamics in play in the operational stage of buildings. Solutions in this field propose the adoption of monitoring systems, combined with water recycling systems to inform and sensitize buildings’ users towards a reduction of energy and water consumption.

Finally, this research could lead to important considerations and discoveries regarding disassemblable building components and accessible joints. Indeed, the L3 case studied proposed here has been examined by means of life cycle assessment to understand the environmental benefits of applying the circular economy to buildings. One noticeable boundary of this work, however, is the exploration of disassemblable components via accessible joints. Many different types of joints have been employed in L3 and investigating how each one of them was optimised to work in a complex building represents an important future research opportunity. Describing how these components have been designed and built is a fundamental aspect that could be exposed and studied in further research, by thoroughly examining the L3 technical drawings.

6.2 Final remarks

This PhD attempts to bridge the gap between CE theory and practice.

The CE framework is considered a possible solution to the environmental impact linked to industrial contexts. One substantially impactful context is represented by the built environment. However, several barriers stand in the way of applying the CE framework to the building context. Therefore, the CE building is in its infancy. To go some way towards enabling the disassembly and reuse of buildings — as proposed in the CE framework — this PhD delivers a unique prototype modular building, the L3, designed to be disassemblable, movable and reusable. Studies of the L3 have revealed the environmental benefits of the thorough application of the CE framework to the design stage of modular buildings. Such empirical and theoretical applications help us understanding the implications of the CE in the building context.

Although applications of the CE to buildings remain limited, this PhD proves that modular building technology represents a feasible option to help manufacture disassemblable and reusable buildings. The results obtained in this PhD can inform practitioners and policy makers on directions that could lead to a substantially more sustainable built environment.

Chapter 7. **Post Scriptum: Considerations of operation and management for the Circular Economy Legacy Living Lab**

The building that we designed and built during this PhD, the Legacy Living Lab (L3) has been built to study the implications of applying the circular economy (CE) to modular buildings. In Publications I to IV, I addressed the problem of applying this application to modular buildings as their material dimension. However, in considering the importance to apply the CE more holistically (Hartley et al., 2020; Linder et al., 2020), we designed the building to further foster circular innovation. That was the basis for ideation of the L3 as a Living Laboratory.

Living Labs are defined as space and place where three types of actors coexist, namely universities or research institutes, industry partners or emerging manufacturers, and society (Rosado et al., 2015). This definition applies not only to actual buildings, but also to the broader research methodology (Eriksson, Niitamo, & Kulkki, 2005). Therefore, living labs foster open-innovation and co-innovation between these three actors (Veeckman et al., 2013). While the combination of the three actors generates mutual value, it might also lead to tensions and therefore increase the complexities related to collective decision making.

The literature divides Living Labs' managerial configuration into two main branches: service organization and consortium based (Schuurman & Protic, 2018). One of the main differences between these two configurations is their management structure. While the service organization of Living Labs typically belongs to a project owner, and research and development are employed to commercialize products for customers, the consortium-based approach has a less clear project ownership and the activities seek to accomplish the interests of all the involved partners (Rust, 2019; Venselaar, Gruis, & Verhoeven, 2015). Blurred lines between ownership, management and the responsibilities of the three actors involved in the Living Lab could generate tensions and conflicts (Vaaland & Håkansson, 2003). Although one can argue that conflicts could generate positive criticism and new perspectives more often conflicts create difficulties in executing the research activities, and eventually lead to a failure of the Living Lab project (Mele, 2011). Solving these tensions is therefore paramount in Living Lab management.

Against this backdrop, the focus of Publication V (manuscript) is to recognize which tensions could be generated during the Living Lab activities, and how an optimized management of the L3 can avoid these tensions and foster the co-creation of research on circular economy and the commercialization of related products.

7.1 Case Study Method

The last research question that this PhD addresses is “How can the Living Laboratory network foster and project further innovation in the field of circular economy?”. The methodology adopted to address this question in Manuscript V is a case study method. More specifically, the case study method was designed to analyse qualitative data regarding complex changing contexts (Yin, 2011). However, in Living Laboratories a dichotomy between project goals and actors’ goals might emerge. This dichotomy might, in the long run, harm the workflow of Living Labs and undermine their effectiveness. In addressing this issue, the scope of the research undertaken in Manuscript V was to investigate the alignment of Living Laboratories’ goals during their operation and management stage. Specifically, two Living Laboratories were selected and examined in Manuscript V. A juxtaposition of the two Living Laboratories’ design aspects and management operations allowed the investigation of Living Laboratories goals’ definition and alignment.

7.1.1 The Living Lab Goals

Living Labs provide innovation and prototyping places and spaces where researchers, industry and society work together to co-create and optimize products towards a central goal (Nambisan & Sawhney, 2011). The goal of Living Labs is defined in their project design stage, and it inspires and affects all three features of Living Labs: research, business and society’s involvement. A specific central goal of a Living Lab allows the orchestration and harmonization of operations of these three features. Conversely, a vague or undefined central goal might cause the Living Lab itself to be inefficient in producing research or in developing new products, and eventually result in the failure of the project. Similarly, the misalignment between the Living Lab’s goal and the actor’s goals might create tensions between the actors, which in turn might impair the quality of Living Lab operations. To explore the ramifications of these misalignments and how to solve them, we applied a case study method to study the management of the Sustainable Home Living Lab and the L3 (more information on the case study method adopted are provided in Section 3.6.2).

The research undertaken in Manuscript V helped frame how roles’ shifts that necessarily occur during the Living Labs’ production and management is linked to central goal misalignment.

7.2 Conflict management in the Living Lab context

Designing and manufacturing a disassemblable reusable building results in substantial environmental benefits, as highlighted in this thesis. Additionally, the efforts of this PhD also aimed to create a research facility that could be used to foster further research on the CE of buildings and products related to buildings, facilitate research on CE and contribute to increase the popularity of the CE among society members. For this reason, the CE building that was built through this PhD, the L3, was designed as a multi-purpose Living Lab. By definition, however, Living Labs are characterized by a substantial number of involved actors, and different goal orientations of these actors might lead to tensions and slow-down the accomplishment of the Living Lab's central goals.

The management of Living Labs is therefore a complex task and studying how to optimize it was the central focus of Publication V (manuscript). Publication V resulted in four propositions that are summarized follows:

Proposition 1. The existence and success of a Living Lab and its related projects depend on a network of the involved actors, their interconnected relationships and their willingness to share expertise and experience. Therefore, building the Living Lab is the beginning of the project, not its ultimate goal.

Proposition 2. Three types of actors are involved in the Living Lab: universities, industry partners, and society. The interrelationships of these actors should aim towards co-innovation. The goal of each actors might be different, and this difference might be due to the role that each actor plays in the Living Lab (for example universities might use the Living Lab as a knowledge creation platform, industry partners as test and demonstration space).

Proposition 3. The equilibrium between the goals of the three actors might vary within a central goal (in the case of the L3 the central goal is the CE), but the distance between the actors' goals and the central goal should be kept within a minimal range (see Fig. 7.1). If this distance is minimal, the goals are aligned, if the distance grows beyond an acceptable limit, the goals are misaligned.

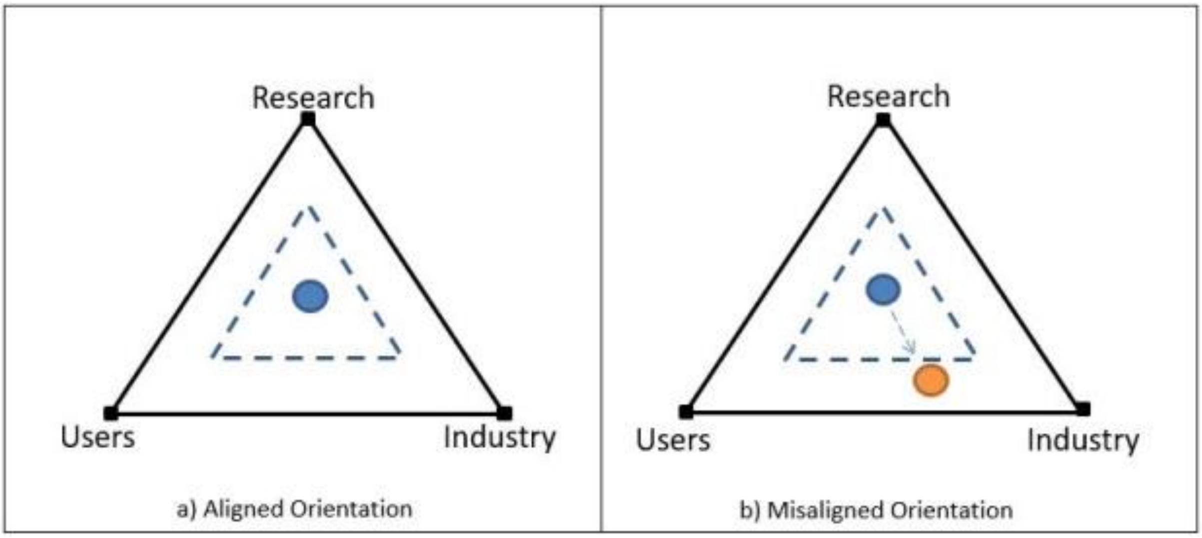

Fig. 7.1 – Living lab orientation of actors' goals and central goal. The actors' goal could be aligned with the living lab's central goal (left) or misaligned (right). Extracted from Publication V (manuscript)

Proposition 4. The alignment of actors' goals and central goal can be re-established and maintained by a peer-to-peer control system, which could be seen as a coach actor. Such a coach should foster the harmony of activities in the Living Lab, by maintaining the alignment between actors' and Living Lab central goals.

These four propositions can help the maintenance of a balance during the operations of the L3, so that the space could be operative and functional to its purposes of fostering research and innovation towards a CE of buildings.

7.3 Conclusion

The L3, beyond being a CE building, is a building whose purpose (or goal) is to foster research and innovation of CE products and buildings. The concluding research of this PhD (Publication V, manuscript) aimed to understand the complex dynamics of Living Labs management and conflicts moderation. It was found that often, in Living Labs management, there is a misalignment between the central goal of the Living Lab (in the case of the L3 that is the circular economy of buildings) and the goals of the industry partners or universities involved. A consequence of such misalignment might undermine the operations within Living Lab (Cantù, Corsaro, Tunisini, & Lind, 2015; Mele, 2011). A central, neutral Figure, that is defined as a coach in Publication V (manuscript) can be appointed to maintain the alignment between the Living Lab partners' goals' and the central goal of the Living Lab. This result adds a new role to the list of roles involved in the management of a Living Lab previously identified by (Nyström et al., 2014).

Exegesis References

Å vajlenka, J., Kozlovská, M., & Spišáková, M. (2017). The benefits of modern method of construction based on wood in the context of sustainability. *International journal of environmental science and technology, 14*(8), 1591-1602. doi:http://dx.doi.org/10.1007/s13762-017-1282-6

Abuzied, H., Senbel, H., Awad, M., & Abbas, A. (2020). A review of advances in design for disassembly with active disassembly applications. *Engineering Science and Technology, an International Journal, 23*(3), 618-624. doi:https://doi.org/10.1016/j.jestch.2019.07.003

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). *Circular economy in construction: current awareness, challenges and enablers*. Paper presented at the Proceedings of the Institution of Civil Engineers-Waste and Resource Management.

Ahmed, I. M., & Tsavdaridis, K. D. (2018). Life cycle assessment (LCA) and cost (LCC) studies of lightweight composite flooring systems. *Journal of Building Engineering, 20*, 624-633. doi:https://doi.org/10.1016/j.jobe.2018.09.013

Ajayi, S. O., Oyedele, L. O., & Ilori, O. M. (2019). Changing significance of embodied energy: A comparative study of material specifications and building energy sources. *Journal of Building Engineering, 23*, 324-333. doi:10.1016/j.jobe.2019.02.008

Ajayi, S. O., Oyedele, L. O., Jaiyeoba, B., Kadiri, K., & David, S. A. (2016). Are sustainable buildings healthy? An investigation of lifecycle relationship between building sustainability and its environmental health impacts. *World Journal of Science Technology and Sustainable Development, 13*(3), 190-204. doi:10.1108/wjstsd-01-2016-0015

Akanbi, L. A., Oyedele, L. O., Omoteso, K., Bilal, M., Akinade, O. O., Ajayi, A. O., . . . Owolabi, H. A. (2019). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. *Journal of Cleaner Production, 223*, 386-396. doi:https://doi.org/10.1016/j.jclepro.2019.03.172

Alaerts, L., Van Acker, K., Rousseau, S., De Jaeger, S., Moraga, G., Dewulf, J., . . . Eyckmans, J. (2019). Towards a more direct policy feedback in circular economy monitoring via a societal needs perspective. *Resources, Conservation and Recycling*, *149*, 363-371. doi:https://doi.org/10.1016/j.resconrec.2019.06.004

Alembagheri, M., Sharafi, P., Hajirezaei, R., & Tao, Z. (2020). Anti-collapse resistance mechanisms in corner-supported modular steel buildings. *Journal of Constructional Steel Research*, *170*, 106083. doi:https://doi.org/10.1016/j.jcsr.2020.106083

Allwood, J. M. (2014). Chapter 30 - Squaring the Circular Economy: The Role of Recycling within a Hierarchy of Material Management Strategies. In E. Worrell & M. A. Reuter (Eds.), *Handbook of Recycling* (pp. 445-477). Boston: Elsevier.

Allwood, J. M. (2014). Squaring the circular economy: the role of recycling within a hierarchy of material management strategies. In *Handbook of recycling* (pp. 445-477): Elsevier.

Arora, M., Raspall, F., Cheah, L., & Silva, A. (2020). Buildings and the circular economy: Estimating urban mining, recovery and reuse potential of building components. *Resources, Conservation and Recycling*, *154*, 104581. doi:https://doi.org/10.1016/j.resconrec.2019.104581

Atmaca, A. (2016). Life-cycle assessment and cost analysis of residential buildings in South East of Turkey: part 2—a case study. *International Journal of Life Cycle Assessment*, *21*(7), 925-942. doi:10.1007/s11367-016-1051-7

Aye, L., Ngo, T., Crawford, R. H., Gammampila, R., & Mendis, P. (2012). Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy and Buildings*, *47*, 159-168. doi:doi.org/10.1016/j.buildenv.2019.106290

Azzouz, A., Borchers, M., Moreira, J., & Mavrogianni, A. (2017). Life cycle assessment of energy conservation measures during early stage office building design: A case study in London, UK. *Energy and Buildings*, *139*, 547-568. doi:https://doi.org/10.1016/j.enbuild.2016.12.089

Balasbaneh, A. T., Bin Marsono, A. K., & Gohari, A. (2019). Sustainable materials selection based on flood damage assessment for a building using LCA and LCC. *Journal of Cleaner Production, 222*, 844-855. doi:https://doi.org/10.1016/j.jclepro.2019.03.005

Basta, A., Serror, M. H., & Marzouk, M. (2020). A BIM-based framework for quantitative assessment of steel structure deconstructability. *Automation in Construction, 111*, 103064. doi:https://doi.org/10.1016/j.autcon.2019.103064

Baumann, H., & Tillman, A.-M. (2004). The hitch hiker's guide to LCA. doi:ISBN-13: 978-9144023649

Baumann, H. a. (2004). *The hitch hiker's guide to LCA : an orientation in life cycle assessment methodology and application / Henrikke Baumann & Anne-Marie Tillman*: Lund, Sweden : Studentlitteratur.

Benachio, G. L. F., Freitas, M. d. C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. *Journal of Cleaner Production, 260*, 121046. doi:https://doi.org/10.1016/j.jclepro.2020.121046

Björklund, A. E. (2002). Survey of approaches to improve reliability in LCA. *The International Journal of Life Cycle Assessment, 7*(2), 64. doi:htto://dx.doi.org/10.1065/Ica2001.12.071

Blengini, G. A. (2009). Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. *Building and Environment, 44*(2), 319-330. doi:10.1016/j.buildenv.2008.03.007

Boulding, K. (1966). E., 1966, the economics of the coming spaceship earth. *New York*.

Brambilla, G., Lavagna, M., Vasdravellis, G., & Castiglioni, C. A. (2019). Environmental benefits arising from demountable steel-concrete composite floor systems in buildings. *Resources, Conservation and Recycling, 141*, 133-142. doi:https://doi.org/10.1016/j.resconrec.2018.10.014

Brown, M. T., & Buranakarn, V. (2003). Emergy indices and ratios for sustainable material cycles and recycle options. *Resources, Conservation and Recycling, 38*(1), 1-22. doi:https://doi.org/10.1016/S0921-3449(02)00093-9

Browning, T. R., & Heath, R. D. (2009). Reconceptualizing the effects of lean on production costs with evidence from the F-22 program.

Journal of Operations Management, 27(1), 23-44. doi:https://doi.org/10.1016/j.jom.2008.03.009
Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and sustainable energy reviews, 29*, 394-416. doi:https://doi.org/10.1016/j.rser.2013.08.037
Cantù, C., Corsaro, D., Tunisini, A., & Lind, F. (2015). Goal diversity and resource development in an inter-organisational project. *Journal of Business & Industrial Marketing*.
Cao, X., Li, X., Zhu, Y., & Zhang, Z. (2015). A comparative study of environmental performance between prefabricated and traditional residential buildings in China. *Journal of Cleaner Production, 109*, 131-143. doi:https://doi.org/10.1016/j.jclepro.2015.04.120
Cesprini, E., Resente, G., Causin, V., Urso, T., Cavalli, R., & Zanetti, M. (2020). Energy recovery of glued wood waste – A review. *Fuel, 262*, 116520. doi:https://doi.org/10.1016/j.fuel.2019.116520
Chan, J., Bachmann, C., & Haas, C. (2020). Potential economic and energy impacts of substituting adaptive reuse for new building construction: A case study of Ontario. *Journal of Cleaner Production, 259*, 120939. doi:https://doi.org/10.1016/j.jclepro.2020.120939
Chang, C. C., Shi, W., Mehta, P., & Dauwels, J. (2019). Life cycle energy assessment of university buildings in tropical climate. *Journal of Cleaner Production, 239*. doi:10.1016/j.jclepro.2019.117930
Chang, Y., Ries, R. J., & Lei, S. (2012). The embodied energy and emissions of a high-rise education building: A quantification using process-based hybrid life cycle inventory model. *Energy and Buildings, 55*, 790-798. doi:https://doi.org/10.1016/j.enbuild.2012.10.019
Chau, C. K., Hui, W. K., Ng, W. Y., & Powell, G. (2012). Assessment of CO 2 emissions reduction in high-rise concrete office buildings using different material use options. *Resources, Conservation and Recycling, 61*, 22-34. doi:10.1016/j.resconrec.2012.01.001

Chau, C. K., Xu, J. M., Leung, T. M., & Ng, W. Y. (2017). Evaluation of the impacts of end-of-life management strategies for deconstruction of a high-rise concrete framed office building. *Applied Energy, 185*, 1595-1603. doi:10.1016/j.apenergy.2016.01.019

Chomkhamsri, K., Wolf, M.-A., & Pant, R. (2011). International reference life cycle data system (ILCD) handbook: review schemes for life cycle assessment. In *Towards life cycle sustainability management* (pp. 107-117): Springer.

Co., L. S. (2015). To Infinity and Beyond: How We're Embracing the Circular Economy. Retrieved from https://www.levistrauss.com/2015/07/21/embracing-the-circular-economy/

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and psychological measurement, 20*(1), 37-46. doi:doi.org/10.1177/001316446002000104

Cornaro, C., Zanella, V., Robazza, P., Belloni, E., & Buratti, C. (2020). An innovative straw bale wall package for sustainable buildings: experimental characterization, energy and environmental performance assessment. *Energy and Buildings, 208*, 1. doi:http://dx.doi.org/10.1016/j.enbuild.2019.109636

Cruz Rios, F., Chong, W. K., & Grau, D. (2019). Reusing exterior wall framing systems: A cradle-to-cradle comparative life cycle assessment. *Waste Management, 94*, 120-135. doi:http://dx.doi.org/10.1016/j.wasman.2019.05.040

Cuellar-Franca, R. M., & Azapagic, A. (2012). Environmental impacts of the UK residential sector: Life cycle assessment of houses. *Building and Environment, 54*, 86-99. doi:10.1016/j.buildenv.2012.02.005

da Rocha, C. G., & Sattler, M. A. (2009). A discussion on the reuse of building components in Brazil: An analysis of major social, economical and legal factors. *Resources, Conservation and Recycling, 54*(2), 104-112. doi:https://doi.org/10.1016/j.resconrec.2009.07.004

Dantata, N., Touran, A., & Wang, J. (2005). An analysis of cost and duration for deconstruction and demolition of residential buildings in Massachusetts. *Resources, Conservation and*

Recycling, 44(1), 1-15. doi:https://doi.org/10.1016/j.resconrec.2004.09.001

Dara, C., Hachem-Vermette, C., & Assefa, G. (2019). Life cycle assessment and life cycle costing of container-based single-family housing in Canada: A case study. *Building and Environment, 163*, 106332. doi:https://doi.org/10.1016/j.buildenv.2019.106332

Dean, B., Dulac, J., Petrichenko, K., & Graham, P. (2016). Towards zero-emission efficient and resilient buildings.: Global Status Report. Retrieved from https://www.worldgbc.org/sites/default/files/UNEP%20188_GABC_en%20%28web%29.pdf

Densley Tingley, D., Cooper, S., & Cullen, J. (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *Journal of Cleaner Production*, *148*, 642-652. doi:https://doi.org/10.1016/j.jclepro.2017.02.006

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019). *Comparing life cycle assessment modelling of linear vs. circular building components*. Paper presented at the Iop Conference Series: Earth and Environmental Science.

Eberhardt, L. C. M., Birgisdottir, H., & Birkved, M. (2019). Life cycle assessment of a Danish office building designed for disassembly. *Building Research and Information*, *47*(6), 666-680. doi:10.1080/09613218.2018.1517458

Eckelman, M. J., Brown, C., Troup, L. N., Wang, L., Webster, M. D., & Hajjar, J. F. (2018). Life cycle energy and environmental benefits of novel design-for-deconstruction structural systems in steel buildings. *Building and Environment*, *143*, 421-430. doi:https://doi.org/10.1016/j.buildenv.2018.07.017

Eriksson, M., Niitamo, V.-P., & Kulkki, S. (2005). State-of-the-art in utilizing Living Labs approach to user-centric ICT innovation-a European approach. *Lulea: Center for Distance-spanning Technology. Lulea University of Technology Sweden: Lulea*.

Ferdous, W., Bai, Y., Ngo, T. D., Manalo, A., & Mendis, P. (2019). New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review. *Engineering*

Structures, 183, 883-893. doi:https://doi.org/10.1016/j.engstruct.2019.01.061

Figge, F., & Thorpe, A. S. (2019). The symbiotic rebound effect in the circular economy. *Ecological Economics, 163*, 61-69.

Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative inquiry, 12*(2), 219-245.

Formoso Carlos, T., Soibelman, L., De Cesare, C., & Isatto Eduardo, L. (2002). Material Waste in Building Industry: Main Causes and Prevention. *Journal of Construction Engineering and Management, 128*(4), 316-325. doi:10.1061/(ASCE)0733-9364(2002)128:4(316)

Gan, V. J. L., Chan, C. M., Tse, K. T., Lo, I. M. C., & Cheng, J. C. P. (2017). A comparative analysis of embodied carbon in high-rise buildings regarding different design parameters. *Journal of Cleaner Production, 161*, 663-675. doi:10.1016/j.jclepro.2017.05.156

Gan, V. J. L., Cheng, J. C. P., & Lo, I. M. C. (2019). A comprehensive approach to mitigation of embodied carbon in reinforced concrete buildings. *Journal of Cleaner Production, 229*, 582-597. doi:10.1016/j.jclepro.2019.05.035

Gan, V. J. L., Cheng, J. C. P., Lo, I. M. C., & Chan, C. M. (2017). Developing a CO2-e accounting method for quantification and analysis of embodied carbon in high-rise buildings. *Journal of Cleaner Production, 141*, 825-836. doi:10.1016/j.jclepro.2016.09.126

Gangolells, M., Casals, M., Forcada, N., & Macarulla, M. (2014). Analysis of the implementation of effective waste management practices in construction projects and sites. *Resources Conservation and Recycling, 93*, 99-111. doi:10.1016/j.resconrec.2014.10.006

Ganiron Jr, T. U., & Almarwae, M. (2014). Prefabricated technology in a modular house. *International Journal of Advanced Science and Technology, 73*, 51-74.

Gao, W., Ariyama, T., Ojima, T., & Meier, A. (2001). Energy impacts of recycling disassembly material in residential buildings. *Energy and Buildings, 33*(6), 553-562. doi:https://doi.org/10.1016/S0378-7788(00)00096-7

Garcez, M. n. R., Abrahão Bernardo, R., & Luis Gabriel Graupner de, G. (2018). The role of concrete compressive strength on the service life and life cycle of a RC structure: Case study. *Journal of Cleaner Production, 172*, 27-38. doi:http://dx.doi.org/10.1016/j.jclepro.2017.10.153

Gaustad, G., Krystofik, M., Bustamante, M., & Badami, K. (2018). Circular economy strategies for mitigating critical material supply issues. *Resources, Conservation and Recycling, 135*, 24-33. doi:https://doi.org/10.1016/j.resconrec.2017.08.002

GBCA. (2014). Materials Life cycle Impacts.

Ghayeb, H. H., Razak, H. A., & Sulong, N. H. R. (2020). Evaluation of the CO2 emissions of an innovative composite precast concrete structure building frame. *Journal of Cleaner Production, 242*. doi:10.1016/j.jclepro.2019.118567

Goh, M., & Goh, Y. M. (2019). Lean production theory-based simulation of modular construction processes. *Automation in Construction, 101*, 227-244. doi:https://doi.org/10.1016/j.autcon.2018.12.017

Gontia, P., Thuvander, L., & Wallbaum, H. (2020). Spatiotemporal characteristics of residential material stocks and flows in urban, commuter, and rural settlements. *Journal of Cleaner Production, 251*, 119435. doi:https://doi.org/10.1016/j.jclepro.2019.119435

Gorgolewski, M. (2008). Designing with reused building components: some challenges. *Building Research & Information, 36*(2), 175-188. doi:10.1080/09613210701559499

Govindan, K., Soleimani, H., & Kannan, D. (2015). Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. *European Journal of Operational Research, 240*(3), 603-626. doi:https://doi.org/10.1016/j.ejor.2014.07.012

Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., . . . Rydberg, T. (2011). Life Cycle Assessment: Past, Present, and Future. *Environmental Science & Technology, 45*(1), 90-96. doi:10.1021/es101316v

Guo, H., Huang, H., Liu, Y., Meng, Y., Sun, C., & Shao, Y. (2017). A Comparison of the Energy Saving and Carbon Reduction Performance between Reinforced Concrete and Cross-Laminated Timber Structures in Residential Buildings in the Severe Cold

Region of China. *Sustainability, 9*(8). doi:http://dx.doi.org/10.3390/su9081426

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. *Journal of Industrial Ecology, 19*(5), 765-777. doi:10.1111/jiec.12244

Hartley, K., van Santen, R., & Kirchherr, J. (2020). Policies for transitioning towards a circular economy: Expectations from the European Union (EU). *Resources, Conservation and Recycling, 155*, 104634. doi:https://doi.org/10.1016/j.resconrec.2019.104634

Hasibul, I. M., Gustav, B., & Malin, T. (2018). Adoption of lean philosophy in car dismantling companies in Sweden-a case study. *Procedia Manufacturing, 25*, 620-627. doi:https://doi.org/10.1016/j.promfg.2018.06.093

Heravi, G., Rostami, M., & Kebria, M. F. (2020). Energy consumption and carbon emissions assessment of integrated production and erection of buildings' pre-fabricated steel frames using lean techniques. *Journal of Cleaner Production, 253*, 120045. doi:https://doi.org/10.1016/j.jclepro.2020.120045

Hölzle, I. (2019). Contaminant patterns in soils from landfill mining. *Waste Management, 83*, 151-160. doi:https://doi.org/10.1016/j.wasman.2018.11.013

Honic, M., Kovacic, I., & Rechberger, H. (2019). Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study. *Journal of Cleaner Production, 217*, 787-797. doi:https://doi.org/10.1016/j.jclepro.2019.01.212

Hossain, M. U., & Poon, C. S. (2018). Global warming potential and energy consumption of temporary works in building construction: A case study in Hong Kong. *Building and Environment, 142*, 171-179. doi:https://doi.org/10.1016/j.buildenv.2018.06.026

Hossain, M. U., Poon, C. S., Lo, I. M. C., & Cheng, J. C. P. (2016). Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *Resources, Conservation and Recycling, 109*, 67-77. doi:https://doi.org/10.1016/j.resconrec.2016.02.009

Hosseini, M. R., Rameezdeen, R., Chileshe, N., & Lehmann, S. (2015). Reverse logistics in the construction industry. *Waste Management & Research, 33*(6), 499-514. doi:10.1177/0734242X15584842

Hu, M. (2019). Building impact assessment—A combined life cycle assessment and multi-criteria decision analysis framework. *Resources, Conservation and Recycling, 150*, 104410. doi:https://doi.org/10.1016/j.resconrec.2019.104410

Jamieson, E., McLellan, B., van Riessen, A., & Nikraz, H. (2015). Comparison of embodied energies of Ordinary Portland Cement with Bayer-derived geopolymer products. *Journal of Cleaner Production, 99*, 112-118. doi:https://doi.org/10.1016/j.jclepro.2015.03.008

Jia Wen, T., Chin Siong, H., & Noor, Z. Z. (2015). Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia. *Energy and Buildings, 93*, 295-302. doi:https://doi.org/10.1016/j.enbuild.2014.12.002

Kalmykova, Y., Sadagopan, M., & Rosado, L. (2018). Circular economy – From review of theories and practices to development of implementation tools. *Resources, Conservation and Recycling, 135*, 190-201. doi:https://doi.org/10.1016/j.resconrec.2017.10.034

Khasreen, M. M., Banfill, P. F. G., & Menzies, G. F. (2009). Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability, 1*(3), 674-701. doi:https://doi.org/10.3390/su1030674

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., & Hekkert, M. (2018). Barriers to the circular economy: evidence from the European Union (EU). *Ecological Economics, 150*, 264-272.

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

Kirchherr, J., & van Santen, R. (2019). Research on the circular economy: A critique of the field. *Resources, Conservation and*

Recycling, 151, 104480. doi:https://doi.org/10.1016/j.resconrec.2019.104480

Kumanayake, R., Luo, H., & Paulusz, N. (2018). Assessment of material related embodied carbon of an office building in Sri Lanka. *Energy and Buildings, 166*, 250-257. doi:https://doi.org/10.1016/j.enbuild.2018.01.065

Kupwade-Patil, K., De Wolf, C., Chin, S., Ochsendorf, J., Hajiah, A. E., Al-Mumin, A., & Büyüköztürk, O. (2018). Impact of Embodied Energy on materials/buildings with partial replacement of ordinary Portland Cement (OPC) by natural Pozzolanic Volcanic Ash. *Journal of Cleaner Production, 177*, 547-554. doi:https://doi.org/10.1016/j.jclepro.2017.12.234

Le, H.-B., & Bui, Q.-B. (2020). Recycled aggregate concretes – A state-of-the-art from the microstructure to the structural performance. *Construction and Building Materials, 257*, 119522. doi:https://doi.org/10.1016/j.conbuildmat.2020.119522

Lederer, J., Trinkel, V., & Fellner, J. (2017). Wide-scale utilization of MSWI fly ashes in cement production and its impact on average heavy metal contents in cements: The case of Austria. *Waste Management, 60*, 247-258. doi:https://doi.org/10.1016/j.wasman.2016.10.022

Leising, E., Quist, J., & Bocken, N. (2018). Circular Economy in the building sector: Three cases and a collaboration tool. *Journal of Cleaner Production, 176*, 976-989. doi:https://doi.org/10.1016/j.jclepro.2017.12.010

Leminen, S., Nyström, A.-G., Westerlund, M., & Kortelainen, M. J. (2016). The effect of network structure on radical innovation in living labs. *Journal of Business & Industrial Marketing*. doi:doi.org/10.1108/JBIM-10-2012-0179

Li, H., Deng, Q., Zhang, J., Xia, B., & Skitmore, M. (2019). Assessing the life cycle CO2 emissions of reinforced concrete structures: Four cases from China. *Journal of Cleaner Production, 210*, 1496-1506. doi:https://doi.org/10.1016/j.jclepro.2018.11.102

Li, S., & Altan, H. (2012). Environmental Impact Balance of Building Structures and Substitution Effect of Wood Structure in Taiwan. *International Journal of Environmental Protection, 2*(1), 1. doi:10.5963/IJEP0201001

Lin, Y.-K., Chang, P.-C., & Chen, J. C. (2012). Reliability evaluation for a waste-reduction parallel-line manufacturing system. *Journal of Cleaner Production, 35*, 93-101. doi:https://doi.org/10.1016/j.jclepro.2012.05.023

Linder, M., Boyer, R. H. W., Dahllöf, L., Vanacore, E., & Hunka, A. (2020). Product-level inherent circularity and its relationship to environmental impact. *Journal of Cleaner Production, 260*, 121096. doi:https://doi.org/10.1016/j.jclepro.2020.121096

Littell, J. H., Corcoran, J., & Pillai, V. (2008). *Systematic reviews and meta-analysis*: Oxford University Press.

Liu, Y., Guo, H., Sun, C., & Chang, W.-S. (2016). Assessing Cross Laminated Timber (CLT) as an Alternative Material for Mid-Rise Residential Buildings in Cold Regions in China—A Life-Cycle Assessment Approach. *Sustainability, 8*(10). doi:http://dx.doi.org/10.3390/su8101047

Lonca, G., Muggéo, R., Imbeault-Tétreault, H., Bernard, S., & Margni, M. (2018). Does material circularity rhyme with environmental efficiency? Case studies on used tires. *Journal of Cleaner Production, 183*, 424-435. doi:https://doi.org/10.1016/j.jclepro.2018.02.108

London, B. (1932). Ending the depression through planned obsolescence. *Retrieved March, 25*, 2016.

MacArthur, E. (2013). Towards the circular economy, economic and business rationale for an accelerated transition. *Ellen MacArthur Foundation: Cowes, UK*.

Machado, R. C., de Souza, H. A., & Verissimo, G. D. (2018). Analysis of Guidelines and Identification of Characteristics Influencing the Deconstruction Potential of Buildings. *Sustainability*, *10*(8). doi:10.3390/su10082604

Mele, C. (2011). Conflicts and value co-creation in project networks. *Industrial Marketing Management, 40*(8), 1377-1385.

Merli, R., Preziosi, M., & Acampora, A. (2018). How do scholars approach the circular economy? A systematic literature review. *Journal of Cleaner Production, 178*, 703-722. doi:https://doi.org/10.1016/j.jclepro.2017.12.112

Mesa, J., González-Quiroga, A., & Maury, H. (2020). Developing an indicator for material selection based on durability and environmental footprint: A Circular Economy perspective. *Resources, Conservation and Recycling, 160*, 104887. doi:https://doi.org/10.1016/j.resconrec.2020.104887

Meyer, C. (2009). The greening of the concrete industry. *Cement and Concrete Composites, 31*(8), 601-605. doi:https://doi.org/10.1016/j.cemconcomp.2008.12.010

Monahan, J., & Powell, J. C. (2011). An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings, 43*(1), 179-188. doi:https://doi.org/10.1016/j.enbuild.2010.09.005

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling, 153*, 104553. doi:https://doi.org/10.1016/j.resconrec.2019.104553

Mulder, E., de Jong, T. P. R., & Feenstra, L. (2007). Closed Cycle Construction: An integrated process for the separation and reuse of C&D waste. *Waste Management, 27*(10), 1408-1415. doi:https://doi.org/10.1016/j.wasman.2007.03.013

Munaro, M. R., Tavares, S. F., & 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*, 121134. doi:https://doi.org/10.1016/j.jclepro.2020.121134

Musa, M. F., Yusof, M. R., Mohammad, M. F., & Samsudin, N. (2016). Towards the adoption of modular construction and prefabrication in the construction environment: A case study in Malaysia. *Journal of Engineering and Applied Sciences, 11*(13), 8122-8131.

Nambisan, S., & Sawhney, M. (2011). Orchestration processes in network-centric innovation: Evidence from the field. *Academy of management perspectives, 25*(3), 40-57.

Nässén, J., Holmberg, J., Wadeskog, A., & Nyman, M. (2007). Direct and indirect energy use and carbon emissions in the production phase of buildings: An input-output analysis. *Energy, 32*(9), 1593-1602. doi:10.1016/j.energy.2007.01.002

Nußholz, J. L. K., Nygaard Rasmussen, F., & 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
Nwodo, M. N., & Anumba, C. J. (2019). A review of life cycle assessment of buildings using a systematic approach. *Building and Environment, 162*, 106290. doi:https://doi.org/10.1016/j.buildenv.2019.106290
Nyström, A.-G., Leminen, S., Westerlund, M., & Kortelainen, M. (2014). Actor roles and role patterns influencing innovation in living labs. *Industrial Marketing Management*, *43*(3), 483-495.
Papanikolaou, I., Arena, N., & Al-Tabbaa, A. (2019). Graphene nanoplatelet reinforced concrete for self-sensing structures – A lifecycle assessment perspective. *Journal of Cleaner Production, 240*. doi:10.1016/j.jclepro.2019.118202
Paulsen, J. S., & Sposto, R. M. (2013). A life cycle energy analysis of social housing in Brazil: Case study for the program "MY HOUSE MY LIFE". *Energy and Buildings*, *57*, 95-102. doi:https://doi.org/10.1016/j.enbuild.2012.11.014
Pearce, D. W., & Turner, R. K. (1990). *Economics of natural resources and the environment*: JHU Press.
Peng, C. (2016). Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. *Journal of Cleaner Production, 112*, 453-465. doi:http://dx.doi.org/10.1016/j.jclepro.2015.08.078
Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., . . . Scherman, O. (2017). The wood from the trees: The use of timber in construction. *Renewable and sustainable energy reviews, 68*, 333-359. doi:https://doi.org/10.1016/j.rser.2016.09.107
Rios, F. C., Chong, W. K., & Grau, D. (2015). Design for Disassembly and Deconstruction - Challenges and Opportunities. *Procedia Engineering, 118*, 1296-1304. doi:https://doi.org/10.1016/j.proeng.2015.08.485
Rosado, L., Hagy, S., Kalmykova, Y., Morrison, G., & Ostermeyer, Y. (2015). A living lab co-creation environment exemplifying Factor 10 improvements in a city district. *Journal of Urban Regeneration & Renewal, 8*(2), 171-185.

Rust, R. T. (2019). Outside-in marketing: Why, when and how? *Industrial Marketing Management*.

Sacks, R., Radosavljevic, M., & Barak, R. (2010). Requirements for building information modeling based lean production management systems for construction. *Automation in Construction, 19*(5), 641-655. doi:doi.org/10.1016/j.autcon.2010.02.010

Saghafi, M. D., & Teshnizi, Z. A. H. (2011). Building Deconstruction and Material Recovery in Iran: An Analysis of Major Determinants. *Procedia Engineering, 21*, 853-863. doi:https://doi.org/10.1016/j.proeng.2011.11.2087

Salama, T., Salah, A., Moselhi, O., & Al-Hussein, M. (2017). Near optimum selection of module configuration for efficient modular construction. *Automation in Construction, 83*, 316-329. doi:https://doi.org/10.1016/j.autcon.2017.03.008

Salama, W. (2017). Design of concrete buildings for disassembly: An explorative review. *International Journal of Sustainable Built Environment, 6*(2), 617-635. doi:https://doi.org/10.1016/j.ijsbe.2017.03.005

Sanchez, B., Rausch, C., Haas, C., & Saari, R. (2020). A selective disassembly multi-objective optimization approach for adaptive reuse of building components. *Resources, Conservation and Recycling, 154*, 104605. doi:https://doi.org/10.1016/j.resconrec.2019.104605

Sarc, R., Curtis, A., Kandlbauer, L., Khodier, K., Lorber, K. E., & Pomberger, R. (2019). Digitalisation and intelligent robotics in value chain of circular economy oriented waste management – A review. *Waste Management, 95*, 476-492. doi:https://doi.org/10.1016/j.wasman.2019.06.035

Scheuer, C., Keoleian, G. A., & Reppe, P. (2003). Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. *Energy and Buildings, 35*(10), 1049-1064. doi:https://doi.org/10.1016/S0378-7788(03)00066-5

Schuurman, D., & Protic, S. M. (2018). Living Labs versus Lean Startups: An Empirical Investigation. *Technology Innovation Management Review, 8*(12).

Sedláková, A., Vilčeková, S., Burák, D., Tomková, Ž., Moňoková, A., & Doroudiani, S. (2020). Environmental impacts assessment for conversion of an old mill building into a modern apartment building through reconstruction. *Building and Environment*, *172*, 106734. doi:https://doi.org/10.1016/j.buildenv.2020.106734

Senaratne, S., Lambrousis, G., Mirza, O., Tam, V. W. Y., & Kang, W.-H. (2017). Recycled Concrete in Structural Applications for Sustainable Construction Practices in Australia. *Procedia Engineering*, *180*, 751-758. doi:https://doi.org/10.1016/j.proeng.2017.04.235

Serrano, A. A. R., & Alvarez, S. P. (2016). Life Cycle Assessment in Building: A Case Study on the Energy and Emissions Impact Related to the Choice of Housing Typologies and Construction Process in Spain. *Sustainability*, *8*(3). doi:10.3390/su8030287

Sharma, A., Saxena, A., Sethi, M., Shree, V., & Varun. (2011). Life cycle assessment of buildings: A review. *Renewable and sustainable energy reviews*, *15*(1), 871-875. doi:https://doi.org/10.1016/j.rser.2010.09.008

Sicignano, E., Di Ruocco, G., & Melella, R. (2019). Mitigation Strategies for Reduction of Embodied Energy and Carbon, in the Construction Systems of Contemporary Quality Architecture. *Sustainability*, *11*(14). doi:10.3390/su11143806

Siddaway, A. P., Wood, A. M., & Hedges, L. V. (2019). How to do a systematic review: a best practice guide for conducting and reporting narrative reviews, meta-analyses, and meta-syntheses. *Annual review of psychology*, *70*, 747-770. doi:https://doi.org/10.1146/annurev-psych-010418-102803

Singh, J., & Ordoñez, I. (2016). Resource recovery from post-consumer waste: important lessons for the upcoming circular economy. *Journal of Cleaner Production*, *134*, 342-353. doi:https://doi.org/10.1016/j.jclepro.2015.12.020

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333-339. doi:https://doi.org/10.1016/j.jbusres.2019.07.039

Sormunen, P., & Kärki, T. (2019). Recycled construction and demolition waste as a possible source of materials for composite

manufacturing. *Journal of Building Engineering, 24*, 100742. doi:https://doi.org/10.1016/j.jobe.2019.100742
Sovacool, B. K., Axsen, J., & Sorrell, S. (2018). Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. *Energy Research & Social Science, 45*, 12-42. doi:https://doi.org/10.1016/j.erss.2018.07.007
Srisangeerthanan, S., Hashemi, M. J., Rajeev, P., Gad, E., & Fernando, S. (2020). Review of performance requirements for inter-module connections in multi-story modular buildings. *Journal of Building Engineering, 28*, 101087. doi:https://doi.org/10.1016/j.jobe.2019.101087
Stahel, W. R. (1997). Some Thoughts on Sustainability, Insurability and Insurance. *The Geneva Papers on Risk and Insurance - Issues and Practice, 22*(4), 477-495. doi:10.1057/gpp.1997.33
Stahel, W. R. (2016). The circular economy. *Nature, 531*(7595), 435-438. doi:10.1038/531435a
Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., . . . Midgley, P. M. (2013). Climate change 2013: The physical science basis. In: Cambridge University Press Cambridge.
Su, S., Li, X. D., Wang, T., & Zhu, Y. M. (2016). A comparative study of environmental performance between CFST and RC columns under combinations of compression and bending. *Journal of Cleaner Production, 137*, 10-20. doi:10.1016/j.jclepro.2016.07.043
Suwaed, A. S. H., & Karavasilis, T. L. (2020). Demountable steel-concrete composite beam with full-interaction and low degree of shear connection. *Journal of Constructional Steel Research, 171*, 106152. doi:https://doi.org/10.1016/j.jcsr.2020.106152
Svajlenka, J., & Kozlovska, M. (2017). Modern method of construction based on wood in the context of sustainability. *Civil Engineering and Environmental Systems, 34*(2), 127-143. doi:10.1080/10286608.2017.1340458
Takano, A., Hughes, M., & Winter, S. (2014). A multidisciplinary approach to sustainable building material selection: A case study

in a Finnish context. *Building and Environment, 82*, 526-535. doi:10.1016/j.buildenv.2014.09.026

Takano, A., Pal, S. K., Kuittinen, M., Alanne, K., Hughes, M., & Winter, S. (2015). The effect of material selection on life cycle energy balance: A case study on a hypothetical building model in Finland. *Building and Environment, 89,* 192-202. doi:https://doi.org/10.1016/j.buildenv.2015.03.001

Tam, V. W. Y., & Tam, C. M. (2006). A review on the viable technology for construction waste recycling. *Resources, Conservation and Recycling, 47*(3), 209-221. doi:https://doi.org/10.1016/j.resconrec.2005.12.002

Tavares, V., Lacerda, N., & Freire, F. (2019). Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The "Moby" case study. *Journal of Cleaner Production, 212*, 1044-1053. doi:10.1016/j.jclepro.2018.12.028

Teh, S. H., Wiedmann, T., Castel, A., & de Burgh, J. (2017). Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. *Journal of Cleaner Production, 152*, 312-320. doi:10.1016/j.jclepro.2017.03.122

Thormark, C. (2002). A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Building and Environment, 37*(4), 429-435. doi:https://doi.org/10.1016/S0360-1323(01)00033-6

Tingley, D. D., Cooper, S., & Cullen, J. (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *Journal of Cleaner Production, 148*, 642-652. doi:doi.org/10.1016/j.jclepro.2017.02.006

Tingley, D. D., & Davison, B. (2011). Design for deconstruction and material reuse. *Proceedings of the institution of civil engineers-energy, 164*(4), 195-204. doi:doi.org/10.1680/ener.2011.164.4.195

Toniolo, S., Mazzi, A., Pieretto, C., & Scipioni, A. (2017). Allocation strategies in comparative life cycle assessment for recycling: Considerations from case studies. *Resources, Conservation and Recycling, 117*, 249-261. doi:https://doi.org/10.1016/j.resconrec.2016.10.011

Tumminia, G., Guarino, F., Longo, S., Ferraro, M., Cellura, M., & Antonucci, V. (2018). Life cycle energy performances and environmental impacts of a prefabricated building module. *Renewable and sustainable energy reviews, 92*, 272-283. doi:https://doi.org/10.1016/j.rser.2018.04.059

Urbinati, A., Chiaroni, D., & Chiesa, V. (2017). Towards a new taxonomy of circular economy business models. *Journal of Cleaner Production, 168*, 487-498. doi:https://doi.org/10.1016/j.jclepro.2017.09.047

Vaaland, T. I., & Håkansson, H. (2003). Exploring interorganizational conflict in complex projects. *Industrial Marketing Management, 32*(2), 127-138.

van den Berg, M., Voordijk, H., & Adriaanse, A. (2020). Recovering building elements for reuse (or not) – Ethnographic insights into selective demolition practices. *Journal of Cleaner Production, 256*, 120332. doi:https://doi.org/10.1016/j.jclepro.2020.120332

Van den Berghe, K., & Vos, M. (2019). Circular area design or circular area functioning? A discourse-institutional analysis of circular area developments in Amsterdam and Utrecht, The Netherlands. *Sustainability (Switzerland), 11*(18). doi:10.3390/su11184875

Veeckman, C., Schuurman, D., Leminen, S., & Westerlund, M. (2013). Linking living lab characteristics and their outcomes: Towards a conceptual framework. *Technology Innovation Management Review, 3*(12 december), 6-15. doi:10.22215/timreview/748

Venselaar, M., Gruis, V., & Verhoeven, F. (2015). Implementing supply chain partnering in the construction industry: Work floor experiences within a Dutch housing association. *Journal of Purchasing and Supply Management, 21*(1), 1-8.

Wang, J., Yu, C., & Pan, W. (2018). Life cycle energy of high-rise office buildings in Hong Kong. *Energy and Buildings, 167*, 152-164. doi:https://doi.org/10.1016/j.enbuild.2018.02.038

Wei, W., Larrey-Lassalle, P., Faure, T., Dumoulin, N., Roux, P., & Mathias, J.-D. (2015). How to Conduct a Proper Sensitivity Analysis in Life Cycle Assessment: Taking into Account Correlations within LCI Data and Interactions within the LCA Calculation Model. *Environmental Science & Technology, 49*(1), 377-385. doi:10.1021/es502128k

Wu, H. J. J., Yuan, Z. W. W., Zhang, L., & Bi, J. (2012). Life cycle energy consumption and CO2 emission of an office building in China. *International Journal of Life Cycle Assessment*, *17*(2), 105-118. doi:10.1007/s11367-011-0342-2

Xiao, J., Wang, C., Ding, T., & Akbarnezhad, A. (2018). A recycled aggregate concrete high-rise building: Structural performance and embodied carbon footprint. *Journal of Cleaner Production*, *199*, 868-881. doi:https://doi.org/10.1016/j.jclepro.2018.07.210

Yan, H., Shen, Q., Fan, L. C. H., Wang, Y., & Zhang, L. (2010). Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. *Building and Environment*, *45*(4), 949-955. doi:https://doi.org/10.1016/j.buildenv.2009.09.014

Yang, X. N., Hu, M. M., Wu, J. B., & Zhao, B. (2018). Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China. *Journal of Cleaner Production*, *183*, 729-743. doi:10.1016/j.jclepro.2018.02.070

Yellishetty, M., Mudd, G. M., & Ranjith, P. G. (2011). The steel industry, abiotic resource depletion and life cycle assessment: a real or perceived issue? *Journal of Cleaner Production*, *19*(1), 78-90. doi:https://doi.org/10.1016/j.jclepro.2010.08.020

Yin, R. K. (2011). *Applications of case study research*: sage.

Yu, D., Tan, H., & Ruan, Y. (2011). A future bamboo-structure residential building prototype in China: Life cycle assessment of energy use and carbon emission. *Energy and Buildings*, *43*(10), 2638-2646. doi:https://doi.org/10.1016/j.enbuild.2011.06.013

Yuan, Z., Sun, C., & Wang, Y. (2018). Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. *Automation in Construction*, *88*, 13-22. doi:https://doi.org/10.1016/j.autcon.2017.12.021

Zhao, Z., Courard, L., Groslambert, S., Jehin, T., LÉOnard, A., & Xiao, J. (2020). Use of recycled concrete aggregates from precast block for the production of new building blocks: An industrial scale study. *Resources, Conservation and Recycling*, *157*, 104786. doi:https://doi.org/10.1016/j.resconrec.2020.104786

Zink, T., & Geyer, R. (2017). Circular economy rebound. *Journal of Industrial Ecology*, *21*(3), 593-602.

Publications

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Publication I

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Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments

Abstract

Life cycle assessment is an established systems approach to the quantification of the environmental impact of products, and it has been widely studied in the context of buildings. This is an important context given the building sector's substantial embodied energy and greenhouse gas emissions. Against this backdrop, this study has two main objectives. The first objective is to create a benchmark of buildings' environmental impact. The second objective is to develop a procedural guideline that, integrated into the life cycle assessment method, assists practitioners in decreasing the environmental impact of buildings. To achieve the first objective, a systematic review of the relevant literature was conducted to categorize and summarize relevant studies. A meta-analysis followed to synthesize the life cycle assessment results that emerged from the collected articles. The articles were categorized into two main groups: articles on construction materials and articles on entire buildings. Eight construction materials (i.e. concrete, reinforcement bars, structural steel, timber, tiles, insulation and plaster) and three building types (i.e. concrete, timber and steel) were identified, and related embodied energy and carbon were extracted. Subsequently, to meet the second objective, the data were analysed through descriptive and inferential statistics. Findings from the meta-analysis informed a theoretical regression model, which helps inform life cycle assessment procedural guidelines for practitioners who seek to reduce the environmental impact of their construction activities'. Further, our results help shed light on previously equivocal results concerning the impact of construction materials and buildings. Among other contributions, the authors also underline earlier findings for structural materials, showing, for example, that the use of timber structures results in substantial savings over concrete structures in terms of both embodied energy (43%) and carbon (68%).

Keywords. Meta-analysis; systematic literature review; life cycle assessment; buildings; embodied energy; embodied carbon; circular economy.

1. Introduction

Globally, 60% of raw materials, by mass, are used in the building sector (Hossain and Poon, 2018), which embodies 6% of global energy use and releases 11% of related carbon dioxide into the atmosphere (Dean et al., 2016; Hu, 2019; Sedláková et al., 2020). During construction, operation and demolition stages, materials such as concrete, steel and timber are produced and discarded (Zabalza Bribián et al., 2011) which increases material depletion and pressure on landfill (Hölzle, 2019). In an attempt to measure and decrease buildings' environmental impact, the life cycle assessment (LCA) tool has gained considerable traction (Hoxha et al., 2017). Applying this tool to the building context can help quantify and ultimately reduce the adverse impact that materials and components have on various environmental impact indicators, including buildings' embodied energy and carbon emissions (Cabeza et al., 2014).

Previous LCA results have largely failed to provide a consistent picture with LCA results on the embodied energy and carbon of construction materials varying substantially between different studies. For example, while some results state that the recycling of concrete allows material saving (e.g. Blengini (2009) and Visintin et al. (2020)), others claim that the use of steel yields a greater decrease in terms of embodied energy over concrete structures (Hoxha et al., 2017; Saade et al., 2020; Yazdanbakhsh and Lagouin, 2019). Additionally, a quantitative integration between end of life practices and related savings of buildings' environmental impact is lacking. Consequently, many LCA scholars and practitioners are confused about measuring, verifying and comparing LCA results. Further, they might be uncertain about the most beneficial effects of strategies to reduce buildings' environmental impact. LCA practitioners could solve this issue by investing more time and effort into collecting data, carrying out sensitivity analyses and creating laborious LCA comparative scenarios (Reap et al., 2008; Saade et al., 2020). However, since LCAs are complex, time consuming and data hungry procedures, practitioners often prefer to avoid these steps and present their results as mere point estimates rather than relative metrics (Fenner et al., 2018). However, without relative metrics providing comparative interval values, even when LCA results are presented, they only provide a partial picture of practices' impact (Björklund, 2002).

To address this issue, we combined a systematic literature review (SLR) with a meta-analysis method to collect and analyse the LCAs of construction materials and buildings. SLR is a structured approach for the collection, selection and review of the literature on a predefined scientific topic – in our case LCA of construction materials and entire buildings (Baumeister and Leary, 1997; Siddaway et al., 2019). Meta-analysis can be used to aggregate the quantitative results extracted from collected studies (Littell et al., 2008; Siddaway et al., 2015). This is important because meta-analyses zoom out over the diversities of study methods and results, and, in taking into account these diversities, can help resolve inconsistences and provide further guidance to future LCA practitioners.

Consistent with SLR guidelines (e.g. Littell et al. (2008)), we adapted a few essential reviewing and coding steps to our context. Specifically, we collected the majority of studies on LCAs, extracted the relevant data and combined it with descriptive and inferential statistical tools. Within the collected 159 studies we identified the eight most commonly used construction materials: concrete, reinforcement bars, structural steel, timber, tiles, bricks, insulation and plaster; and three building structure materials: concrete, timber and steel. Once the studies were categorized between construction materials and entire building structures, we extracted their results in terms of embodied energy and carbon. We completed the analysis by summarizing the most common end of life alternatives.

In so doing, the first objective of this paper is to create a benchmark of embodied energy and carbon of construction materials and building. The second objective is to employ this benchmark in producing an evidence-based procedural guideline that can inform future LCAs that aim to compare and diminish buildings' negative environmental impact. The SLR and meta-analysis employed in this paper result in a comprehensive collection representative of the range of results for related LCAs to date. The collected results were then analysed through descriptive and inferential statistical tools (e.g. box-whisker charts, regression lines) to create benchmarks of eight construction materials (concrete, reinforcement bars, structural steel, timber, bricks, tiles, insulation (EPS) and plaster) and three structural materials (concrete, timber and steel). The analysed data were then employed to create a two-step procedural guideline. By providing a benchmark of the embodied energy and carbon of construction materials and buildings, the first step assists practitioners in ranking and comparing their preliminary LCA results with our synthesized benchmark. This benchmark helps the practitioners in ranking and comparing their results with the results obtained in the identified LCA studies. The second step guides LCA practitioners to select and adopt several strategies that we distilled from the literature aimed at decreasing buildings' adverse environmental impact. In short, the guideline can be used to make important design decisions on which materials and strategies to adopt so as to diminish buildings' environmental impact.

In addition to the creation of the procedural guidelines, our study makes three important knowledge contributions. First, it provides a comprehensive summary of the environmental impact of construction materials and buildings. This summary could be used as databases and inventories for future LCAs. Second, it explores and solves contradictory results linked to the choice of LCAs' functional units. The importance of defining LCA's functional unit is often underestimated. This oversight could, in turn, lead to wrong conclusions concerning assessments. Third, we uncover important results for the LCA of structural materials, quantifying the total amount of embodied energy and carbon that can be saved by different strategies. For example, using timber structure could result in substantial savings over concrete structures in terms of both embodied energy (43%) and carbon (68%).

2. Methodology

SLRs have been identified as a comprehensive, reproducible and rigorous method to scan, identify and report findings from selected literature (Siddaway et al., 2019; Snyder, 2019). We combined the SLR method with a meta-analysis to aggregate and statistically analyse the extracted quantitative results from the papers identified with the SLR (Siddaway et al., 2019). Consistent with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; see Moher et al. (2009) and PRISMA Checklist, Appendix 1), our SLR unfolds in four main steps, and lays the foundations of a meta-analysis method (see Figure 1). First, we identified a list of relevant keywords that form the Boolean search string (step 1). We applied the search string to the most used databases in the field of construction, waste management and environmental sustainability and imported the data into EndNote X9 and Excel v.1908, where we eliminated the copies (step 2), and applied our exclusion criteria to reach the shortlisted articles (step 3). Finally, we categorized the shortlisted articles, followed by an extraction and analysis of the data (step 4). The articles were divided into two main categories: environmental impact of construction materials and impact of entire buildings. The resultant shortlist is reviewed in Section 4.

Step 1) Keywords and search string. We determined the research keywords linked to our research problem, then combined them in the Boolean research string: (life cycle assessment OR lca) AND (embodied energy OR carbon emissions) AND building. Where keywords were two words, they were included in quotation marks. The search engines automatically search for plural spelling of the same keyword.

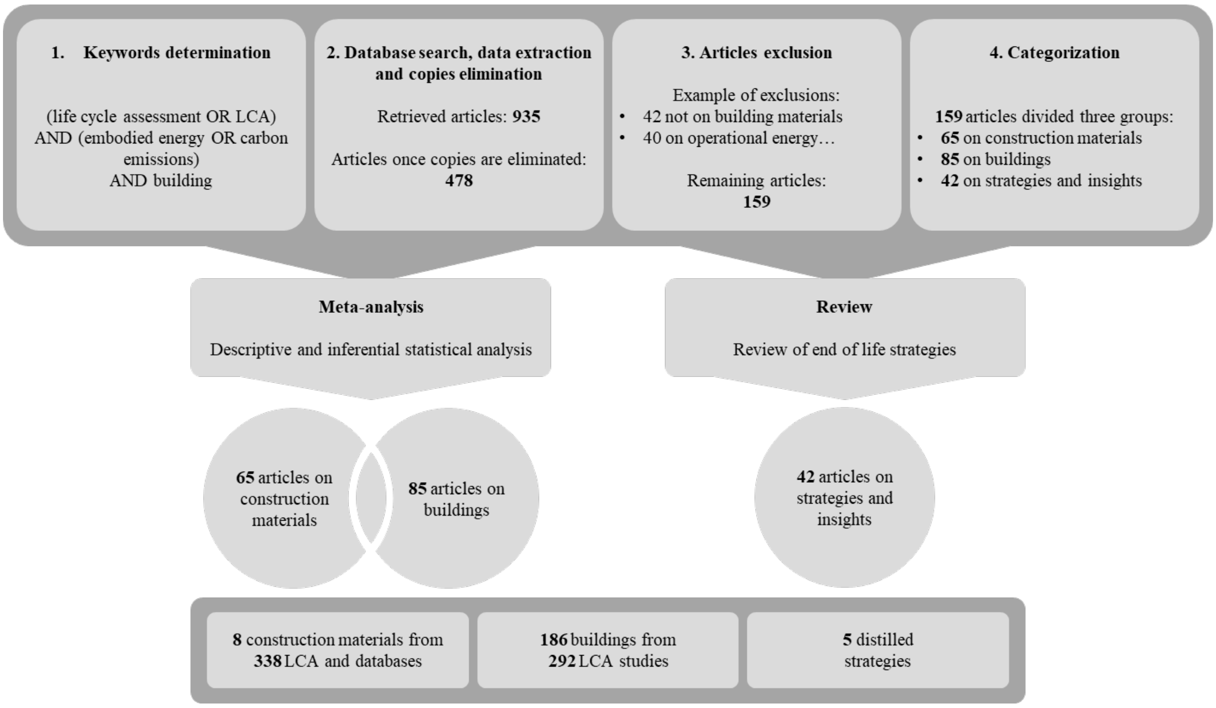

Figure 1 – Systematic literature review and meta-analysis flow chart and results

Step 2) Database search, data extraction and copies elimination. We applied the search string to four selected databases: ScienceDirect, Scopus, ProQuest and Web of Science, searching in the titles, abstracts or articles' keywords (search date: April 2020). We did not apply a year limit or interval, but limited the search to journal articles in English, and in the subject area environmental science. This search resulted in 935 articles. We then extracted the source meta-data into EndNote X9 and Excel v.1908, and reduced the number of articles to 487 by eliminating the copies.

Step 3) Shortlist creation. To minimize bias at this stage, we formulated our exclusion criteria in preparing the review, before starting the search, so that in formulating these criteria we would not be affected by self-bias mechanisms (Siddaway et al., 2019). Two authors independently surveyed the 487 articles and decided to keep or exclude the references. To test our level of agreement, we calculated a Cohen's kappa as shown in section 2.2 (Cohen, 1960). Among the references included in the shortlist, we systematically excluded those that did not answer the research questions, did not provide enough information, used incompatible functional units or could not be retrieved. In this step, the shortlist was reduced from 487 references to 159.

Step 4) Categorization. The 159 shortlisted articles were categorized according to their focus. Two main categories were identified: articles on construction materials (65) and articles on entire buildings (85). The most common construction materials included concrete, reinforcement bars, steel and timber. Articles on entire buildings quantified the impact of producing building structures or focused their efforts on calculating the environmental footprint of whole buildings (including finishing materials). Moreover, 42 articles were included in this literature review as they advise on new materials, provide insights on sustainable waste management strategies, or are included and used across this paper because of their relevant findings.

Once the articles were selected and categorized, we extracted the data in Excel and carried out our meta-analysis. The meta-analysis consisted of descriptive statistics to describe the data and find correlations between variables (box-whisker plots to visualize the ranges of data and identify outliers), and inferential statistics (correlation and regression patterns between embodied energy and carbon) to compare and investigate relationships between the exported data on the environmental impact of materials and buildings. In so doing, we allow scholars and LCA practitioners to predict and verify the embodied energy of a material starting from its embodied carbon, and *vice versa,* hypothesize the environmental impact of a building given its dimensions and structural material, and categorize the quality of the assessed building.

Meanwhile, we reviewed the remaining 42 articles that were selected in the SLR process. In doing so, we focused on strategies that has been adopted to diminish buildings' impact throughout their life cycle. We extracted the results linked to these strategies and employed them in the second step of our procedural guideline, namely project improvement. We present these strategies in Section 4.2.

It is also important to mention that, on top of the selected 159 articles, 55 articles were manually selected. These articles, despite their relevance, were not retrieved through our SLR method because the keywords we used were not mentioned in their titles or abstracts. However, because of their relevance, we used them across this paper to complete some aspects of this study that would otherwise have been neglected. For example, Jamieson et al. (2015), Kupwade-Patil et al. (2018) and Yan et al. (2010) were added because through the SLR we could not source enough information on embodied energy related to integrating by-products into construction materials. Further, we referenced to Kamali and Hewage (2016) and Fenner et al. (2018) as they provide seminal reviews of LCA of buildings.

For transparency we provide a complete list of the 55 manually sourced references in the Appendix, Table A1.

2.1. Life cycle stages and research boundaries

The LCA of buildings is divided into four main stages: building construction (stage A), maintenance and operation (stage B), end of life and disposal (stage C) and next product (stage D) (Finkbeiner et al., 2006; Rashid and Yusoff, 2015). The focus of this research is construction materials with particular attention paid to strategies that diminish the related energy consumed and carbon emissions produced. Therefore, we included all the life cycle stages and excluded the operational stage, the energy required to operate the building during its entire service life. Further, because of the limited number of applications to the next product stage, in our analysis we grouped it with the end of life stage (C+D).

2.2. Cohen's kappa

The shortlisted articles of this SLR were filtered by two authors. To do so, each author scanned through the titles and abstracts of the articles that were downloaded from the databases, independently. The author decided whether an article was to be included or excluded and stated the reasons for exclusion (examples of reasons can be found in section 1, step 3). We then adopted Cohen's kappa to calculate the level of agreement between the two authors, as suggested by Gwet (2008). Our Cohen's kappa is 0.84, representing a high agreement between the authors (see Appendix, Table A2 in the supporting material; Cohen (1968)).

2.3. *Embodied energy, embodied carbon and functional units*

In this paper, we use the terms environmental impact, environmental footprint and impact interchangeably. With these terms we intend to express the effect that construction materials and buildings have on the environment in terms of embodied energy and embodied carbon.

We define embodied energy as the sum of primary renewable and non-renewable energy that was employed to extract raw material sources, transport and process them, to produce and dispose of the selected construction materials (Ajayi et al., 2019). The overall embodied energy of a building then is the amount of energy that is derived from renewable and non-renewable resources to produce building materials and components, and used to produce the building (Jia Wen et al., 2015). Similarly, the embodied carbon related to the same processes (often referred to as global warming potential) is the amount of the emissions that are produced in creating the construction materials and components, and to manufacture the buildings (Monahan and Powell, 2011; Robati et al., 2019). Among more than 20 environmental impact indicators, we chose to analyse the embodied energy and carbon because they are the most commonly used in the literature of construction materials and buildings.

Two functional units were adopted for two different purposes. In the first purpose, when we evaluated the environmental impact of construction materials, we employed the most commonly used functional unit related to materials: the mass measured in kg (as we will discuss later, we will modify the functional unit of some of the construction materials in section 4.1). Therefore, the results belonging to this category are measured in MJ/kg (embodied energy) and in kg CO_2 eq/kg (embodied carbon). When data were provided in volume, we converted it in mass. When this occurred, we used values of density equal to 2.400 kg/m3 for concrete, 400 to 600 kg/m3 for timber (depending on the specific timber) and 8.000 kg/m3 for steel (Gontia et al., 2018). Meanwhile, the functional unit adopted to compare the impact of entire buildings is the measure of usable area: m^2 (Aste et al., 2010; Eleftheriadis et al., 2018). Some of the shortlisted studies calculated the buildings' environmental impact using the entire building as the functional unit and expressed in total floor area (Atmaca and Atmaca, 2015; Robertson et al., 2012). When that was the case, we normalized the results by dividing their findings by this amount. Therefore, the functional unit employed in our second part of the meta-analysis is 1 m^2, and our results are presented as GJ/m^2 (embodied energy) and in t CO_2 eq/m^2 (embodied carbon).

3. Calculation

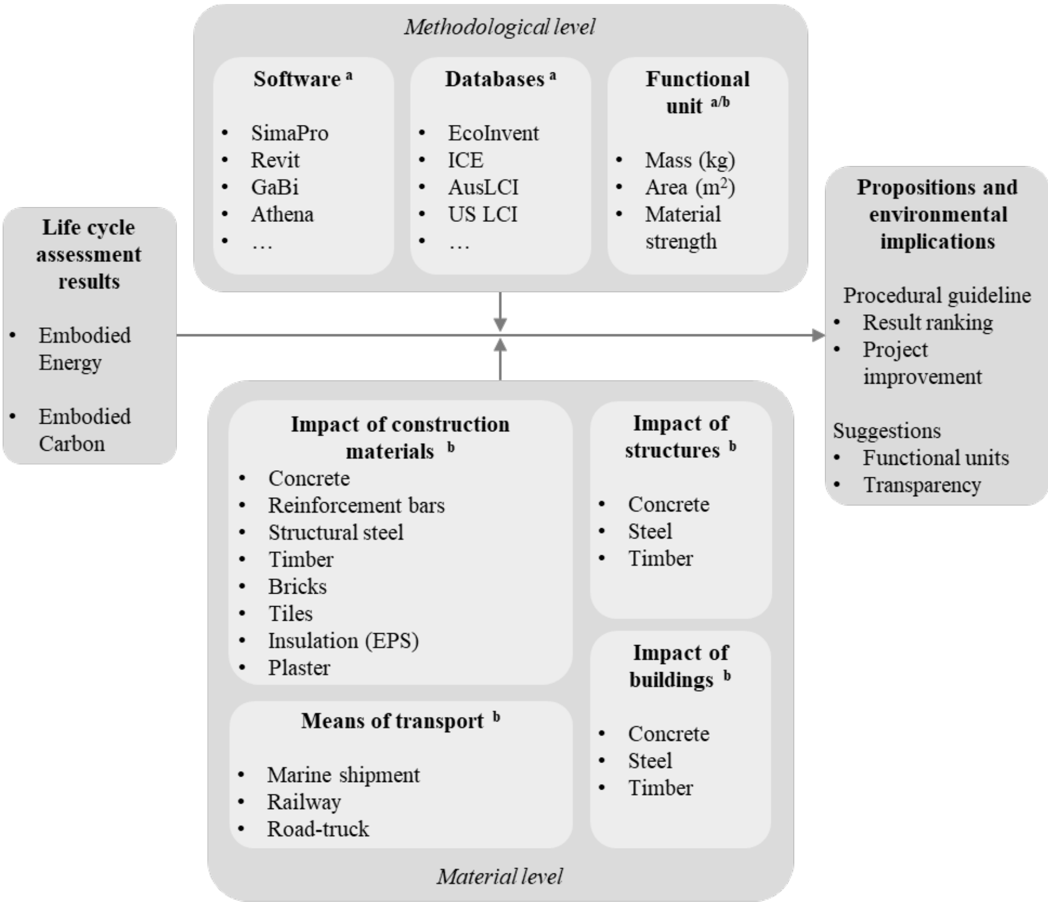

Figure 2 – Theoretical framework of buildings' environmental impact. (EPS = expanded polystyrene.)
[a] Evidence collected from the systematic literature review
[b] Evidence collected from the meta-analysis

Figure 2 presents the theoretical framework adopted in this research. We lay out the link between the environmental impact, the LCA methodological decisions and the LCA results of the materials studied in the literature.

The framework results in a set of procedural guidelines, suggestions for practitioners and its associated environmental implications. Results from the SLR informed the LCAs' methodological level of our final propositions and environmental implications. For example, we observed that a lack of transparency in the definition of the adopted functional unit as well as other methodological choices make several LCA results impossible to replicate which leads to the results being perceived as unreliable or not trustorthy. Meanwhile, we employed the results from our meta-analysis to inform our proposed procedural guideline. Specifically, statistical analyses of the collected 630 LCA results were adopted to produce the benchmark proposed in our guideline.

3.1. Distribution and trends

3.1.1. Distribution by year and geography

Of the selected articles, more than 20% of the articles on the LCA of building materials were produced after 2014. This demonstrates that research on the sustainability of buildings is a recent topic which is gaining traction (Figure 3).

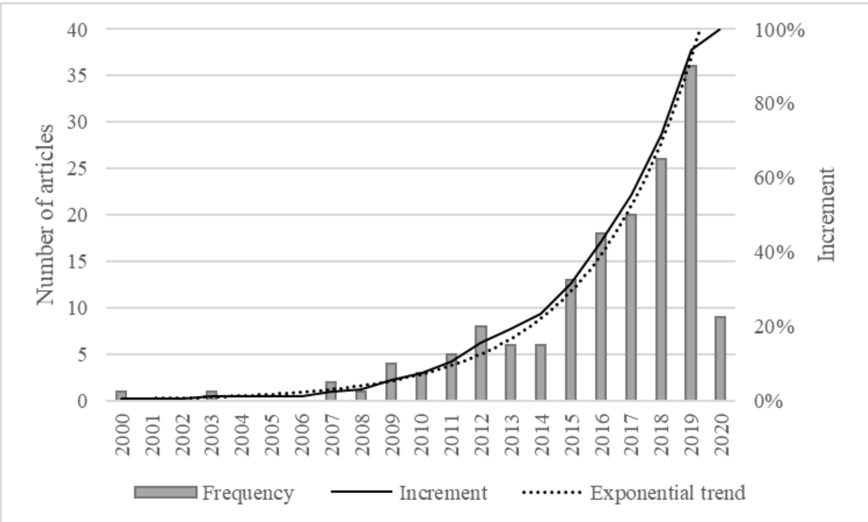

Figure 3 – Distribution of the shortlisted articles across the years and comparison with the exponential trend.

Furthermore, more than half of the building and materials studied in this meta-analysis provide data from Asia, where LCA has been adopted to study 111 buildings, distributed between Hong Kong, China, Singapore and other Asian countries. About 44% of the studies focused on buildings in Europe, North America and Oceania (Figure 4).

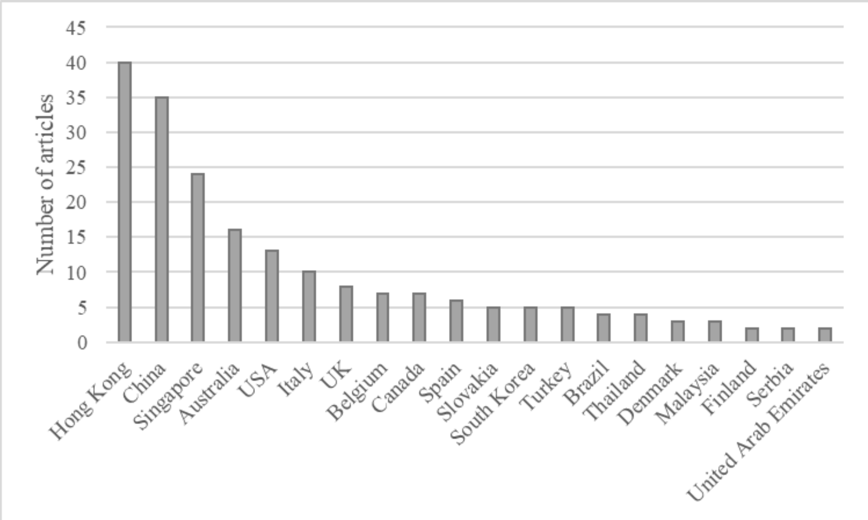

Figure 4 – Distribution of the shortlisted articles across the countries.

3.1.2. Distribution by materials and building characteristics

We reviewed 65 articles on construction materials, extracting data on concrete, reinforcement steel bars, steel, timber, bricks, tiles, expanded polystyrene insulation and plaster (Figure 5). Concrete is the most studied material, and its environmental impact has been studied in 56 different articles (for example Bribian et al. (2011), Invidiata et al. (2018), Moazzen et al. (2019) and Zaman et al. (2018)). Data on steel was extracted from 28 articles as structural steel (Dong et al., 2020; Kofoworola and Gheewala, 2009), and 16 as reinforcement bars (Bribian et al., 2011; Hay and Ostertag, 2018).

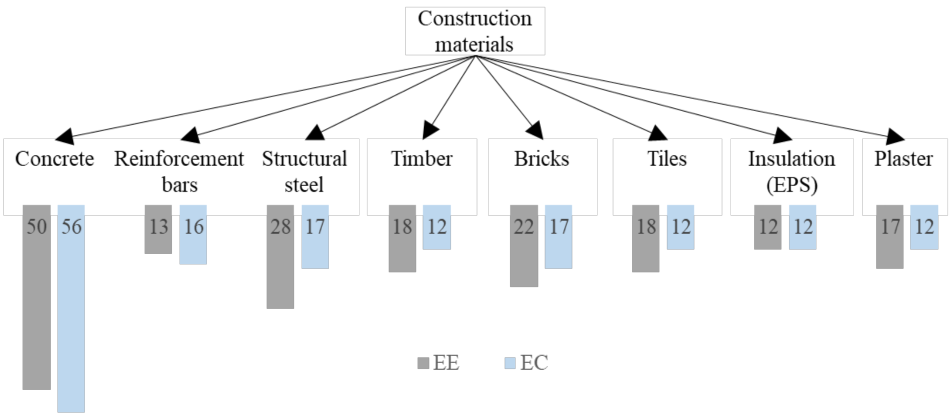

Figure 5 – Number of articles categorized by building material. EPS=expanded polystyrene.

Embodied energy and carbon of bricks were reported 22 and 17 times respectively (D'Amico et al., 2019). Data on the remaining materials were reported more than 12 times, allowing us to carry out related statistical analysis (Dong et al., 2020; Roh et al., 2018).

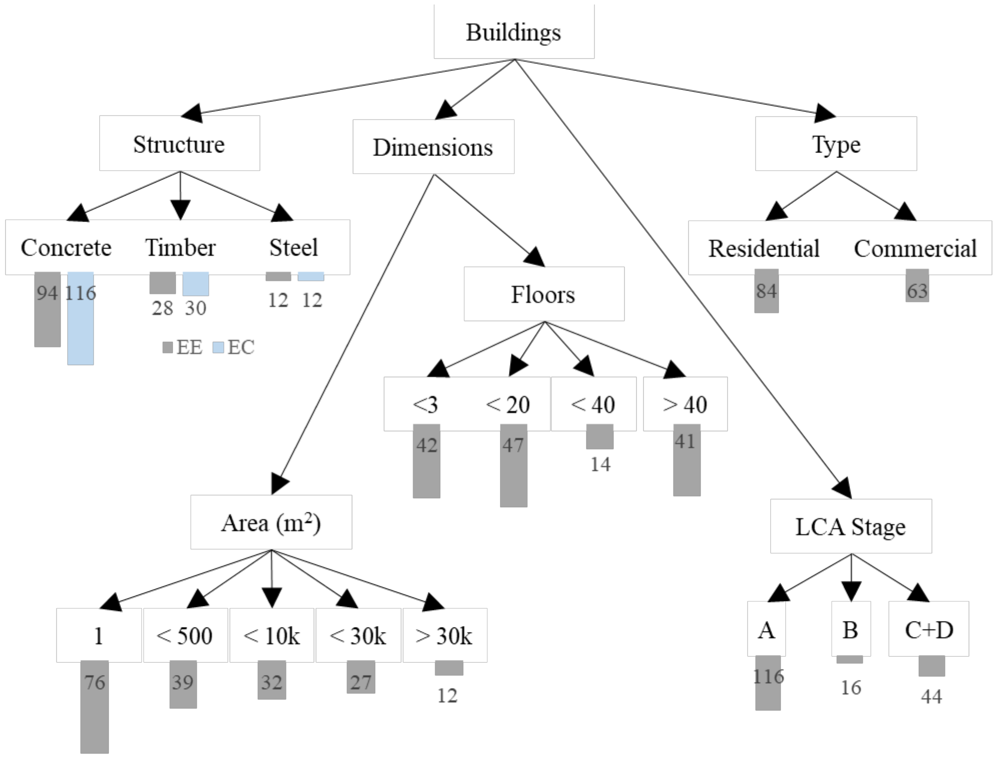

Figure 6 – Number of articles categorized by buildings studied, structural materials, building dimensions, LCA stages and building type. Some studies did not declare the overall area of the analysed case study, but used 1 m^2 as functional unit.

In addition, 55 articles have analysed the overall impact of entire buildings (Motuzienė et al., 2016; Sicignano et al., 2019; Tulevech et al., 2018). A total of 186 buildings were studied in these 55 articles. Of these, the majority were concerned with concrete (studied 116 times; see Georges et al. (2015), Scheuer et al. (2003) and Varun et al. (2012)), 30 for timber (Guo et al., 2017; Li and Altan, 2012), and only 12 for steel (Azzouz et al., 2017; Takano et al., 2014). Further, most of the scholars preferred the square meter as a functional unit, and did not provide further information on the dimensions of their case studies (this occurred 76 times; see, for example Gan et al. (2019), Sicignano et al. (2019) or Wang et al. (2018)). The remaining case studies were mostly buildings with less than 20 floors and smaller than 30 000 m^2 (Biswas, 2014; Petrovic et al., 2019; Su and Zhang, 2016; Wu et al., 2012). Of the case studies which informed on the type of building, 84 were residential (Iddon and Firth, 2013; Zhang et al., 2016) and 63 commercial, further divided between offices (Georges et al., 2015; Hu, 2019), hospitals (Li et al., 2019; Lu et al., 2019) and schools or universities (Chang et al., 2019; Emami et al., 2016). We further categorized the investigated buildings according to the life cycle stage analysed (A, B and C+D – see section 2.1 and Figure 6).

3.2. Software and life cycle inventory database

SimaPro is the LCA software that has been used most frequently, in 56% of the papers (Asdrubali et al., 2019; Motuzienė et al., 2016; Sartori and Calmon, 2019), and the second most used software is Revit (12%; e.g. Nizam et al. (2018) and Peng (2016)). This result is interesting because Revit – a software better known for building information modelling of constructions – is proving its flexibility in calculating many aspects of buildings, including their environmental impact. Other software includes GaBi, Athena, used in different versions (Rossi et al., 2012; Sim et al., 2016). Once the practitioner chooses the software, the most important aspect of any LCA is the choice of the life cycle inventory. This is because the inventories provide the environmental impact of materials and processes, representing the base that the LCA practitioners then modify to fit their purposes. Our comprehensive meta-analysis highlights that the most used life cycle inventory database is Ecoinvent (in its different versions, depending on when the research was conducted; e.g. Bribian et al. (2011), Feng et al. (2020), Feng et al. (2020)). Ecoinvent was used in almost a third of the shortlisted articles, which not only proves its popularity, but how it can be adapted to provide LCAs across the globe: it has been used in studies across all continents, where its data was then adapted to fit the local energy consumption and carbon emissions. The second most used database was the University of Bath's Inventory of Carbon and Energy (ICE) database (e.g. Atmaca (2017), Topalovic et al. (2018)), which has been used in 13% of the articles where the database was declared, mainly in European countries. Most of the Australian studies employed the Australian database AusLCI, North American studies preferred US LCI, and three of the five Southern Korean articles employed the local Korea LCI Information Network (e.g. Azzouz et al. (2017), Chau et al. (2017), Salazar and Meil (2009)). This also underlines the feasibility of adopting local databases, whenever possible, and fill the eventual lack of data with international databases, such as Ecoinvent (Blengini, 2009; Invidiata et al., 2018). Finally, another option when creating the life cycle inventory, is using previous literature or environmental product declarations. These solutions have been adopted in several of the collected articles (Pierobon et al. (2019), for example, combined several different databases and sourced more information from the literature).

3.3. Embodied energy and carbon of construction materials

We analysed the 65 selected papers concerning construction materials: concrete, reinforcement bars, steel, timber, bricks, tiles, insulation, and plaster (Figure 7 and Figure 8). Interestingly and despite the overlap of the databases used (as highlighted in section 3.2), the data extracted from the literature are distributed over a wide range of both embodied energy and carbon, with the exclusion of concrete. By investigating the median, mean, interquartile range, and outliers it was possible to delineate the tendency of the environmental impact of the selected materials.

3.3.1. Environmental impact of concrete

As shown above in Figure 6, concrete is the most studied material. This meta-analysis shows that it is also related to the smallest impact per kg: the median of embodied energy and carbon is equal

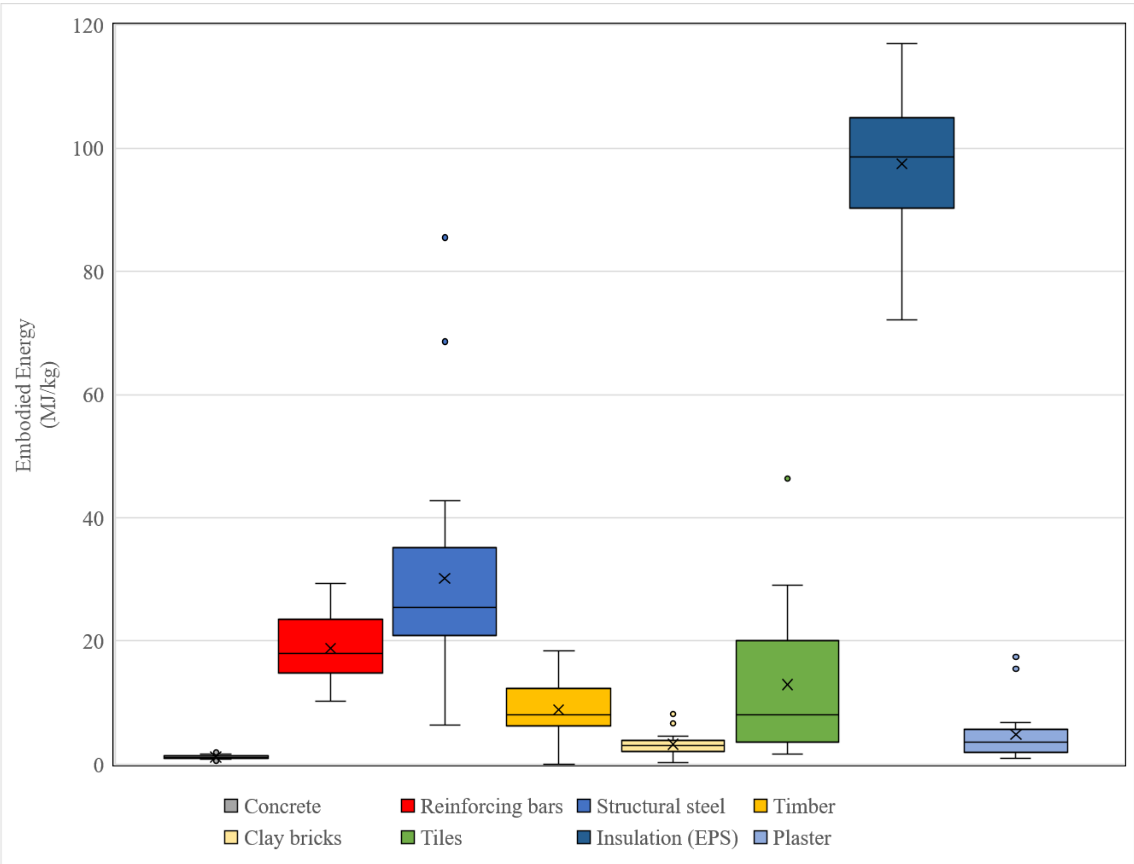

Figure 7 – Environmental impact of the studied materials, in terms of embodied energy. Outliers are represented by dots outside the fences, and the crosses mark the mean values.

to 1.11 MJ/kg and 0.19 kg CO_2 eq/kg, respectively. Further, meta-analysis results show that concrete is the material which results in the smallest variability of outcomes: its interquartile range varies between 1 and 1.3 MJ/kg, and 0.13 and 0.28 kg CO_2 eq/kg. By comparison, the interquartile range of structural steel varies between 21.5 and 35 MJ/kg, and 1.7 and 2.8 kg CO_2 eq/kg. The reason why the results of impact assessments of concrete converge to a central value might be either because concrete is widely known and studied (Vieira et al., 2016), or because its manufacturing processes involve fairly simple steps, machinery and established chemical reactions (Shetty, 2005).

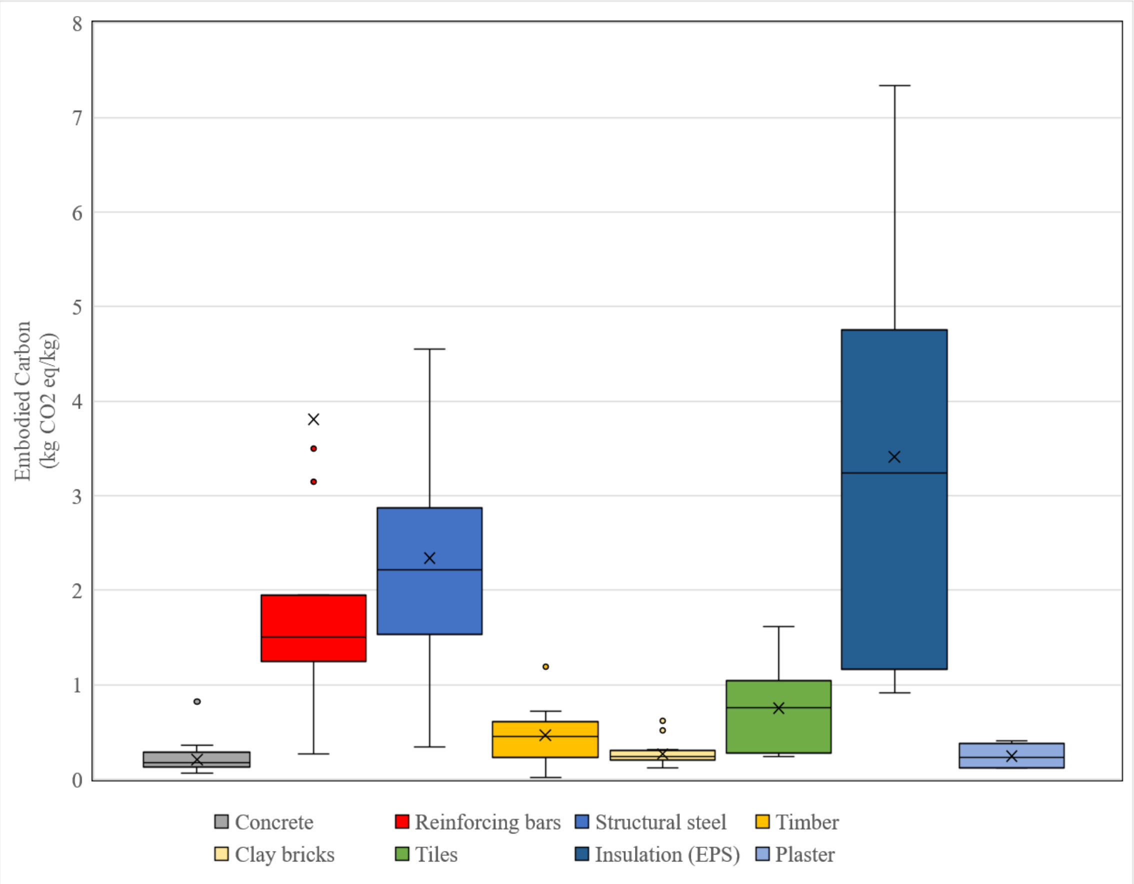

Figure 8 – Environmental impact of the studied materials, in terms of embodied carbon. Outliers are represented by dots outside the fences, and the crosses mark the mean values. The reinforcing bar series shows its mean value outside of the interquartile range because of a top-outlier value that lies outside of the plot area.

3.3.2. *Environmental impact of steel*

Steel, both as reinforcement bars and structural steel, is the second most impacting material (after expanded polystyrene). It embodies 25.5 MJ/kg and 2.2 kg CO_2 eq/kg as structural steel, and 18.0 MJ/kg and 1.5 kg CO_2 eq/kg as reinforcement bars (median values). Despite being one of the most popular construction materials, we found that its embodied energy and carbon vary substantially, from 6.36 to 85.5 MJ/kg (which has been considered an outlier value in the representation), and from 0.34 to 4.55 kg CO_2 eq/kg. This might be related to the geography of the study, as the highest environmental impact of structural steel was registered in Australian and European studies (e.g. Crawford (2014), Fay et al. (2000), Monahan and Powell (2011)): Australia usually imports virgin steel from China which increases the impact of such materials due to transport (material transport is included in the production stage, A.4; see EeBGuide (2011), Qiangfeng et al. (2018), Yellishetty and Mudd (2014)).

3.3.3. Environmental impact of timber

Timber is considered one of the most sustainable materials, because its structure captures carbon from the atmosphere as CO_2 (Hassan et al., 2019). It might then appear counterintuitive that producing one kg of timber for buildings embodies high amounts of energy (8.0 MJ/kg, median), but its embodied carbon per kg remains comparable to the embodied carbon for concrete (0.45 kg CO_2 eq/kg, median). This might be due to three main factors. First, although trees capture carbon from their environment, the industrial processes involved in harvesting, drying, sawing and transport are energy intensive (Adhikari and Ozarska, 2018; Pittau et al., 2019). The gap between the embodied energy of timber structures and their embodied carbon has been assessed and can be explained by the fact that timber absorbs CO_2 from the atmosphere, contributing to a low amount of embodied energy. Second, this outcome might be affected by the chosen functional unit (kg); we will investigate this aspect in section 4.1. Third, the analysed studies do not take into consideration the end of life of timber, which is typically a stage when timber positively impacts on the environment. Furthermore, timber from demolished structures is often biodegradable, limiting the impact due to landfill. We will cover this aspect in detail in evaluating the whole life cycle of timber structure (including end of life and next product stages, C+D) in section 3.4.

3.3.1. Environmental impact of expanded polystyrene

In terms of embodied energy, the most impacting construction material by kg is expanded polystyrene, a common insulation material. Polystyrene embodies 98.6 MJ/kg and 3.2 kg CO_2 eq/kg (median values). This is not surprising: of this embodied energy, the greatest amount (between 70%

and 90%) is embodied during the acquisition of its primary raw material, hydrocarbon fuels (Ahmed and Tsavdaridis, 2018; Biswas et al., 2016; Pargana et al., 2014).

3.3.2. Environmental impact of bricks, tiles and plaster

Bricks, tiles and plaster impact 3.0 MJ/kg and 0.24 kg CO_2 eq/kg, 8.0 MJ/kg and 0.76 kg CO_2 eq/kg, 3.6 MJ/kg and 0.23 kg CO_2 eq/kg, respectively (median values). Both clay and gypsum are natural materials, and their impact is mainly due to the heat required in their production processes: baking in ovens (bricks and tiles), and calcination (gypsum) (Melià et al., 2014). Therefore, their impact contributes to increase the overall impact of buildings by up to 18% of the total embodied energy and 19% in terms of embodied carbon (Asif et al., 2007).

3.3.3. *Correlation between embodied energy and carbon*

In this meta-analysis it was possible to extract embodied energy and carbon to produce the studied construction materials, and, to not lose information on individual data points, we link this information to the countries where these materials were produced. This allows us to explore an eventual correlation between the data collected. Figure 9 shows that there is a linear correlation between embodied energy and carbon. Although this might not be surprising, further insights are revealed from a closer look to the clusters of data of the single materials.

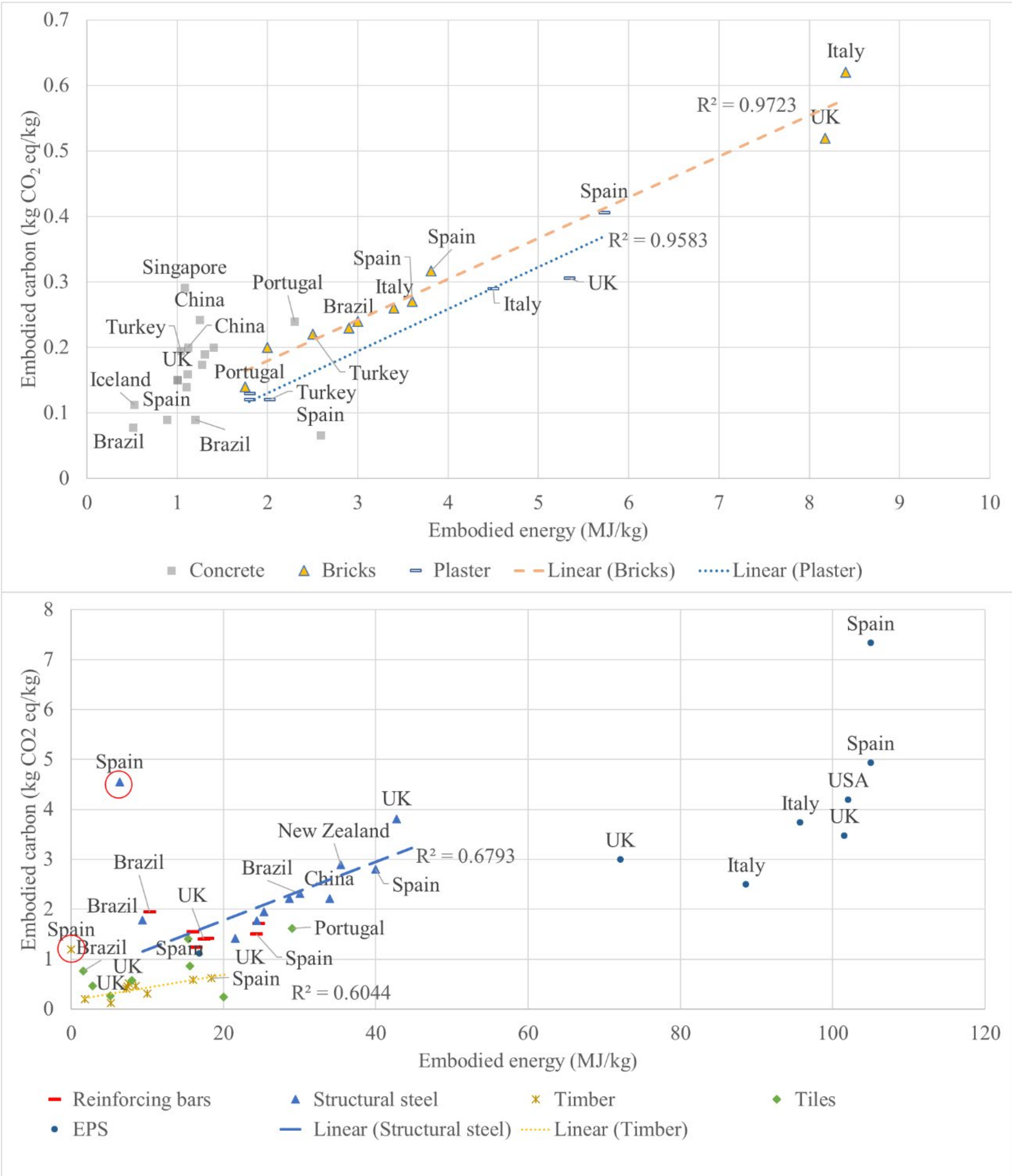

Figure 9 – Relationship between the embodied energy and carbon to produce the studied building materials in selected countries. Regression lines are drawn in dashed lines, and outliers are circled in red.

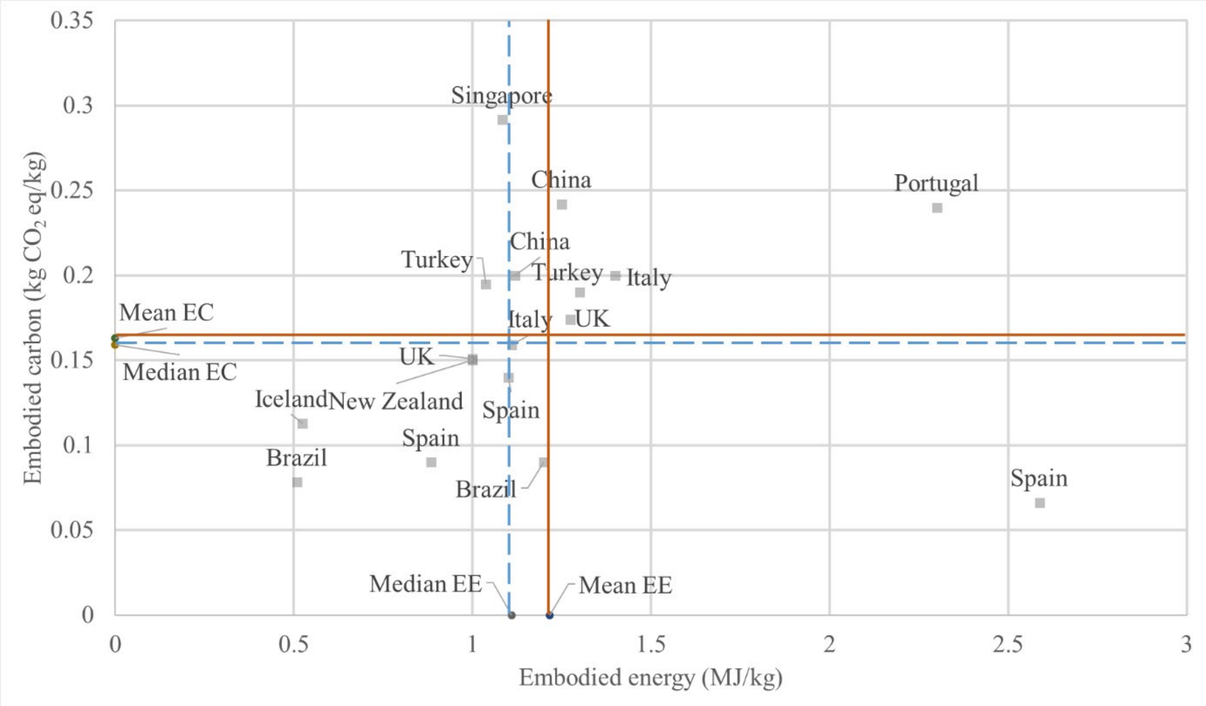

Figure 10 – Relationship between the embodied energy and carbon of concrete production.

The charts in Figure 9 show a positive linear trend for bricks and plaster embodied energy and emissions (and in both cases the coefficient of determination R^2 is close to 1). This means that the energy required to produce these two materials might be directly linked to the consequent carbon emissions of production processes. The values that have been recorded for structural steel are also distributed along the regression line, with the exception of one outlier study in Spain (which was excluded from the calculation of the R^2 in the chart; Galan-Marin et al. (2018)). Similarly, results on embodied energy and carbon of timber are distributed along their regression line, with the exclusion of another outlier (another Spanish study, Moyano et al. (2019)).

Although the impact of the other materials seems characterized by a random behaviour, it is still possible to observe important patterns. For example, as Figure 10 shows, results for concrete are distributed mainly below and above both means of the two datasets, demonstrating a positive correlation between embodied energy and carbon related to concrete production. This means that concrete follows the same pattern identified for structural steel, plaster and brick. Further, data show that Spain and Italy consume more energy and produce more carbon emissions to produce expanded polystyrene, bricks and structural steel, among the studied countries. Finally, from this data it was not possible to identify any pattern related to reinforcement bars and tiles, whose impact appears distributed randomly (Figure 9 and Figure 10).

It is important to report that the correlation analysis was possible only for a sub-group of the data analysed above in the box-whisker diagrams (Figure 7 and Figure 8). This is because not all the analysed articles studied both embodied energy and carbon: we could apply the scatter plot analysis only to embodied energy and carbon coupled in the same article.

3.4. Embodied energy and carbon of buildings

This SLR shows that most of the studies of the LCA of buildings attempt to investigate the environmental impact of concrete, timber and steel structures. This allowed us to divide the sources depending on which structural materials were employed in their case studies.

3.4.1. Environmental impact of bare structures

Of the collected studies, 66 focused on building structures and excluded additional components, such as finishing materials, insulation, doors, windows, roof and cladding. In so doing, they gave us a better understanding of the differences between concrete, timber and steel of bare structures. In contrast, these studies do not provide enough information on maintenance and end of life to infer related conclusions. Consequently, in this section we focus only on the impact of the production stage.

Embodied energy of structures. As summarized in Table 1, structures in concrete impact from a minimum of 0.3 GJ/m^2 to a maximum of 8.4 GJ/m^2 (e.g. Moyano et al. (2019), Wu et al. (2012)), but the majority of the results are found between 1.1 and 4.6 GJ/m^2, which can be considered a narrow interquartile range. Conversely, the majority of timber structures embody between 2.3 and 5.5 GJ/m^2 (e.g. Li and Altan (2012), Pierobon et al. (2019)), which means that generally, they embody more energy than concrete structures. Similarly, steel structures embody between 1.4 and 6.5 GJ/m^2 (e.g. Li and Altan (2012), Su and Zhang (2016)). These results seem to suggest that, in terms of embodied energy, concrete structures are preferable over timber and steel structures. It is important to consider that, in this evaluation, we could not measure the difference between energy produced from fossil fuels and energy from renewable resources. If the energy used to manufacture these structures were partially renewable, the direct impact of these values on the environment could be abated.

Table 1 – Interquartile and total range of embodied energy of the concrete, timber and steel structures (GJ/m²).

	IQ Range	***Total Range***	***Minimum***	***Maximum***	***Q1***	***Median***	***Mean***	***Q3***
Concrete	3.5	8.1	0.3	8.4	1.1	3.1	3.4	4.6
Timber	3.2	7.1	1.1	8.2	2.3	3.0	3.8	5.5
Steel	5.1	5.9	0.8	6.7	1.4	6.3	4.4	6.5

Embodied carbon of structures. Table 2 summarizes the results of the embodied carbon of concrete, timber and steel structures. This meta-analysis shows that steel embodies slightly less carbon than concrete, although the difference in embodied carbon between concrete and steel structures is small. When it comes to embodied carbon, timber demonstrates its potential as more environmentally friendly material, because it stores carbon in the structure and thereby removes it from the atmosphere. This results in a range between -445.6 and 333.5 kg CO_2 eq/m^2 (e.g. Mackova et al. (2016), Pierobon et al. (2019)), and a median equal to 0.1 t CO_2 eq/m^2.

Table 2 – Interquartile and total range of embodied carbon of the concrete, timber and steel structures (10^2 kg CO_2 eq/m2).

	IQ Range	***Total Range***	***Minimum***	***Maximum***	***Q1***	***Median***	***Mean***	***Q3***
Concrete	0.2	0.2	0.5	7.2	0.3	0.4	0.4	0.5
Timber	0.5	0.7	-4.5	3.3	-0.3	0.1	0.0	0.2
Steel	0.2	0.2	2.4	3.9	0.2	0.3	0.3	0.4

3.4.2. Differences across construction materials and life cycle stages

We gathered several articles that quantified the LCA of the whole building, including non-structural materials, and analysed the impact from production to demolition. We divided the results of these articles into the three main life cycle stages: building (stage A), maintenance (stage B) and demolition (stages C+D). This was not always possible, because some studies evaluated only the production stage (e.g. Cornaro et al. (2020), Takano et al. (2014)), and others focused only on production and end of life, excluding the impact of maintenance (e.g. Guo et al. (2017), Liu et al. (2016)). Interestingly, although the results are distributed over a wide range, only a few outliers were identified. This means that buildings' impact does not deviate considerably from the median and average results. This fact allows us to explore in detail the correlation between materials and life cycle stages.

The SLR produced 116 LCAs of entire buildings, which include the structure and the finishing materials. Some of these studies include in their assessment both maintenance and end of life stages. Both embodied energy and carbon increment throughout the life cycle, as more materials are consumed to maintain and refurbish the buildings. However, recycling of concrete allows the saving of up to ~0.8GJ/m^2 once the structure is demolished. Similarly, timber and steel enable savings in terms of embodied carbon (~0.1 t CO_2 eq/m^2; Figure 12 and Figure 13).

Across the entire life cycle, buildings with timber structure embody significantly less energy and carbon. In summary, when considering the median of the datasets, the impact of timber structures is 57% of the concrete structures in terms of embodied energy and only 32% in terms of embodied carbon. In contrast, steel buildings save only 9% in terms of embodied energy, and 15% in terms of embodied carbon, compared to concrete structures (Figure 11).

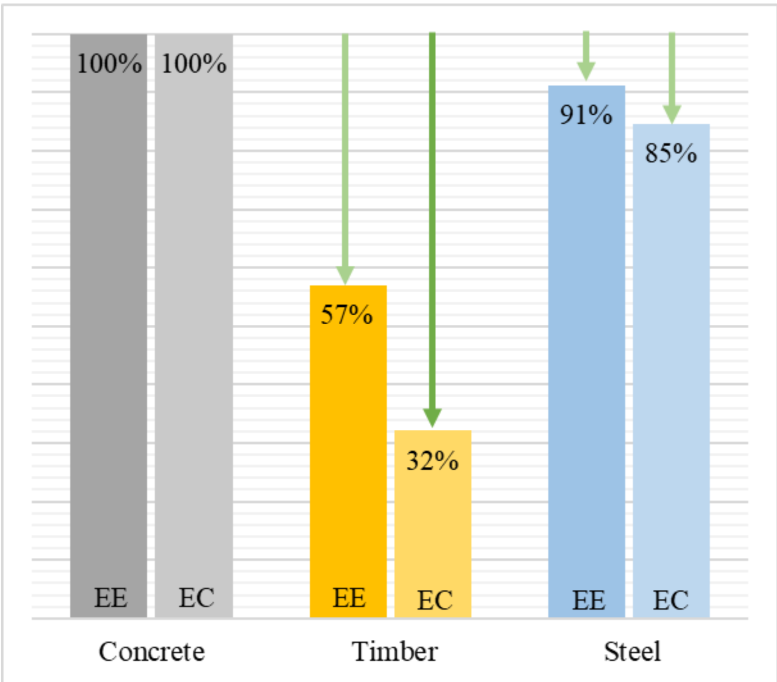

Figure 11 – Medians of embodied energy and carbon of the timber and steel buildings relative to concrete buildings over the whole life cycle.EE= embodied energy, EC=embodied carbon.

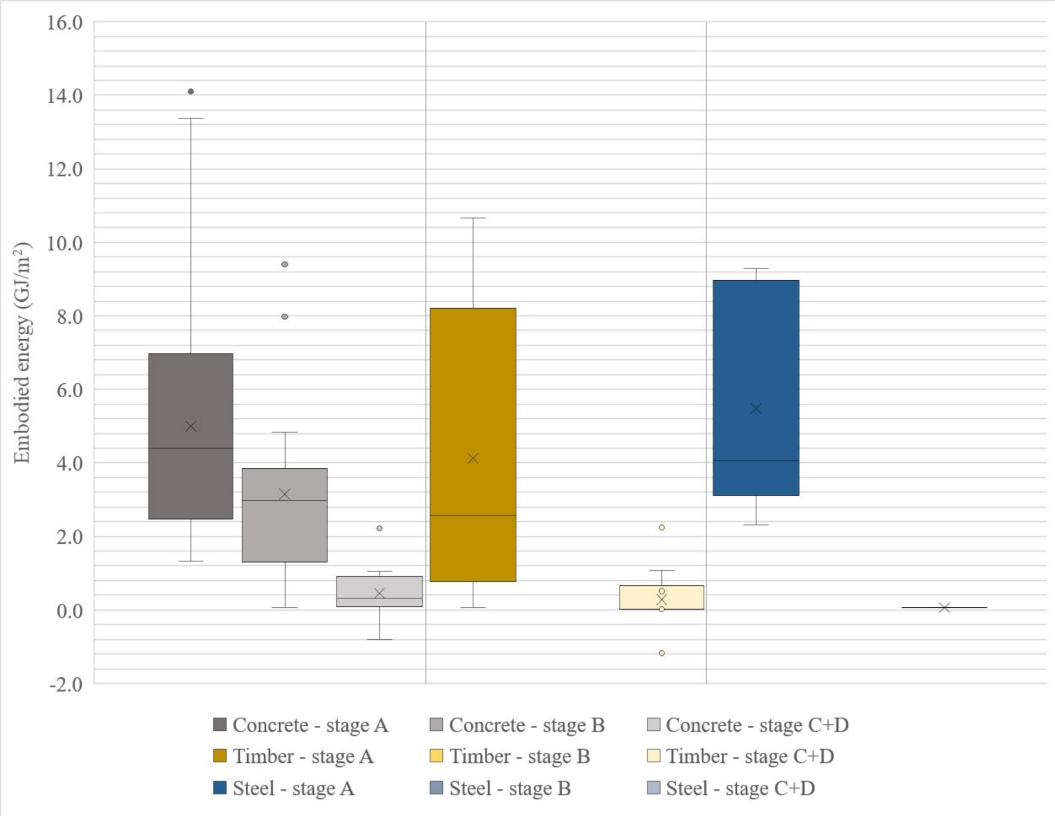

Figure 12 – Embodied energy of buildings built with concrete, timber and steel structure, divided into the three life cycle assessment stages. Construction (A), maintainance (B) and end of life (C+D). The vertical axis of this chart starts at -2.0 GJ/m².

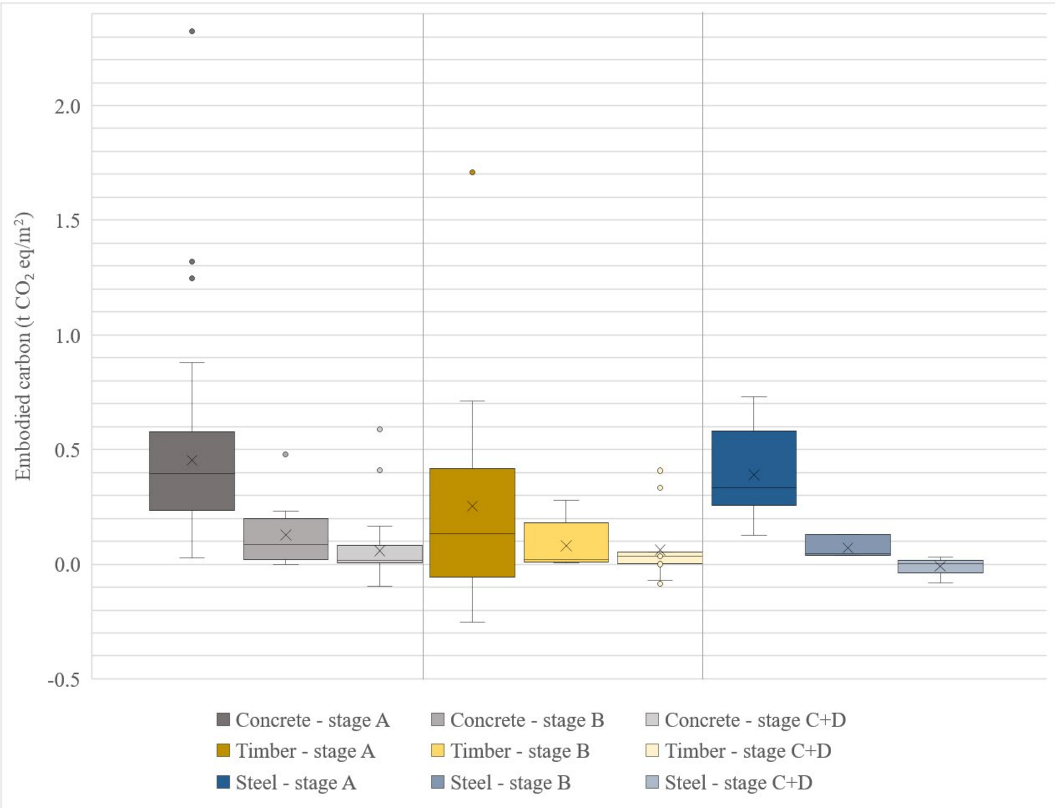

Figure 13 – Embodied carbon of buildings built with concrete, timber and steel structure, divided into the three life cycle assessment stages. Construction (A), maintenance (B) and end of life (C+D). The vertical axis of this chart starts at -0.5 t CO_2 eq/m².

3.5. Transport

Transport of construction materials and components is a significant factor when compared to the environmental impact of construction. Being dependent on the geographical location of the building and industry-to-site distances, the impact of transport varies substantially. For example, it could impact from 0.1% to 4% of the total building (results comparable in terms of embodied energy and carbon; see Chang et al. (2012), Li et al. (2019), Scheuer et al. (2003), and Nässén et al. (2007)). In this meta-analysis we collected the impact of the three main means of transport, truck/road, train/railway and marine shipment. Materials transport has often been the subject of uncertainty analysis due to its variable nature (Brambilla et al., 2019; Hossain et al., 2016), and finding its related embodied energy and carbon could be challenging (Li et al., 2019). In addressing this issue, we propose the collected values in

Table 3, measured in impact per mass of transport material (in tons) and shipping distance (in km), their median and mean values and the related useful sources.

	Embodied energy (MJ/t/km)	***Embodied carbon (kg CO_2 eq/t/km)***	***Source***
Marine shipment	0.20	0.0327	Chang et al. (2019) Wang et al. (2018)
	0.16	0.0330	
Median	*0.18*	*0.0329*	
Mean	*0.17*	*0.0329*	
Railway	0.22	0.017	Gan et al. (2017a) Wang et al. (2018)
Road -truck	3.10	0.0835	Chang et al. (2019) Ghayeb et al. (2020) Jia Wen et al. (2015) Li et al. (2019) Liu et al. (2016) Monahan and Powell (2011) Paulsen and Sposto (2013) Peng (2016) Scheuer et al. (2003) Svajlenka and Kozlovska (2017) Wang et al. (2018) Wu et al. (2012) Yang et al. (2018) Yu et al. (2011)
	2.42	0.1281	
	2.30	0.1500	
	2.14	0.1286	
	1.62	0.1680	
	1.40	0.0942	
	1.09	1.2065	
Median	*2.14*	*0.1286*	
Mean	*2.01*	*0.2798*	

Median	*2.14*	*0.1286*	Wang et al. (2018) Wu et al. (2012)
Mean	*2.01*	*0.2798*	Yang et al. (2018) Yang et al. (2018) Yu et al. (2011)

Table 3 – Embodied energy and carbon of transport by marine shipment, railway and road, including median values and sources.

4. Results and discussion

4.1. Making sense of the impact of structural materials – from mass to specific strength

A limited number of cases employed the volume (in m^3) of concrete as a functional unit to measure its environmental footprint (for example Gan et al. (2017b), Teh et al. (2017)). More often, the chosen functional unit was the mass of materials, expressed in kg. Therefore, in section 3.3, we followed the literature and calculated the energy and carbon embodied to produce 1 kg of concrete, timber and steel. It should be recognised, though that this might be misleading. The design of a typical structural element (a beam, or a column) must primarily take into account its load-bearing capacity, its structural strength and its strength at failure point. In normal circumstances, its mass must be optimized only to reduce any additional load. In other words, the mass of a structural element – or of a structural material – says little about its function as a structural component.

To address this issue, we shift the functional unit of concrete, timber and steel from mass to specific strength[1]. Specific strength can be defined as the force per unit area at failure (measured in kN/m^2), divided by the density of the material (measured in kg/m^3). This new functional unit is measured in (kN m)/kg, and, in considering the strength of the materials, it better suits the purpose of analysing the impact of structural materials.

Shifting the functional units can be done by dividing the previously calculated embodied energy and carbon of concrete, timber and steel by their specific strength. This means that the new functional units of embodied energy and carbon are MJ/(kN m) and kg CO_2 eq/(kN m), respectively (the results are summarized in Table 4).

[1] To be precise, the functional unit shifts from mass to specific strength per unit of mass, or from kg to kN m. For the sake of simplicity, we refer to it as specific strength.

The new functional unit helps in understanding the impact of structural materials. Specifically, in terms of embodied energy, timber impacts about a 54% concrete and 10% of steel in terms of embodied energy, and only 17% of concrete and 7% of steel in terms of embodied carbon. In combination with the fact that typically steel structures are built with the support of substantial amounts of concrete, this results confirms (cf section 3.4.1) that timber structures help decrease buildings' environmental impact, especially in terms of embodied carbon.

Table 4 – Embodied energy and carbon of concrete, timber (radiata pine) and structural steel with the varied functional unit.

	Strength at failure (MN/m^2)	***Density (kg/m3)***	***Specific strength (kN m/kg)***	***Embodied energy (MJ/kg)[1]***	***Embodied carbon (kg CO_2 eq/kg)[1]***	***Embodied energy (kJ/(kN m))[2]***	***Embodied carbon (CO_2 eq/(kN m))[2]***	***Sources***
Concrete – M35	35.0	2400.0	14.6	1.1	0.19	75.4	13.71	Bischoff and Perry (1991) Vecchio and Collins (1986)
Timber – pine	78.0	400.0	195.0	8.0	0.45	41.0	2.30	Tsoumis (1991) Chauhan and Walker (2006)
Structural steel	505.0	8000.0	64.7	25.5	2.20	404.0	34.85	Ames et al. (2011)

[1] Median values of embodied energy and carbon discussed in Section 3.3.
[2] Embodied energy and carbon expressed in the new unit prefix (from MJ to kJ and from k CO_2 eq to CO_2 eq) to improve readability of these smaller values.

4.2. Classifying the impact of buildings – A procedural guideline

The main goal of this paper is to create a procedural guideline that is of benefit for future practitioners in three ways. First, the guideline can help LCA practitioners to classify their results in a ranking chart, providing the structural material is concrete, timber or steel. Second, the guideline can help develop strategies to diminish the environmental impact of the used materials. This matters especially in consideration of the end of life stage, next product and waste management. Third, the ranking chart helps practitioners to identify whether their case studies are outliers because their impact is particularly low, standing below a provided limit, or excessive, meaning that the LCA is leaving room for improvement (or that the practitioners could have made a mistake in their LCA).

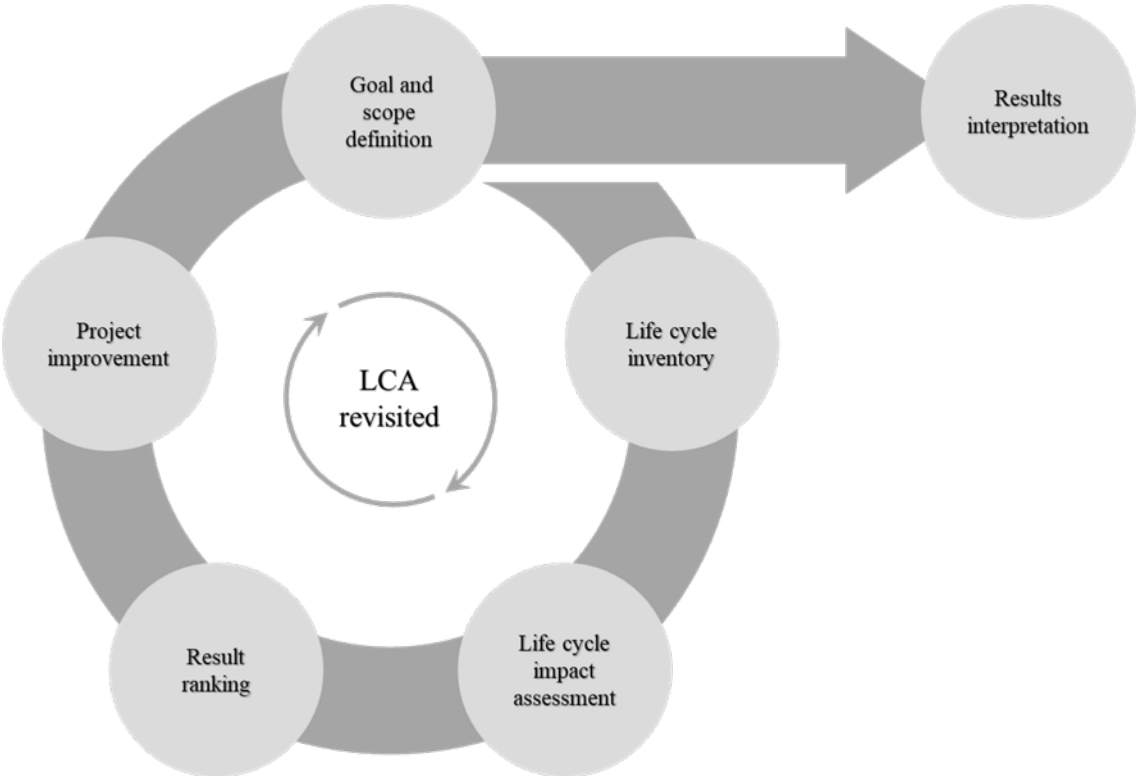

Figure 14 – LCA revisited with the addition of our Result ranking and Project improvement steps.

The procedural guideline is based on the extensively applied LCA method and expands it with the addition of two steps: ranking and improvement (Figure 14).

4.2.1. Result ranking

The result ranking step follows the life cycle impact assessment step, in which the results of the application of the LCA to the studied building are obtained first. The value obtained could fall into one of the six possible sections of Figure 15. To rank the results obtained through the previous LCA steps, the values in Figure 16 can be used. These values were calculated in considering the sum of the results obtained for all the four life cycle stages considered.

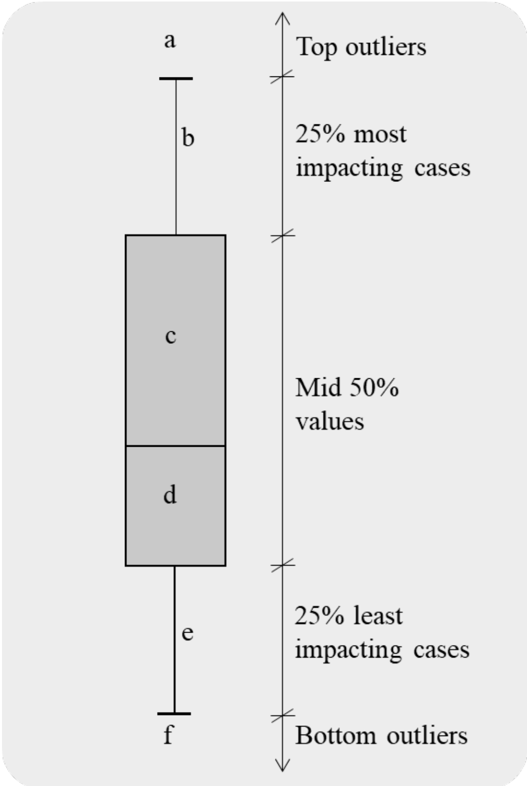

Figure 15 – Six different scenarios of building impact ranking.

In summary:

a) Results in this section are highly impacting outliers. These buildings embody an excessive amount of energy and carbon. This could be due to factors such as the amount of non-recyclable materials used, non-optimised material use and long-distance transport. These buildings can be improved by following the suggestions proposed in the next LCA step (project improvement). A check of the calculation is recommended.

b) Results that fall into this category belong to the 25% of the most impacting buildings analysed. Practitioners should consider applying the strategies proposed in the next LCA step (project improvement) to decrease their environmental impact.

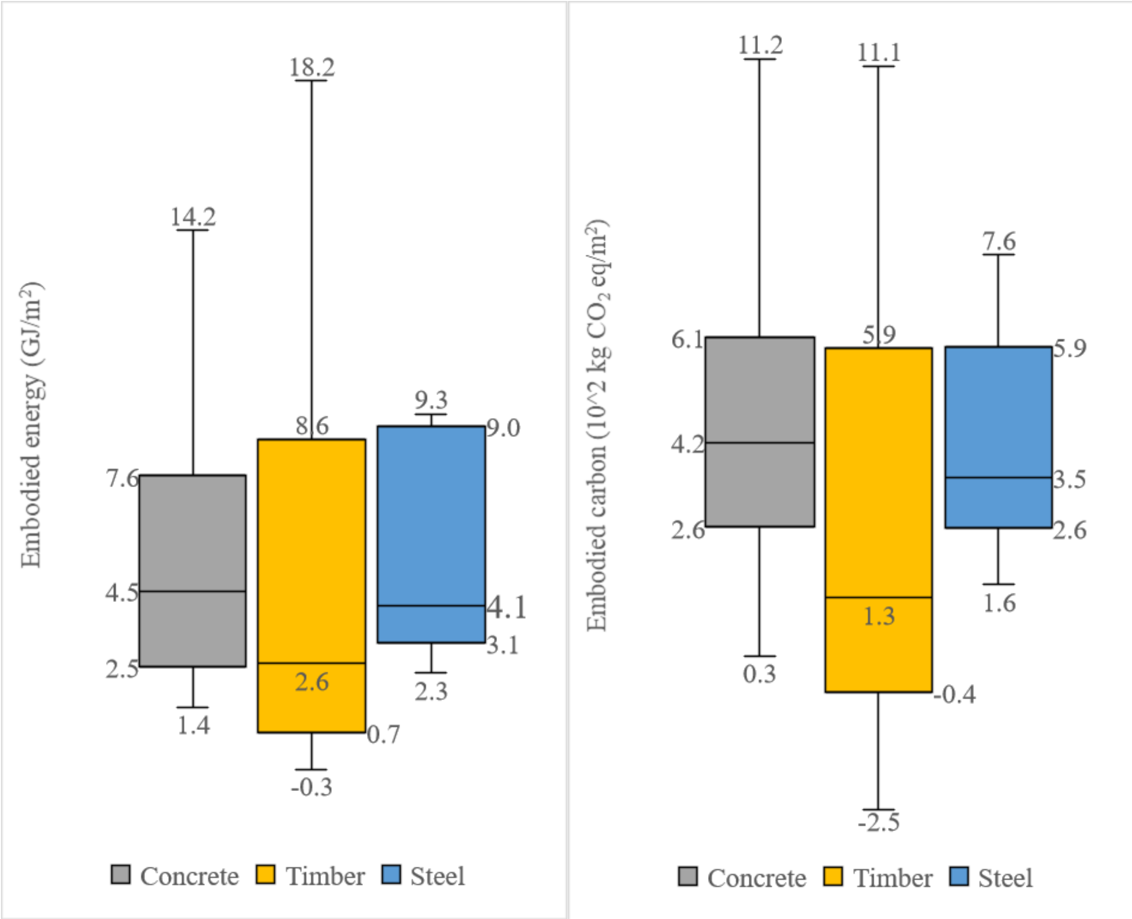

Figure 16 – Box whiskers plot of embodied energy (left) and embodied carbon (right) of the building results collected in three construction materials: concrete, timber and steel.

c & d) These sections include the interquartile range of results, or the 50% of the results that are closer to the median value. A building whose impacts are within these groups are considered average, however improvements are strongly recommended.

e) Buildings whose results fall into this section are considered the lowest impacting cases. The practitioners could decide to test the outcome of applying strategies proposed in the project improvement step to decrease the impact of the studied building.

f) LCAs that result in this section are characterized by a substantially low impact, and, although the strategies proposed in the project improvement step could still be applied, these might not result in great improvements. Because studies in this category are considered outliers, we recommend checking calculations, as they might be flawed.

4.2.2. Project improvement

In the project improvement stage the practitioners are celled to apply one or more of the following strategies that have been distilled from the shortlisted articles.

Table 5 summarizes the strategies, the percentage of the impact that could be saved by adopting them, and selected references. These percentages represent the possible savings of embodied energy and carbon over the whole buildings.

Table 5 – Strategies to decrease the buildings' embodied energy and carbon, and their percentual savings.

Strategy	***Saving of EE (%)***	***Saving of EC (%)***	***Notes***	***Sources***
1. Material substitution				
Timber in place of concrete	43	68	Results calculated for a mix of CLT and timber studs, joists and trusses structures. Timber structure usually involve substantial amount of concrete. End of life and next product stages not included.	Ajayi et al. (2016) Ajayi et al. (2019) Å vajlenka et al. (2017) Azzouz et al. (2017) Cornaro et al. (2020) Guo et al. (2017) Svajlenka and Kozlovska (2017) Takano et al. (2014) Tavares et al. (2019)
Steel in place of concrete	9	15	Steel structure usually involve substantial amount of concrete. End of life and next product stages not included.	
2. Recycle				
Concrete	-5÷29	6÷18	Recycling concrete is related to a negative saving, meaning that this operation has an adverse environmental impact. Further, although the literature refers to recycling of concrete, concrete is usually down-cycled into aggregates.	Blengini (2009) Chang et al. (2019) Chau et al. (2012) Gan et al. (2017b) Gao et al. (2001) Li and Altan (2012) Liu et al. (2016) Yan et al. (2010) Thormark (2002)
Timber	7÷22	15÷200	Recyclability of timber products varies substantially between countries and regulations. Some studies considered energy and carbon recovery using timber as fuel as a recycling strategy.	
Steel	40÷45	22÷60	Up to 80% of steel is typically recycled into new material, which maintain the structural characteristics of virgin steel.	
3. By-product integration and cement substitution	16÷33	21÷63	Results related to the substitution of different amounts of by-products (i.e. Bayer liquor[b], fly ash, volcanic ash, ground granulated blast-furnace slag) instead of cement into concrete. Cement's EC is 248 higher than graphene nanoplatelets' EC, which is a safe substitution in concrete.	Jamieson et al. (2015) Gan et al. (2017b) Kupwade-Patil et al. (2018) Papanikolaou et al. (2019) Teh et al. (2017)
4. Design for disassembly and reuse	81	18÷70	Although the literature suggests that concrete structures can be reused	Aye et al. (2012) Cruz Rios et al. (2019) Dara et al. (2019)

			multiple times, specific regulations could depend on counties.	Eberhardt et al. (2019)
5. Change of means of transport [c]	92	20÷74	The environmental impact of transport could undermine the savings due to recycling and reuse practices. Percentages calculated for the same number of km in comparing marine shipping with transport by truck.	Cruz Rios et al. (2019) Gan et al. (2017b) Paulsen and Sposto (2013) Peng (2016) Svajlenka and Kozlovska (2017) Yang et al. (2018) Yu et al. (2011)

[a] *Recycling concrete yields a negative saving, meaning that this operation has an adverse environmental impact in terms of EC. Further, although the literature refers to recycling of concrete, concrete is usually down-cycled into aggregates.*
[b] *Bayer liquor is by-product derived from processing of bauxite to alumina.*
[c] *The savings due to changes of means of transport are intended over the median impact of transports, not over the whole building.*

Strategy 1. Material substitution

Timber in place of concrete. The most commonly applied strategy to diminish buildings' impact is material substitution (Azzouz et al., 2017; Motuzienė et al., 2016; Salazar and Meil, 2009). More specifically, to decrease buildings' impact, timber is preferred over both concrete and steel. Depending on the dimensions of the building, cross laminated timber has been used in high-rise structures (up to 53 meters, 18 floors; see Pei et al. (2016)) because of its high structural resistance (Lukacs et al., 2019). Engineered timber can be employed in low- to mid-rise structures (up to 30 meters, 6 floors; see Tollefson (2017)). A less popular, yet promising type of material is agricultural waste products such as straw bales, which could substitute concrete and other traditional materials, and in doing so, diminish the carbon emissions by storing carbon in its structure (Cornaro et al., 2020; Sodagar et al., 2011). Using timber instead of concrete, whenever feasible, allows a decrease in buildings' environmental impact up to 43% in terms of embodied energy and 68% in terms of embodied carbon.

Steel in place of concrete. Substituting concrete with steel is a popular approach when it comes to comparing the LCA of buildings, although it has proven to offset buildings' impact in only a limited number of cases (including, for example Azzouz et al. (2017) and Tavares et al. (2019)). The main issue related to steel structures is that, in high-rise buildings, it still requires a considerable amount of concrete both in foundations and in supporting components, such as load-bearing staircases (Li and Altan, 2012; Takano et al., 2014). It is worth noting that, despite the impact of steel and concrete being similar in terms of embodied energy and carbon, steel structures have several advantages over concrete. For example, they are usually lighter, requiring less material and in turn decreasing material depletion (Azzouz et al., 2017). Steel components are manufactured in controlled factories, with lean production systems that help save waste (Heravi et al., 2020). They can be employed in modular buildings, which are quicker to build, which entails less site and surrounding disruption (Aye et al., 2012). Further, steel is preferred when it comes to material separation and recycling (Allwood, 2014). Because of the considerable amount of concrete that is still required in steel constructions, this strategy helps reduce buildings' impact up to 9% in terms of embodied energy and 15% in terms of embodied carbon.

Strategy 2. Recycle

Recycled concrete. Recycling is often associated with the circular economy concept, the practice of turning waste into new resources (Nußholz et al., 2019). Although recycling implies substantial amounts of materials saved from landfill, this practice often under-delivers. Concrete, for example, is not fully recyclable, as, after the recycling process, its next product—typically aggregates such as gravel—has inferior structural qualities (Xiao et al., 2018). Further, concrete made from recycled components often requires virgin components, such as cement. Down-cycling is the preferred term to describe this process (Zhao et al., 2020). Moreover, recycling concrete has proven to allow savings in terms of embodied energy and carbon in only a limited number of cases Chau et al. (2012). Overall, recycling concrete allows a range of saving between -5% and 29% in terms of embodied energy and between 6% and 18% in terms of embodied carbon.

Recycled timber. Similarly, timber is a down-cyclable material. It could be down-cycled, but often paints, glues and other chemicals used to protect the components during the building operation hinder the feasibility of timber recycling. End-of-life strategies of timber components include reprocessing it as a fibrous material, burnt or convert it to a gaseous or liquid fuel (Ramage et al., 2017). In terms of embodied energy, these practices allow a saving between 7% and 22% in terms of embodied energy, and between 15% and 200% in terms of embodied carbon. In considering turning timber into a fuel, this last extreme amount is obtained in calculating the CO_2 that would have been emitted to produce the same heat with similar non-renewable fuel.

Recycled steel. Recycled steel produces a material with structural characteristics similar to virgin steel. To date, steel recycling is considered (one of) the best end-of-life strategy of construction materials (Azzouz et al., 2017; Scheuer et al., 2003). This is because of both its considerable savings in terms of embodied energy (between 40% and 45%) and embodied carbon (up to 60%), and because nearly 100% of steel scrap can be reintegrated into new steel (Gan et al., 2017b).

Strategy 3. By-product integration and cement substitution

The environmental impact of concrete is largely due to the impact of cement (Abrão et al., 2020). For this reason, integration of industrial waste as by-products into concrete could be a successful strategy to decrease the cement-ratio in concrete, and at the same time manage waste from other industries (Teh et al., 2017). Slag, in different forms such as ground granulated slag from blast-furnace could be used in concrete structures in place of up to 75% of cement. This helps to diminish the overall embodied carbon of concrete production by up to 66% (Gan et al., 2017b; Saade et al., 2014). Bayer liquor, which results from the production of alumina, can be used to substitute cement into concrete, and it helps decrease the embodied energy of up to 33% of concrete made with Portland cement (Jamieson et al., 2015). Similarly, up to 35% of fly ash could successfully be used instead of cement into concrete production, without affecting the structural characteristics of concrete. The concrete prepared with fly ash could impact up to 33% less than concrete mixed with cement only (Gan et al., 2017b).

Interestingly, not only by-products are used as cement substitution. Researchers are experimenting innovative materials to substitute cement into concrete. One of these, Pozzolanic volcanic ash, could take the place of up to 50% of cement in concrete. Doing so decreases concrete's embodied energy by up to 16% (Kupwade-Patil et al., 2018). Another novel material, graphene nanoplatelet could be used to substitute up to 5% of cement in reinforced concrete, resulting in 21% reduction of concrete's embodied carbon (Papanikolaou et al., 2019).

Strategy 4. Design for disassembly and reuse

Design for disassembly is a promising strategy to reuse components as they are or with little modifications (Allwood, 2014; Kamali and Hewage, 2016). Reuse of building components has the potential to drastically decrease buildings' impact, as reused components would require little modification from their original shape and structure (Tumminia et al., 2018). Therefore, once disassembled and adapted, these components could be reintegrated into the market of construction materials (Cruz Rios et al., 2019). This strategy could be applied to both panels or volumetric prefabricated constructions, such as modular buildings, but at the time of this writing, it is still under-researched and only a limited number of cases surfaced in this meta-analysis (Dara and Hachem-Vermette, 2019). Despite the limited research on disassembly and reuse, in some cases it proved a decrease of up to 81% in terms of embodied energy and 70% in terms of embodied carbon (Aye et al., 2012).

Strategy 5. Change of means of transport

The impact of material transport varies substantially depends on the geographical location of the building and the means of transport. The means of transport can increase the overall embodied energy and carbon from as little as 0.04% to 8.4% in terms of embodied carbon and energy respectively (Paulsen and Sposto, 2013; Yang et al., 2018). Three main means of transport can be employed for construction materials: road/truck, railway and marine shipping. Although marine shipping is, for some countries, the only available option for sourcing materials (Emami et al., 2016), in other cases it could also help decrease the impact of building for two main reasons. First, our results prove that marine shipping impacts only about 8% in terms of embodied energy and 26% in terms of embodied carbon, when compared to transport by truck (Chang et al., 2019; Wang et al., 2018). Therefore, for every 100km of transport by road, materials could be sourced from distances of up to 400km by sea, producing half of the impact in terms of embodied energy, and the same impact in terms of embodied carbon (Scheuer et al., 2003; Yu et al., 2011). Second, sourcing from overseas often allows designers to choose from a greater variety of products than those which would be available locally (Häfliger et al., 2017; Thormark, 2006). This could help designers find and consider materials with a lower environmental footprint.

5. Suggestions to LCA practitioners

5.1. Considerations on functional units

Substantial efforts are required throughout the LCA steps. Gathering accurate data, choosing the appropriate software, calculation method, impact databases, analysing the results and consideration of possible improvements – LCAs can be overwhelming processes. Among these steps, the importance of selecting the most appropriate functional unit could easily be disregarded. As we have illustrated in this article, however, functional units could drastically change the results of an LCA. Studying the impact of producing 1 kg of a material could be useful to compare the environmental impact of materials that have the same function. Conversely, it would give little information on the product whose function and use are substantially different. Therefore, we suggest future LCA practitioners to adopt and test results according to two or more functional units: if a selected functional unit is used to measure the mass of materials, another functional unit should be employed to evaluate their actual use.

5.2. Notes on transparency

Transparency when reporting the data collection process, buildings dimensions and material amounts is necessary to create knowledge more rigorously (Sovacool et al., 2018). The most effective way to improve transparency is by reporting all the steps taken during an LCA, related data input and results (Nwodo and Anumba, 2019; Saade et al., 2020). Many of the studies collected in this SLR followed this criterion, by reporting the amount of materials related and results thoroughly (for example Monahan and Powell (2011), Padilla-Rivera et al. (2018), Sicignano et al. (2019) and Wang et al. (2018)). This exhaustive reporting adds three main benefits to an LCA. First, listing the methodological details, bills of materials, transport distances and other details allows other practitioners to repeat the same method and customize their future results. This is beneficial because it helps to add findings on top of previously built knowledge. Second, the transparency in methodological choices helps to compare results of similarly defined methods. Comparison of results, in turn, helps researchers to test and validate their own results. Third, articles that report with transparency their LCA steps, methods and data input and results are considered more rigorous and trustworthy.

6. Conclusions

6.1. Summary

This review collects, summarizes and reports the results of a meta-analysis of 159 academic articles on LCA. From these articles, we distilled 630 results, of which 332 are related to eight construction materials and 292 to buildings' embodied energy and carbon. From the empirical evidence, we provide a summary of the energy and carbon embodied in construction materials and buildings. Data on construction materials show that producing 1 kg of concrete is associated with minor adverse environmental impact (1.11 MJ/kg, or 0.19 kg CO_2 eq/kg). This result is consistent with the literature and suggests that concrete is between three and eight times more sustainable than timber as a structural material. In stark contrast, however, when the functional unit employed in an LCA takes into consideration the specific strength of a material, substituting concrete with timber reduces the expended embodied energy and carbon by 46% and 83%, respectively. Literature on LCAs of bare building structures confirm these results. In exploring the use of construction materials in the structure of entire buildings, we found that timber structures have a reduced impact of 57% and 68% compared to concrete constructions in terms of embodied energy and carbon.

Further, the literature shows that steel is another promising structural material that is often associated with lower environmental impact than concrete. This is not only because less energy and carbon are embodied during its production phases, but also because of its recyclability and versatility (Tingley et al., 2017). Steel can be recycled infinite times without impacting its mechanical characteristics, which can contribute to a decrease in the environmental impact of steel products (Cao et al., 2015; Su et al., 2016). Additionally, steel's versatility allows designers to create disassemblable and reusable structures (Akanbi et al., 2019; Aye et al., 2012; Sanchez and Haas, 2018).

Following the observations on construction materials' and buildings' environmental impact, the combination of the SLR and meta-analysis of related literature allowed us to produce a practical guideline to assist LCA practitioners that aim to compare and diminish the adverse impact of their analysed building. The guideline unfolds in two steps. In the first step we propose a ranking system of buildings' embodied energy and carbon. LCA practitioners can use the ranking system to compare the preliminary results of their LCAs with the results we comprehensively collected in this review. In so doing, practitioners can demonstrate the validity of their results. In the second step we suggest several strategies to diminish buildings' impact. We linked these strategies with the related savings in terms of embodied energy and carbon that emerged from our meta-analysis to further inform the LCA practitioners of how much saving can be yielded by each strategy. In so doing, we make significant theoretical and practical contributions, which we outline in more detail in the following sub-section.

6.2. Main contributions

We make three main contributions to the body of knowledge concerned with LCAs in the building context. First, we make a conceptual contribution by defining and adding new procedural guidelines to the established LCA method. Our simple two-step procedural guideline is designed to help LCA practitioners to rank and improve their LCA results. In the first step, LCA practitioners can compare their results with those obtained in the identified 292 LCAs. This step helps overcome several difficulties that are typically found when comparing LCA results (for an overview of these difficulties, we refer to Cabeza et al. (2014), Eberhardt et al. (2019), Hu (2019) and Nwodo and Anumba (2019)). For example, functional units could be poorly aligned between similar LCA reports: when a study selects 1 m^2 of usable area, another might use the weight of materials used, or the entire area of the studied building. The project improvement step suggests five strategies that could be applied to a building to decrease its embodied energy and carbon. In carrying out a meta-analysis of relevant quantitative data, we linked these strategies with their expected percentage of savings. In summary, this step reveals that, for example, substituting cement with by-product integration could yield savings of up to 33% saving in terms of embodied energy and up to 63% in terms of embodied carbon. Or, designing a building for disassembly and reuse allows a saving of up to 81% of embodied energy and 70% of embodied carbon. In so doing, we provide the LCA practitioners with a preliminary insight of the amount of savings that each strategy enables. We designed the proposed procedural guidelines to be integrated with any standard LCA method; specifically, the two steps follow the traditional life cycle inventory analysis step. The integration of our guideline with the LCA method allows LCA practitioners to adopt our guideline in juxtaposition with the standard iterative and recursive LCA method. Such juxtaposition is beneficial to the practitioners because it allows the practitioners to integrate our suggested guideline into their LCAs using the same data that had been collected and maintaining the goal and scopes as they had already been defined.

Our second contribution is empirical. Through our meta-analysis, we help in comparing and controlling the environmental impact of construction material and buildings. Further, in making sense of the embodied energy and carbon related to the construction sector, we inform scholars, practitioners and policy makers on the impact related to different materials. Our findings could thus be beneficial to anyone seeking to make evidence-based choices on new or existing policies on construction materials production, building maintenance and end of life practices.

Our third contribution consists in identifying and describing patterns and correlation between the 630 results of the LCAs that we collected and analysed. These results contribute to further corroborate and validate the usefulness of applying LCAs in a building context thus supporting several previous findings and contentions (e.g. Bakhshi and Sharon (2009), Rashid and Yusoff (2015) and Sharma et al. (2011)). More specifically, the narrow interquartile ranges and the presence of only a few outliers amongst the analysed LCA results suggest that the data are homogeneously clustered around the median values examined. Such homogeneity confirms that LCA is a potentially invaluable tool to quantify buildings' environmental footprint.

Although we have gone some way towards resolving underlying uncertainties related to LCA results and helping practitioners to predict the outcomes of their LCAs, more research is needed to drastically decrease the impact that buildings have on the environment. The commitment of future scholars and practitioners could be the decisive factor in the race for a greener and more sustainable built environment. Therefore, we suggest further research to examine the impact of buildings' operations and logistics, include in their studies additional environmental indicators and push the boundaries of the here reviewed LCA method.

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References

Å vajlenka, J., Kozlovská, M., Spišáková, M., 2017. The benefits of modern method of construction based on wood in the context of sustainability. International journal of environmental science and technology. 14, 1591-1602. http://dx.doi.org/10.1007/s13762-017-1282-6.

Abrão, P.C.R.A., Cardoso, F.A., John, V.M., 2020. Efficiency of Portland-pozzolana cements: Water demand, chemical reactivity and environmental impact. Construction and Building Materials. 247, 118546. https://doi.org/10.1016/j.conbuildmat.2020.118546.

Adhikari, S., Ozarska, B., 2018. Minimizing environmental impacts of timber products through the production process "From Sawmill to Final Products". Environmental Systems Research. 7, 6. 10.1186/s40068-018-0109-x.

Ahmed, I.M., Tsavdaridis, K.D., 2018. Life cycle assessment (LCA) and cost (LCC) studies of lightweight composite flooring systems. Journal of Building Engineering. 20, 624-633. https://doi.org/10.1016/j.jobe.2018.09.013.

Ajayi, S.O., Oyedele, L.O., Ilori, O.M., 2019. Changing significance of embodied energy: A comparative study of material specifications and building energy sources. Journal of Building Engineering. 23, 324-333. 10.1016/j.jobe.2019.02.008.

Ajayi, S.O., Oyedele, L.O., Jaiyeoba, B., Kadiri, K., David, S.A., 2016. Are sustainable buildings healthy? An investigation of lifecycle relationship between building sustainability and its environmental health impacts. World Journal of Science Technology and Sustainable Development. 13, 190-204. 10.1108/wjstsd-01-2016-0015.

Akanbi, L.A., Oyedele, L.O., Omoteso, K., Bilal, M., Akinade, O.O., Ajayi, A.O., Davila Delgado, J.M., Owolabi, H.A., 2019. Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. Journal of Cleaner Production. 223, 386-396. https://doi.org/10.1016/j.jclepro.2019.03.172.

Allwood, J.M., 2014. Chapter 30 - Squaring the Circular Economy: The Role of Recycling within a Hierarchy of Material Management Strategies, in: Worrell, E., Reuter, M.A. (Eds.), Handbook of Recycling. Elsevier, Boston, pp. 445-477.

Ames, D., Droessler, T., Hoit, M., 2011. Structures Congress 2011. American Society of Civil Engineers.

Asdrubali, F., Baggio, P., Grazieschi, G., Guattari, C., Prada, A., 2019. Dynamic life cycle assessment modelling of a NZEB building. Energy. http://dx.doi.org/10.1016/j.energy.2019.116489.

Asif, M., Muneer, T., Kelley, R., 2007. Life cycle assessment: A case study of a dwelling home in Scotland. Building and Environment. 42, 1391-1394. 10.1016/j.buildenv.2005.11.023.

Aste, N., Adhikari, R.S., Buzzetti, M., 2010. Beyond the EPBD: The low energy residential settlement Borgo Solare. Applied Energy. 87, 629-642. 10.1016/j.apenergy.2009.05.029.

Atmaca, A., Atmaca, N., 2015. Life cycle energy (LCEA) and carbon dioxide emissions (LCCO2A) assessment of two residential buildings in Gaziantep, Turkey. Energy and Buildings. 102, 417-431. https://doi.org/10.1016/j.enbuild.2015.06.008.

Atmaca, N., 2017. Life-cycle assessment of post-disaster temporary housing. Building Research and Information. 45, 524-538. http://dx.doi.org/10.1080/09613218.2015.1127116.

Aye, L., Ngo, T., Crawford, R.H., Gammampila, R., Mendis, P., 2012. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. Energy and buildings. 47, 159-168. doi.org/10.1016/j.buildenv.2019.106290.

Azzouz, A., Borchers, M., Moreira, J., Mavrogianni, A., 2017. Life cycle assessment of energy conservation measures during early stage office building design: A case study in London, UK. Energy and Buildings. 139, 547-568. https://doi.org/10.1016/j.enbuild.2016.12.089.

Bakhshi, A.A., Sharon, M., 2009. A GIS methodology for estimating the carbon footprint in municipal water ana wastewater in Fairfax county, Virginia. Energy Engineering. 106, 7-24. doi.org/10.1080/01998590909594541.

Baumeister, R.F., Leary, M.R., 1997. Writing Narrative Literature Reviews. Review of General Psychology. 1, 311-320. 10.1037/1089-2680.1.3.311.

Bischoff, P.H., Perry, S.H., 1991. Compressive behaviour of concrete at high strain rates. Materials and Structures. 24, 425-450. 10.1007/BF02472016.

Biswas, K., Shrestha, S.S., Bhandari, M.S., Desjarlais, A.O., 2016. Insulation materials for commercial buildings in North America: An assessment of lifetime energy and environmental impacts. Energy and Buildings. 112, 256-269. https://doi.org/10.1016/j.enbuild.2015.12.013.

Biswas, W.K., 2014. Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. International Journal of Sustainable Built Environment. 3, 179-186. 10.1016/j.ijsbe.2014.11.004.

Björklund, A.E., 2002. Survey of approaches to improve reliability in LCA. The International Journal of Life Cycle Assessment. 7, 64. htto://dx.doi.org/10.1065/Ica2001.12.071

Blengini, G.A., 2009. Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. Building and Environment. 44, 319-330. 10.1016/j.buildenv.2008.03.007.

Brambilla, G., Lavagna, M., Vasdravellis, G., Castiglioni, C.A., 2019. Environmental benefits arising from demountable steel-concrete composite floor systems in buildings. Resources, Conservation and Recycling. 141, 133-142. https://doi.org/10.1016/j.resconrec.2018.10.014.

Bribian, I.Z., Capilla, A.V., Uson, A.A., 2011. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and Environment. 46, 1133-1140. 10.1016/j.buildenv.2010.12.002.

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and sustainable energy reviews. 29, 394-416. https://doi.org/10.1016/j.rser.2013.08.037.

Cao, X., Li, X., Zhu, Y., Zhang, Z., 2015. A comparative study of environmental performance between prefabricated and traditional residential buildings in China. Journal of Cleaner Production. 109, 131-143. https://doi.org/10.1016/j.jclepro.2015.04.120.

Chang, C.C., Shi, W., Mehta, P., Dauwels, J., 2019. Life cycle energy assessment of university buildings in tropical climate. Journal of Cleaner Production. 239. 10.1016/j.jclepro.2019.117930.

Chang, Y., Ries, R.J., Lei, S., 2012. The embodied energy and emissions of a high-rise education building: A quantification using process-based hybrid life cycle inventory model. Energy and Buildings. 55, 790-798. https://doi.org/10.1016/j.enbuild.2012.10.019.

Chau, C.K., Hui, W.K., Ng, W.Y., Powell, G., 2012. Assessment of CO 2 emissions reduction in high-rise concrete office buildings using different material use options. Resources, Conservation and Recycling. 61, 22-34. 10.1016/j.resconrec.2012.01.001.

Chau, C.K., Xu, J.M., Leung, T.M., Ng, W.Y., 2017. Evaluation of the impacts of end-of-life management strategies for deconstruction of a high-rise concrete framed office building. Applied Energy. 185, 1595-1603. 10.1016/j.apenergy.2016.01.019.

Chauhan, S.S., Walker, J.C.F., 2006. Variations in acoustic velocity and density with age, and their interrelationships in radiata pine. Forest Ecology and Management. 229, 388-394. https://doi.org/10.1016/j.foreco.2006.04.019.

Cohen, J., 1960. A coefficient of agreement for nominal scales. Educational and psychological measurement. 20, 37-46. doi.org/10.1177/001316446002000104.

Cohen, J., 1968. Weighted kappa: nominal scale agreement provision for scaled disagreement or partial credit. Psychological bulletin. 70, 213. https://doi.org/10.1037/h0026256.

Cornaro, C., Zanella, V., Robazza, P., Belloni, E., Buratti, C., 2020. An innovative straw bale wall package for sustainable buildings: experimental characterization, energy and environmental performance assessment. Energy and Buildings. 208, 1. http://dx.doi.org/10.1016/j.enbuild.2019.109636.

Crawford, R.H., 2014. Post-occupancy life cycle energy assessment of a residential building in Australia. Architectural Science Review. 57, 114-124. 10.1080/00038628.2013.819556.

Cruz Rios, F., Chong, W.K., Grau, D., 2019. Reusing exterior wall framing systems: A cradle-to-cradle comparative life cycle assessment. Waste management. 94, 120-135. http://dx.doi.org/10.1016/j.wasman.2019.05.040.

D'Amico, A., Ciulla, G., Traverso, M., Lo Brano, V., Palumbo, E., 2019. Artificial Neural Networks to assess energy and environmental performance of buildings: An Italian case study. Journal of Cleaner Production. 239. 10.1016/j.jclepro.2019.117993.

Dara, C., Hachem-Vermette, C., 2019. Evaluation of low-impact modular housing using energy optimization and life cycle analysis. Energy, Ecology and Environment. 4, 286-299. 10.1007/s40974-019-00135-4.

Dara, C., Hachem-Vermette, C., Assefa, G., 2019. Life cycle assessment and life cycle costing of container-based single-family housing in Canada: A case study. Building and Environment. 163, 106332. https://doi.org/10.1016/j.buildenv.2019.106332.

Dean, B., Dulac, J., Petrichenko, K., Graham, P., 2016. Towards zero-emission efficient and resilient buildings.: Global Status Report.

Dong, Y., Qin, T., Zhou, S., Huang, L., Bo, R., Guo, H., Yin, X., 2020. Comparative whole building life cycle assessment of energy saving and carbon reduction performance of reinforced concrete and timber stadiums-a case study in China. Sustainability (Switzerland). 12, 1-24. 10.3390/su12041566.

Eberhardt, L.C.M., Birgisdottir, H., Birkved, M., 2019. Life cycle assessment of a Danish office building designed for disassembly. Building Research and Information. 47, 666-680. 10.1080/09613218.2018.1517458.

EeBGuide, 2011. EeBGuide Guidance Document - Part A: Products. https://www.eebguide.eu/eebblog/wp-content/uploads/2012/10/EeBGuide-A-FINAL-PR_2012-10-29.pdf. (Accessed April 2020.

Eleftheriadis, S., Duffour, P., Mumovic, D., 2018. BIM-embedded life cycle carbon assessment of RC buildings using optimised structural design alternatives. Energy and Buildings. 173, 587-600. https://doi.org/10.1016/j.enbuild.2018.05.042.

Emami, N., Marteinsson, B., Heinonen, J., 2016. Environmental Impact Assessment of a School Building in Iceland Using LCA-Including the Effect of Long Distance Transport of Materials. Buildings. 6. 10.3390/buildings6040046.

Fay, R., Treloar, G., Iyer-Raniga, U., 2000. Life-cycle energy analysis of buildings: a case study. Building Research and Information. 28, 31-41. 10.1080/096132100369073.

Feng, H.B., Liyanage, D.R., Karunathilake, H., Sadiq, R., Hewage, K., 2020. BIM-based life cycle environmental performance assessment of single-family houses: Renovation and reconstruction strategies for aging building stock in British Columbia. Journal of Cleaner Production. 250. 10.1016/j.jclepro.2019.119543.

Fenner, A.E., Kibert, C.J., Woo, J., Morque, S., Razkenari, M., Hakim, H., Lu, X., 2018. The carbon footprint of buildings: A review of methodologies and applications. Renewable and Sustainable Energy Reviews. 94, 1142-1152. https://doi.org/10.1016/j.rser.2018.07.012.

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., Klüppel, H.-J., 2006. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. The International Journal of Life Cycle Assessment. 11, 80-85. 10.1065/lca2006.02.002.

Galan-Marin, C., Martinez-Rocamora, A., Solis-Guzman, J., Rivera-Gomez, C., 2018. Natural Stabilized Earth Panels versus Conventional Facade Systems. Economic and Environmental Impact Assessment. Sustainability. 10. 10.3390/su10041020.

Gan, V.J.L., Chan, C.M., Tse, K.T., Lo, I.M.C., Cheng, J.C.P., 2017a. A comparative analysis of embodied carbon in high-rise buildings regarding different design parameters. Journal of Cleaner Production. 161, 663-675. 10.1016/j.jclepro.2017.05.156.

Gan, V.J.L., Cheng, J.C.P., Lo, I.M.C., 2019. A comprehensive approach to mitigation of embodied carbon in reinforced concrete buildings. Journal of Cleaner Production. 229, 582-597. 10.1016/j.jclepro.2019.05.035.

Gan, V.J.L., Cheng, J.C.P., Lo, I.M.C., Chan, C.M., 2017b. Developing a CO2-e accounting method for quantification and analysis of embodied carbon in high-rise buildings. Journal of Cleaner Production. 141, 825-836. 10.1016/j.jclepro.2016.09.126.

Gao, W., Ariyama, T., Ojima, T., Meier, A., 2001. Energy impacts of recycling disassembly material in residential buildings. Energy and Buildings. 33, 553-562. https://doi.org/10.1016/S0378-7788(00)00096-7.

Georges, L., Haase, M., Wiberg, A.H., Kristjansdottir, T., Risholt, B., 2015. Life cycle emissions analysis of two nZEB concepts. Building Research and Information. 43, 82-93. 10.1080/09613218.2015.955755.

Ghayeb, H.H., Razak, H.A., Sulong, N.H.R., 2020. Evaluation of the CO2 emissions of an innovative composite precast concrete structure building frame. Journal of Cleaner Production. 242. 10.1016/j.jclepro.2019.118567.

Gontia, P., Nägeli, C., Rosado, L., Kalmykova, Y., Österbring, M., 2018. Material-intensity database of residential buildings: A case-study of Sweden in the international context. Resources, Conservation and Recycling. 130, 228-239. https://doi.org/10.1016/j.resconrec.2017.11.022.

Guo, H., Huang, H., Liu, Y., Meng, Y., Sun, C., Shao, Y., 2017. A Comparison of the Energy Saving and Carbon Reduction Performance between Reinforced Concrete and Cross-Laminated Timber Structures in Residential Buildings in the Severe Cold Region of China. Sustainability. 9. http://dx.doi.org/10.3390/su9081426.

Gwet, K.L., 2008. Computing inter-rater reliability and its variance in the presence of high agreement. British Journal of Mathematical and Statistical Psychology. 61, 29-48. 10.1348/000711006X126600.

Häfliger, I.-F., John, V., Passer, A., Lasvaux, S., Hoxha, E., Saade, M.R.M., Habert, G., 2017. Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials. Journal of Cleaner Production. 156, 805-816. https://doi.org/10.1016/j.jclepro.2017.04.052.

Hassan, O.A., Öberg, F., Gezelius, E., 2019. Cross-laminated timber flooring and concrete slab flooring: A comparative study of structural design, economic and environmental consequences. Journal of Building Engineering. 100881. https://doi.org/10.1016/j.jobe.2019.100881.

Hay, R., Ostertag, C.P., 2018. Life cycle assessment (LCA) of double-skin façade (DSF) system with fiber-reinforced concrete for sustainable and energy-efficient buildings in the tropics. Building and Environment. 142, 327-341. https://doi.org/10.1016/j.buildenv.2018.06.024.

Heravi, G., Rostami, M., Kebria, M.F., 2020. Energy consumption and carbon emissions assessment of integrated production and erection of buildings' pre-fabricated steel frames using lean techniques. Journal of Cleaner Production. 253, 120045. https://doi.org/10.1016/j.jclepro.2020.120045.

Hölzle, I., 2019. Contaminant patterns in soils from landfill mining. Waste Management. 83, 151-160. https://doi.org/10.1016/j.wasman.2018.11.013.

Hossain, M.U., Poon, C.S., 2018. Global warming potential and energy consumption of temporary works in building construction: A case study in Hong Kong. Building and Environment. 142, 171-179. https://doi.org/10.1016/j.buildenv.2018.06.026.

Hossain, M.U., Poon, C.S., Lo, I.M.C., Cheng, J.C.P., 2016. Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. Resources, Conservation and Recycling. 109, 67-77. https://doi.org/10.1016/j.resconrec.2016.02.009.

Hoxha, E., Habert, G., Lasvaux, S., Chevalier, J., Le Roy, R., 2017. Influence of construction material uncertainties on residential building LCA reliability. Journal of Cleaner Production. 144, 33-47. https://doi.org/10.1016/j.jclepro.2016.12.068.

Hu, M., 2019. Building impact assessment—A combined life cycle assessment and multi-criteria decision analysis framework. Resources, Conservation and Recycling. 150, 104410. https://doi.org/10.1016/j.resconrec.2019.104410.

Iddon, C.R., Firth, S.K., 2013. Embodied and operational energy for new-build housing: A case study of construction methods in the UK. Energy and Buildings. 67, 479-488. https://doi.org/10.1016/j.enbuild.2013.08.041.

Invidiata, A., Lavagna, M., Ghisi, E., 2018. Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. Building and Environment. 139, 58-68. https://doi.org/10.1016/j.buildenv.2018.04.041.

Jamieson, E., McLellan, B., van Riessen, A., Nikraz, H., 2015. Comparison of embodied energies of Ordinary Portland Cement with Bayer-derived geopolymer products. Journal of Cleaner Production. 99, 112-118. https://doi.org/10.1016/j.jclepro.2015.03.008.

Jia Wen, T., Chin Siong, H., Noor, Z.Z., 2015. Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia. Energy and Buildings. 93, 295-302. https://doi.org/10.1016/j.enbuild.2014.12.002.

Kamali, M., Hewage, K., 2016. Life cycle performance of modular buildings: A critical review. Renewable and Sustainable Energy Reviews. 62, 1171-1183. https://doi.org/10.1016/j.rser.2016.05.031.

Kofoworola, O.F., Gheewala, S.H., 2009. Life cycle energy assessment of a typical office building in Thailand. Energy and Buildings. 41, 1076-1083. https://doi.org/10.1016/j.enbuild.2009.06.002.

Kupwade-Patil, K., De Wolf, C., Chin, S., Ochsendorf, J., Hajiah, A.E., Al-Mumin, A., Büyüköztürk, O., 2018. Impact of Embodied Energy on materials/buildings with partial replacement of ordinary Portland Cement (OPC) by natural Pozzolanic Volcanic Ash. Journal of Cleaner Production. 177, 547-554. https://doi.org/10.1016/j.jclepro.2017.12.234.

Li, H., Deng, Q., Zhang, J., Xia, B., Skitmore, M., 2019. Assessing the life cycle CO2 emissions of reinforced concrete structures: Four cases from China. Journal of Cleaner Production. 210, 1496-1506. https://doi.org/10.1016/j.jclepro.2018.11.102.

Li, S., Altan, H., 2012. Environmental Impact Balance of Building Structures and Substitution Effect of Wood Structure in Taiwan. International Journal of Environmental Protection. 2, 1. 10.5963/IJEP0201001.

Littell, J.H., Corcoran, J., Pillai, V., 2008. Systematic reviews and meta-analysis. Oxford University Press.

Liu, Y., Guo, H., Sun, C., Chang, W.-S., 2016. Assessing Cross Laminated Timber (CLT) as an Alternative Material for Mid-Rise Residential Buildings in Cold Regions in China—A Life-Cycle Assessment Approach. Sustainability. 8. http://dx.doi.org/10.3390/su8101047.

Lu, K., Jiang, X.Y., Tam, V.W.Y., Li, M.Y., Wang, H.Y., Xia, B., Chen, Q., 2019. Development of a Carbon Emissions Analysis Framework Using Building Information Modeling and Life Cycle Assessment for the Construction of Hospital Projects. Sustainability. 11. 10.3390/su11226274.

Lukacs, I., Björnfot, A., Tomasi, R., 2019. Strength and stiffness of cross-laminated timber (CLT) shear walls: State-of-the-art of analytical approaches. Engineering Structures. 178, 136-147. https://doi.org/10.1016/j.engstruct.2018.05.126.

Mackova, D., Spisakova, M., Kozlovska, M., Svajlenka, J., 2016. Environmental Assessment of Buildings Constructed by Modern Methods of Construction. Applied Mechanics and Materials. 861, 601-608. http://dx.doi.org/10.4028/www.scientific.net/AMM.861.601.

Melià, P., Ruggieri, G., Sabbadini, S., Dotelli, G., 2014. Environmental impacts of natural and conventional building materials: a case study on earth plasters. Journal of Cleaner Production. 80, 179-186. https://doi.org/10.1016/j.jclepro.2014.05.073.

Moazzen, N., Karaguler, M.E., Ashrafian, T., 2019. Assessment of the Life Cycle Energy Efficiency of a Primary School Building in Turkey. Applied Mechanics and Materials. 887, 335-343. http://dx.doi.org/10.4028/www.scientific.net/AMM.887.335.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., The, P.G., 2009. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLOS Medicine. 6, e1000097. 10.1371/journal.pmed.1000097.

Monahan, J., Powell, J.C., 2011. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. Energy and Buildings. 43, 179-188. https://doi.org/10.1016/j.enbuild.2010.09.005.

Motuzienė, V., Rogoža, A., Lapinskienė, V., Vilutienė, T., 2016. Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: a case study. Journal of Cleaner Production. 112, 532-541. https://doi.org/10.1016/j.jclepro.2015.08.103.

Moyano, M., Camporeale, P.E., Cozar-Cozar, E., 2019. ENVIRONMENTAL IMPACT ASSESMENT APPLYING INDICATORS EMBEDDED INTO A SOCIAL HOUSING BIM MODEL. Revista Habitat Sustentable. 9, 79-93. 10.22320/07190700.2019.09.02.07.

Nässén, J., Holmberg, J., Wadeskog, A., Nyman, M., 2007. Direct and indirect energy use and carbon emissions in the production phase of buildings: An input-output analysis. Energy. 32, 1593-1602. 10.1016/j.energy.2007.01.002.

Nizam, R.S., Zhang, C., Tian, L., 2018. A BIM based tool for assessing embodied energy for buildings. Energy and Buildings. 170, 1-14. https://doi.org/10.1016/j.enbuild.2018.03.067.

Nußholz, J.L.K., Nygaard Rasmussen, F., 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. 10.1016/j.resconrec.2018.10.036.

Nwodo, M.N., Anumba, C.J., 2019. A review of life cycle assessment of buildings using a systematic approach. Building and Environment. 162, 106290. https://doi.org/10.1016/j.buildenv.2019.106290.

Padilla-Rivera, A., Amor, B., Blanchet, P., 2018. Evaluating the Link between Low Carbon Reductions Strategies and Its Performance in the Context of Climate Change: A Carbon Footprint of a Wood-Frame Residential Building in Quebec, Canada. Sustainability. 10. 10.3390/su10082715.

Papanikolaou, I., Arena, N., Al-Tabbaa, A., 2019. Graphene nanoplatelet reinforced concrete for self-sensing structures – A lifecycle assessment perspective. Journal of Cleaner Production. 240. 10.1016/j.jclepro.2019.118202.

Pargana, N., Pinheiro, M.D., Silvestre, J.D., de Brito, J., 2014. Comparative environmental life cycle assessment of thermal insulation materials of buildings. Energy and Buildings. 82, 466-481. https://doi.org/10.1016/j.enbuild.2014.05.057.

Paulsen, J.S., Sposto, R.M., 2013. A life cycle energy analysis of social housing in Brazil: Case study for the program "MY HOUSE MY LIFE". Energy and Buildings. 57, 95-102. https://doi.org/10.1016/j.enbuild.2012.11.014.

Pei, S., Rammer, D., Popovski, M., Williamson, T., Line, P., van de Lindt, J.W., 2016. An overview of CLT research and implementation in North America. In: WCTE 2016, August 22-25, 2016 Vienna, Austria.

Peng, C., 2016. Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. Journal of cleaner production. 112, 453-465. http://dx.doi.org/10.1016/j.jclepro.2015.08.078.

Petrovic, B., Myhren, J.A., Zhang, X., Wallhagen, M., Eriksson, O., 2019. Life cycle assessment of a wooden single-family house in Sweden. Applied Energy. 251. 10.1016/j.apenergy.2019.05.056.

Pierobon, F., Huang, M., Simonen, K., Ganguly, I., 2019. Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest. Journal of Building Engineering. 26, 100862. https://doi.org/10.1016/j.jobe.2019.100862.

Pittau, F., Lumia, G., Heeren, N., Iannaccone, G., Habert, G., 2019. Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. Journal of Cleaner Production. 214, 365-376. https://doi.org/10.1016/j.jclepro.2018.12.304.

Qiangfeng, L., Weiqiong, Z., Gaoshang, W., Jinhua, C., Tao, D., Bojie, W., Liang, L., Qindong, Y., 2018. Material and value flows of iron in Chinese international trade from 2010 to 2016. Resources Policy. 59, 139-147. doi.org/10.1016/j.resourpol.2018.06.011.

Ramage, M.H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D.U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., Allwood, J., Dupree, P., Linden, P.F., Scherman, O., 2017. The wood from the trees: The use of timber in construction. Renewable and Sustainable Energy Reviews. 68, 333-359. https://doi.org/10.1016/j.rser.2016.09.107.

Rashid, A.F.A., Yusoff, S., 2015. A review of life cycle assessment method for building industry. Renewable & Sustainable Energy Reviews. 45, 244-248. http://dx.doi.org/10.1016/j.rser.2015.01.043.

Reap, J., Roman, F., Duncan, S., Bras, B., 2008. A survey of unresolved problems in life cycle assessment. The International Journal of Life Cycle Assessment. 13, 374. https://doi.org/10.1007/s11367-008-0009-9.

Robati, M., Daly, D., Kokogiannakis, G., 2019. A method of uncertainty analysis for whole-life embodied carbon emissions (CO2-e) of building materials of a net-zero energy building in Australia. Journal of cleaner production. 225, 541-553. http://dx.doi.org/10.1016/j.jclepro.2019.03.339.

Robertson, A.B., Lam, F.C.F., Cole, R.J., 2012. A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete. Buildings. 2, 245-270. 10.3390/buildings2030245.

Roh, S., Tae, S., Kim, R., 2018. Analysis of Embodied Environmental Impacts of Korean Apartment Buildings Considering Major Building Materials. Sustainability. 10. 10.3390/su10061693.

Rossi, B., Marique, A.F., Glaumann, M., Reiter, S., 2012. Life-cycle assessment of residential buildings in three different European locations, basic tool. Building and Environment. 51, 395-401. 10.1016/j.buildenv.2011.11.017.

Saade, M.R.M., da Silva, M.G., Gomes, V., Franco, H.G., Schwamback, D., Lavor, B., 2014. Material eco-efficiency indicators for Brazilian buildings. Smart and Sustainable Built Environment. 3, 54-71. 10.1108/sasbe-04-2013-0024.

Saade, M.R.M., Guest, G., Amor, B., 2020. Comparative whole building LCAs: How far are our expectations from the documented evidence? Building and Environment. 167, 106449. https://doi.org/10.1016/j.buildenv.2019.106449.

Salazar, J., Meil, J., 2009. Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. Journal of Cleaner Production. 17, 1563-1571. 10.1016/j.jclepro.2009.06.006.

Sanchez, B., Haas, C., 2018. A novel selective disassembly sequence planning method for adaptive reuse of buildings. Journal of Cleaner Production. 183, 998-1010. https://doi.org/10.1016/j.jclepro.2018.02.201.

Sartori, T., Calmon, J.L., 2019. Analysis of the impacts of retrofit actions on the life cycle energy consumption of typical neighbourhood dwellings. Journal of Building Engineering. 21, 158-172. 10.1016/j.jobe.2018.10.009.

Scheuer, C., Keoleian, G.A., Reppe, P., 2003. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy and Buildings. 35, 1049-1064. https://doi.org/10.1016/S0378-7788(03)00066-5.

Sedláková, A., Vilčeková, S., Burák, D., Tomková, Ž., Moňoková, A., Doroudiani, S., 2020. Environmental impacts assessment for conversion of an old mill building into a modern apartment building through reconstruction. Building and Environment. 172, 106734. https://doi.org/10.1016/j.buildenv.2020.106734.

Sharma, A., Saxena, A., Sethi, M., Shree, V., Varun, 2011. Life cycle assessment of buildings: A review. Renewable and Sustainable Energy Reviews. 15, 871-875. https://doi.org/10.1016/j.rser.2010.09.008.

Shetty, M., 2005. Concrete technology. S. chand & company LTD. 420-453.

Sicignano, E., Di Ruocco, G., Melella, R., 2019. Mitigation Strategies for Reduction of Embodied Energy and Carbon, in the Construction Systems of Contemporary Quality Architecture. Sustainability. 11. 10.3390/su11143806.

Siddaway, A.P., Taylor, P.J., Wood, A.M., Schulz, J., 2015. A meta-analysis of perceptions of defeat and entrapment in depression, anxiety problems, posttraumatic stress disorder, and suicidality. Journal of affective disorders. 184, 149-159. https://doi.org/10.1016/j.jad.2015.05.046.

Siddaway, A.P., Wood, A.M., Hedges, L.V., 2019. How to do a systematic review: a best practice guide for conducting and reporting narrative reviews, meta-analyses, and meta-syntheses. Annual review of psychology. 70, 747-770. https://doi.org/10.1146/annurev-psych-010418-102803.

Sim, J., Sim, J., Park, C., 2016. The air emission assessment of a South Korean apartment building's life cycle, along with environmental impact. Building and Environment. 95, 104-115. 10.1016/j.buildenv.2015.09.008.

Snyder, H., 2019. Literature review as a research methodology: An overview and guidelines. Journal of Business Research. 104, 333-339. https://doi.org/10.1016/j.jbusres.2019.07.039.

Sodagar, B., Rai, D., Jones, B., Wihan, J., Fieldson, R., 2011. The carbon-reduction potential of straw-bale housing. Building Research and Information. 39, 51-65. 10.1080/09613218.2010.528187.

Sovacool, B.K., Axsen, J., Sorrell, S., 2018. Promoting novelty, rigor, and style in energy social science: towards codes of practice for appropriate methods and research design. Energy Research & Social Science. 45, 12-42. doi.org/10.1016/j.erss.2018.07.007.

Su, S., Li, X.D., Wang, T., Zhu, Y.M., 2016. A comparative study of environmental performance between CFST and RC columns under combinations of compression and bending. Journal of Cleaner Production. 137, 10-20. 10.1016/j.jclepro.2016.07.043.

Su, X., Zhang, X., 2016. A detailed analysis of the embodied energy and carbon emissions of steel-construction residential buildings in China. Energy and Buildings. 119, 323-330. https://doi.org/10.1016/j.enbuild.2016.03.070.

Svajlenka, J., Kozlovska, M., 2017. Modern method of construction based on wood in the context of sustainability. Civil Engineering and Environmental Systems. 34, 127-143. 10.1080/10286608.2017.1340458.

Takano, A., Hughes, M., Winter, S., 2014. A multidisciplinary approach to sustainable building material selection: A case study in a Finnish context. Building and Environment. 82, 526-535. 10.1016/j.buildenv.2014.09.026.

Tavares, V., Lacerda, N., Freire, F., 2019. Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The "Moby" case study. Journal of Cleaner Production. 212, 1044-1053. 10.1016/j.jclepro.2018.12.028.

Teh, S.H., Wiedmann, T., Castel, A., de Burgh, J., 2017. Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. Journal of Cleaner Production. 152, 312-320. 10.1016/j.jclepro.2017.03.122.

Thormark, C., 2002. A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. Building and Environment. 37, 429-435. https://doi.org/10.1016/S0360-1323(01)00033-6.

Thormark, C., 2006. The effect of material choice on the total energy need and recycling potential of a building. Building and Environment. 41, 1019-1026. https://doi.org/10.1016/j.buildenv.2005.04.026.

Tingley, D.D., Cooper, S., Cullen, J., 2017. Understanding and overcoming the barriers to structural steel reuse, a UK perspective. Journal of Cleaner Production. 148, 642-652. doi.org/10.1016/j.jclepro.2017.02.006.

Tollefson, J., 2017. The wooden skyscrapers that could help to cool the planet. Nature News. 545, 280. doi:10.1038/545280a.

Topalovic, M.N., Stankovic, M., Cirovic, G., Pamucar, D., 2018. Comparison of the Applied Measures on the Simulated Scenarios for the Sustainable Building Construction through Carbon Footprint EmissionsCase Study of Building Construction in Serbia. Sustainability. 10. 10.3390/su10124688.

Tsoumis, G., 1991. Science and technology of wood: structure, properties, utilization. Van Nostrand Reinhold New York.

Tulevech, S.M., Hage, D.J., Jorgensen, S.K., Guensler, C.L., Himmler, R., Gheewala, S.H., 2018. Life cycle assessment: a multi-scenario case study of a low-energy industrial building in Thailand. Energy and Buildings. 168, 191-200. https://doi.org/10.1016/j.enbuild.2018.03.011.

Tumminia, G., Guarino, F., Longo, S., Ferraro, M., Cellura, M., Antonucci, V., 2018. Life cycle energy performances and environmental impacts of a prefabricated building module. Renewable and Sustainable Energy Reviews. 92, 272-283. https://doi.org/10.1016/j.rser.2018.04.059.

Varun, Sharma, A., Shree, V., Nautiyal, H., 2012. Life cycle environmental assessment of an educational building in Northern India: A case study. Sustainable Cities and Society. 4, 22-28. https://doi.org/10.1016/j.scs.2012.03.002.

Vecchio, F.J., Collins, M.P., 1986. The modified compression-field theory for reinforced concrete elements subjected to shear. ACI J. 83, 219-231.

Vieira, D.R., Calmon, J.L., Coelho, F.Z., 2016. Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review. Construction and Building Materials. 124, 656-666. https://doi.org/10.1016/j.conbuildmat.2016.07.125.

Visintin, P., Xie, T., Bennett, B., 2020. A large-scale life-cycle assessment of recycled aggregate concrete: The influence of functional unit, emissions allocation and carbon dioxide uptake. Journal of Cleaner Production. 248, 119243. https://doi.org/10.1016/j.jclepro.2019.119243.

Wang, J., Yu, C., Pan, W., 2018. Life cycle energy of high-rise office buildings in Hong Kong. Energy and Buildings. 167, 152-164. https://doi.org/10.1016/j.enbuild.2018.02.038.

Wu, H.J.J., Yuan, Z.W.W., Zhang, L., Bi, J., 2012. Life cycle energy consumption and CO2 emission of an office building in China. International Journal of Life Cycle Assessment. 17, 105-118. 10.1007/s11367-011-0342-2.

Xiao, J., Wang, C., Ding, T., Akbarnezhad, A., 2018. A recycled aggregate concrete high-rise building: Structural performance and embodied carbon footprint. Journal of Cleaner Production. 199, 868-881. https://doi.org/10.1016/j.jclepro.2018.07.210.

Yan, H., Shen, Q., Fan, L.C.H., Wang, Y., Zhang, L., 2010. Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. Building and Environment. 45, 949-955. https://doi.org/10.1016/j.buildenv.2009.09.014.

Yang, X.N., Hu, M.M., Wu, J.B., Zhao, B., 2018. Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China. Journal of Cleaner Production. 183, 729-743. 10.1016/j.jclepro.2018.02.070.

Yazdanbakhsh, A., Lagouin, M., 2019. The effect of geographic boundaries on the results of a regional life cycle assessment of using recycled aggregate in concrete. Resources, Conservation and Recycling. 143, 201-209. https://doi.org/10.1016/j.resconrec.2019.01.002.

Yellishetty, M., Mudd, G.M., 2014. Substance flow analysis of steel and long term sustainability of iron ore resources in Australia, Brazil, China and India. Journal of Cleaner Production. 84, 400-410. https://doi.org/10.1016/j.jclepro.2014.02.046.

Yu, D., Tan, H., Ruan, Y., 2011. A future bamboo-structure residential building prototype in China: Life cycle assessment of energy use and carbon emission. Energy and Buildings. 43, 2638-2646. https://doi.org/10.1016/j.enbuild.2011.06.013.

Zabalza Bribián, I., Valero Capilla, A., Aranda Usón, A., 2011. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and Environment. 46, 1133-1140. https://doi.org/10.1016/j.buildenv.2010.12.002.

Zaman, A.U., Arnott, J., McLntyre, K., Hannon, J., 2018. Resource Harvesting through a Systematic Deconstruction of the Residential House: A Case Study of the 'Whole House Reuse' Project in Christchurch, New Zealand. Sustainability. 10. 10.3390/su10103430.

Zhang, Y., Zheng, X., Zhang, H., Chen, G., Wang, X., 2016. Carbon emission analysis of a residential building in China through life cycle assessment. Frontiers of Environmental Science and Engineering. 10, 150-158. 10.1007/s11783-014-0684-7.

Zhao, Z., Courard, L., Groslambert, S., Jehin, T., LÉOnard, A., Xiao, J., 2020. Use of recycled concrete aggregates from precast block for the production of new building blocks: An industrial scale study. Resources, Conservation and Recycling. 157, 104786. https://doi.org/10.1016/j.resconrec.2020.104786.

Publication II

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Strategies for Applying the Circular Economy to Prefabricated Buildings

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Abstract: In this paper, a circular-economy framework is applied to the prefabricated building sector to explore the environmental advantages of prefabrication in terms of reduction, reusability, adaptability, and recyclability of its components. A qualitative approach is used to revisit the design, construction, and demolition stages of prefabricated buildings; in so doing, the circular-economy framework is applied to foster circular prefabricated modi operandi. Prefabrication of buildings can be divided into four entities: elements and components, panels (or non-volumetric elements), volumetric, and entire modules. Through an analysis of published research on how the circular economy can be applied to different industry sectors and production processes, seven strategies emerged, each of which revealed the potential of improving the circular economy of buildings. The first strategy is reduction of waste through a lean production chain. By reusing the waste, the second strategy investigates the use of by-products in the production of new components. The third strategy focuses on the reuse of replacement parts and components. The fourth strategy is based on design toward adaptability, respectively focusing on reusability of components and adapting components for a second use with a different purpose. Similarly, the fifth strategy considers the implications of designing for disassembly with Building Information Modeling so as to improve the end-of-life deconstruction phase. The sixth strategy focuses on design with attention to recyclability of used material. Finally, the seventh strategy considers the use of tracking technologies with embedded information on components' geometric and mechanic characteristics as well as their location and life cycle to enable second use after deconstruction. It is demonstrated that prefabricated buildings are key to material savings, waste reduction, reuse of components, and various other forms of optimization for the construction sector. By adopting the identified strategies in prefabricated buildings, a circular economy could be implemented within the construction industry. Finally, seven guidelines were distilled from the review and linked to the identified strategies. Owing to their degree of adaptability and capacity of being disassembled, prefabricated buildings would allow waste reduction and facilitate a second life of components.

Keywords: circular economy; prefabrication; manufacturing; buildings; construction and demolition; waste; reduction; reuse; recycle; adaptability

1. Introduction

1.1. The Circular Economy of Buildings

The relevance of the circular economy (CE) is increasingly recognized among researchers and practitioners in industry, society, and academia [1]. The CE concepts of reduction, reuse, and recyclability of materials and components were already successfully applied to a number of products, from electronic goods to clothing [2], but to a lesser extent for buildings and building components. To understand the level of integration of the CE in the construction industry, we scanned a number of research publication databases (such as Scopus, Science Direct, ProQuest, and Web of Science). In doing so, we discovered that the application of the CE framework on buildings is limited to the use of by-products in concrete production and recycled concrete [3–5]. It is important to note that the use of recycled concrete falls outside CE, as recycled concrete and aggregates is a down-cycling of materials; down-cycling is the practice of using recycled material for an application of less value than the original purpose of that material [6]. However, the barriers that stop the CE from being applied to traditional buildings are mainly related to their monolithic nature, architectural aspects that lead to a lack of standard measures, and an underdeveloped closed-loop supply chain. Prefabrication of buildings could represent a solution to these issues [7–9].

In terms of a construction-based definition, prefabrication is a manufacturing process that takes place in a specialized facility where various materials are joined together to form a component of the final installation procedure [10]. Gibb [11] categorized prefabrication into four levels based on the degree of prefabrication implemented in the product: (1) component manufacturing and subassembly carried out in a factory and not considered for on-site production; (2) non-volumetric pre-assembly that refers to pre-assembled units not enclosing usable space; (3) volumetric pre-assembly refers to pre-assembled units enclosing usable space, which are usually manufactured in factories, but do not form part of the buildings structure; and (4) whole-building prefabrication refers to pre-assembled volumetric units forming the actual structure and fabric of the building. This study's objective is to investigate the CE in the context of prefabricated buildings so as to identify opportunities for the development of a closed-loop supply chain in the construction industry.

1.2. The Evolution of Buildings and the Definition of Traditional and Prefabricated buildings

A building can be defined as an enclosed structure composed of walls, roofs, and floors, built as a permanent shelter. Across the centuries, buildings changed their composition, materials, and dimensions according to people's needs and technological abilities. The Roman invention of concrete allowed the quality of building technology to further develop (around 500 BC), concrete was already commonly used in Roman constructions then, permitting the Romans to create structural continuity with rocks and blocks [12]. The next major milestone in the evolution of architecture and construction was the development of steel and its integration in the construction sector at the end of the 19th century [13]. The first steel-based skyscraper was built in Chicago in 1885 [14]. With innovation in the steel industry, lighter construction is increasingly popular, paving the way for the next innovation: movable prefabricated buildings built with panels or modules that challenge the very notion of permanence. Prefabricated buildings are defined as constructions manufactured at an industrial site and moved and assembled in different degrees on-site [15]. Based on this definition of prefabricated buildings, we define traditional buildings as a construction where structural and non-structural components are manufactured on-site.

2. Research Questions and Objective

We explore the barriers that hinder the CE framework to buildings with a focus on reduced material consumption and waste production. We then propose that, while the CE principles might not be applied to traditional buildings, they can be implemented in prefabricated buildings. We address the following research questions:

1. What does the academic literature say about the application of CE to buildings?
2. What are the barriers to the applications of CE principles for traditional buildings?
3. Which aspects of prefabricated buildings could enable a strategy for overcoming CE barriers?

In answering these questions, this study advances knowledge development on the nature of the relationship between CE and prefabricated buildings. Specifically, we focus on volumetric pre-assembly and whole-building prefabrication, with design for disassembly extending to the components used and the non-volumetric elements of prefabricated buildings.

3. Methodology

The research was conducted in four steps (Figure 1). In the first step, starting with the research questions listed above, a list of keywords related to the scope of this research (circular economy, buildings, reuse, reduce, recycle, and construction waste) was identified. In the second step, studies containing the keywords were searched in Scopus, ProQuest, Web of Science, Science Direct, and other databases. We then identified the most relevant academic studies (i.e., those sources that were most promising in yielding valuable answers to the above outlined research questions). In the third step, these works were analyzed to evaluate strategies applicable to prefabricated construction alongside the barriers of traditional construction in relation to CE. In the fourth step, a list of seven solutions was distilled that potentially fosters the advancement of the CE framework in a building context.

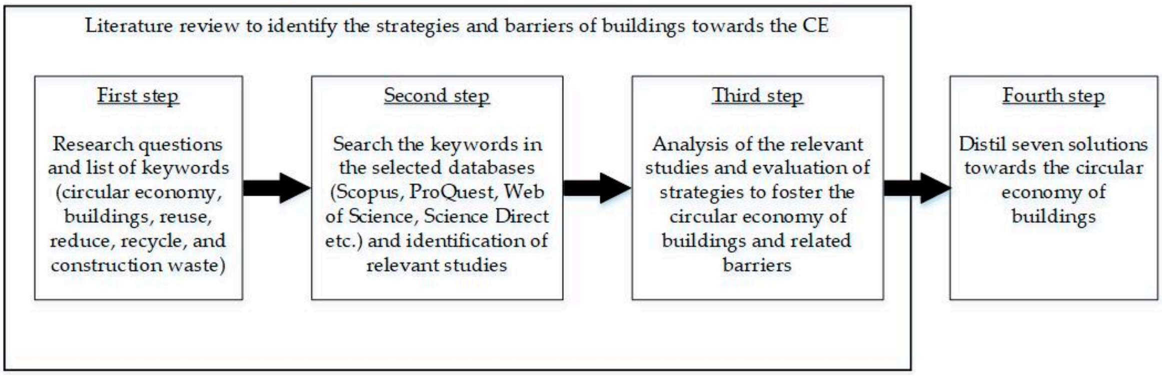

Figure 1. Methodology divided into four steps: research questions and list of keywords, identification of relevant studies, analysis of the studies to discover strategies and barriers toward the circular economy of buildings, and proposal of seven possible solutions.

3.1. First and Second Step—CE Strategies and Barriers Related to Traditional Buildings

The CE framework is often related to the 3Rs concept of reduce, reuse, and recycle [2,16]. From a review of the literature on the CE and how it is applied, we identified the seven most common strategies. In Table 1, we summarize these strategies and identify how they are relevant for buildings.

Table 1. The seven strategies, how they can be applied to buildings, and the barriers of traditional buildings that hinder their application. TB—traditional building; EoL—end of life.

Strategy	Appling the Strategy to Prefabricated and Traditional Buildings	Barriers of Traditional Buildings	References
1. Reduction of construction waste and the lean production chain	Adopt the lean production chain to reduce construction waste	TB degree of complexity and variable measures are a barrier toward lean production	[17–21]
2. Integration of scrap, waste, and by-products into new components	Use of by-products in concrete	No barriers were found in the literature	[22–26]
3. Reuse of replacement parts or entire components	Use of second-life components	Technically complex, elevated time, and cost requested	[27–30]

Table 1. *Cont.*

Strategy	Appling the Strategy to Prefabricated and Traditional Buildings	Barriers of Traditional Buildings	References
4. Design toward adaptability (reduction through life extension) during operational stages	Adaptability during the operational phase	Low adaptability of components due to monolithic nature of the TB; knowledge gap on space adaptability	[31–35]
5. Design toward disassembly of goods into components to be reused	Reusability at the EoL	Monolithic structures with chemically bonded connections	[36–39]
6. Design for recycling of construction materials	Recyclability at the EoL	Concrete is intensively used in TBs; however, in the recycling process, its characteristics decrease with scarce saving of CO_2 emissions	[40–43]
7. Systems to track materials and components within their supply chain	Tracking the components	Practicable only when component can be disassembled and reused	[29,44–46]

3.1.1. Strategy 1: Reduction of Construction Waste and the Lean Production Chain

Modern industries work in a largely linear manner; companies extract raw materials, manufacture and use products, and finally dispose of materials that are no longer required, typically toward the end of their life cycle [8,47]. Although most of the waste in the linear framework of take–manufacture–use–dispose is produced during the disposal stage, waste generated during the manufacturing process must also be considered. However, a significant quantity of scrap and raw materials is wasted in the primary stages of the production chain, when spoil, scrap, or defect materials are generated because of over-production, delays, inventory issues, or damage during transport [17]. For these reasons, manufacturers are increasingly interested in optimizing the production chain toward material savings [48]. Among all the different strategies to improve production efficiency, the integration of lean production and parallel-line manufacturing was shown to be among the most superior approaches to diminish waste during the manufacturing phases [18,21] via the integration of project management tools, such as just-in-time (JIT), design for assembly, and supply management [20].

In the production phase of buildings, most of the waste comes from reinforcement steel-bar cut-offs, lack of precision in constructing concrete elements, damaged or cut-off bricks and tiles, and sand loss during transport [24]. As highlighted, the integration of lean production and parallel-line manufacturing is one of the solutions to decrease waste during the production phase. This solution is applied to the built environment through the adoption of Building Information Modeling (BIM), which has significant potential to reduce waste [49]. However, the complexity of traditional buildings (including their variability in design and materials) does not always allow the application of BIM or other lean-production-related tools [50]. Further, traditional constructions are often seen as the only building technology, thereby acting as a barrier toward innovative systems, such as industrialized housing where lean production is common [51].

3.1.2. Strategy 2: Integration of Scrap, Waste, and By-Products into New Components

Many CE experts consider the reuse of scrap, waste, or by-products as one of the leading strategies to close the waste–resource loop [8,22,52], and, in most cases, more efficient than recycling [53]. By-products generated in different industry sectors, such as agricultural, automotive, and electronics can be successfully reintegrated into the supply chain [5,26,54].

As mentioned, most of the waste from the construction sector is composed of inert materials [24]. Such inert materials can successfully be used to produce new recycled concrete, and mixed with by-products from the construction sector. These by-products also include recycled concrete [55], ceramic tiles [56], and bricks [57] as well as other industries, such as geo-polymer slurry [58] or fly-ash and blast [59]. The addition of by-products into concrete is a practice that delays by-products from being landfilled; however, the substitution is already limited by the actual amount of available by-products. This amount is not enough to fulfil the global cement production [52]. Material saving and other environmental benefits, such as carbon emissions are widely studied and assessed, suggesting that, within all the building materials, concrete contributes the greater proportion of the reuse of by-products [60–62].

3.1.3. Strategy 3: Reuse of Replacement Parts or Entire Components

Reusing disassembled components is one of the fundamental steps toward the CE of any industrial sector [28,63]; yet, this practice is not always possible or convenient [64]. The main obstacles toward disassembly are of a technological and economic nature [65]. Mok, Kim and Moon [30] define the technological disassemblability as the degree of easy disassembly. Disassemblability refers to the ideal baseline of goods that can be disassembled without tools, without the application of any force but only by simple mechanism, standardization of parts, and in the absence of toxic materials. The disassemblability of goods is economically feasible only when the cost of the disassembled component is lower than the cost of the new product, and depends on the value of goods and the cost and revenue of disassembly operations [66]. In the automotive industry, for example, design for disassembly and reuse depends on aspects, such as the durability of materials, reachability and visibility of joints, quality of components at the end of life (EoL) and so forth [67]. In the electronic and electric sectors, standardization is also considered one of the main facilitator drivers (e.g., computer keyboards can be disassembled and reused, while more general parts such as cases of electric goods are usually shredded) [68].

In some cases, it was possible to adapt, repurpose, and reuse entire buildings, reducing the amount of demolished and landfilled materials [27]. This option, however, rarely occurs in the construction sector where demolition is preferred to deconstruction. Even when technologically feasible deconstruction tends to be more time-consuming, the dismounted components have to be stored, tested, and certified, and the supply chain for reused materials and components is not yet mature [69]. Demountable, low-cost, and environmental-impact building components are increasingly studied, but rarely used in real-life case studies [29].

3.1.4. Strategy 4: Design toward Adaptability (Reduction through Life Extension) during Operational Stages

One of the strategies to reduce material consumption is through components' life extension, or design against overconsumption [70]. For example, keep-cups facilitate multiple uses as opposed to a disposable cardboard or plastic takeaway cup [71]. Reusability and life extension share one main barrier: if the cost of a used and adapted good is similar to the new one, the latter is preferred [33]. For goods that produce higher operational environmental impact compared to the ones generated during the production phase, such as fridges or washing machines, life extension is not convenient [35]. On the other hand, goods that have low operational environmental impact should have an extended life and be replaced less frequently [32].

In buildings, many strategies are applied toward closing the material loop; however, through accurate planning, life extension can be obtained with flexible spaces and adaptable elements [7]. The flexibility of buildings and the adaptability of their components is related to the degree of their movability [29]; yet, the use of more standard measures is one of the main drivers toward adaptability of buildings [72]. There is also a recognized knowledge gap in the adaptability of the building sector and building components, which causes resistance from builders to design toward adaptability [34]. Among the proposed strategies, design in modularity and standardization seems the easiest way toward adaptability [31]. In general, both the environmental (in terms of CO_2-equivalent emissions) and the economic cost of disassembly of steel components is less than the disassembly cost of concrete components; thus, off-site construction systems, such as modular buildings potentially play a fundamental role in adaptability [73].

3.1.5. Strategy 5: Design toward Disassembling Goods into Components to Be Reused

Designing for disassembly is defined by Wheaton [74] as pre-emptive, aiming to include serviceability and adaptability in its methodology. Despite the function of a building changing over time, there are several components that will outlast a building's initial design, and therefore, should be disassembled, as opposed to demolished, in order to direct materials back to the supply chain at the EoL [74]. Thus, buildings must be designed with EoL deconstruction in mind [39]. Buildings designed with mechanical connections rather than chemical ones facilitate easy separation of components and materials without force, reducing contamination of materials and damage to components during deconstruction [75]. Mechanical connections should be accessible to improve the dismantling process and allow easy separation of different material types [37].

BIM can play a crucial role in designing the future disassembly of buildings. With the development [37] of BIM, designers can track the location of components in the building, detailed information about the element, and the relationship between the element and the overall structure [38]. Components can be tracked from procurement to installation with their initial input of characteristics into the model [76]. With information entered into the model transferred at the project handover, future life cycles of the building can be managed according to the data, with their conditions of use, exposure to weather, and instructions for disassembly linked individually. A material passport is the term used to describe the link between the physical element and the digital model [36]. This concept is crucial for tracking all available resources in the material bank that can be reused at the EoL.

3.1.6. Strategy 6: Design for Recycling of Construction Materials

In the previous two sections, we analyzed the reduction of material consumption through designing reusable components and through adaptability. By following the 3Rs hierarchy (reduce, reuse, and recycle) of CE, the components that cannot be reused or adapted should be designed with attention to their recyclability potential. In so doing, it should be considered that an issue concealed behind the recyclability potential is that the materials are down-cycled or downgraded, thereby reducing the quality of the second-life product [77]. Concrete and steel are among the most used materials in the construction sector [78], and they can both be recycled [42,43]. While steel can be recycled infinite times without losing its mechanical characteristics [4], the quality of recycled concrete over the new product decreases [40,79] if not properly designed for recycling [80]. Once a building is demolished, the percentage of its concrete that can be separated from reinforcement bars is crushed, becoming sand or gravel that can substitute virgin materials [81]. In order to achieve a recycled concrete with a quality comparable to virgin concrete, the recycled concrete needs an additional amount of cement [55]; thus, recycled concrete is down-cycled into a lower-quality product (from concrete, it becomes an aggregate) [82]. Prefabricated structures are not generally constructed with concrete; therefore, as a whole, the use of concrete material is decreased [63]. In the situation that the prefabricated modules do have a concrete platform or floor, they are cast and poured in a factory environment. Due to the nature of pouring a slab in a controlled, ground-floor environment, there is less waste due to accurate measures and less vertical transportation to get the concrete to different elevations, which is needed for a building that is constructed onsite [17].

Recycling concrete allows material savings and other benefits related to material scarcity and landfill pressure; however, transport and overall additional cement needed in recycled concrete might offset the emission saving owed to the recycling process [41]. Transport-related emissions are a common issue to the recycling of both concrete and steel components; nevertheless, lightweight steel structures deal with less transport because of the reduced weight and volume of steel components compared with concrete components [63]. Hence, from a recycling perspective, steel should be preferred over concrete [41]. Conventional building materials' recyclability should, thus, be considered as an option for existing buildings; however, the best approach for new constructions is through lightweight steel frames [4].

3.1.7. Strategy 7: Systems to Track Materials and Components within Their Supply Chain

Different inter-organizational systems, such as radio-frequency identification (RFID) or standard barcodes, allow companies to identify and track products as they move across the supply chain [46]. With the concept of cities as material banks, we propose the strategy of storing the information of every component of a building. This is achievable through BIM modeling where information on a building's parts is stored on a database to become a feasible supply chain [44]. Doing so could allow the tracking of the components' geometric and mechanical characteristics, location, age, and expected life cycle. In this way, when a barcoded component reaches its EoL, designers of new buildings should know which components could be gathered from the building to then be reused. This strategy could save materials from recycling or landfill, and new components might be manufactured.

Prefabricated construction has the advantage of improving a closed-loop supply chain as construction takes place in one location, allowing for safe storage and inventory of materials. Location of current material stock, and time of availability are current limitations with reuse supply chains [45]. Traditional building techniques cause materials to have a low degree of movability and disassemblability [29]. Traditional construction practitioners employ a decentralized, subcontractor work force to complete projects. This contracting arrangement and the varying location of projects make traceability of components difficult; hence, integrating the RFID system into a prefabricated building would optimize its potential to create a closed-loop supply chain.

3.2. Third Step—Barriers and Proposed Solutions toward the Circular Economy of Buildings

In the previous sections, seven strategies were identified on how to foster the CE of different industry sectors and life-cycle stages. The literature reveals that the application of these strategies to the building sector is hindered by several barriers, strictly related to the monolithic nature of traditional buildings, their lack of standard measures, and no established closed-loop supply chain of materials and components. Table 2 summarizes the strategies, opportunities, and barriers that arose, and the distilled solutions that can be applied to the built environment.

3.2.1. Identified Barriers of the Circular Economy of Buildings

In the explored literature, several barriers to the adoption of the CE framework in a building context emerged. Although the lean or parallel manufacturing allows a reduction of waste from the production phase, traditional buildings are built on-site with non-standard components and parts, making lean manufacturing impractical by design. The use of by-products can be embodied in traditional buildings owing to the more intensive use of concrete, where by-products are more successfully used. Typically, prefabricated buildings have less concrete than traditional buildings; thus, the strategy of integration of by-products suits traditional buildings. Another aspect of the CE is reusability and adaptability. When applying these concepts to building components and parts, it appears clear that the monolithic and permanent nature of traditional buildings limits the disassemblability, making disassembling either technologically or economically unfeasible. In addition, a supply chain toward a closed loop of components is not yet established in the building sector. A fundamental strategy toward the CE is recycling the materials at the EoL of the building. Concrete and steel are among the two most commonly used building materials, and their recyclability performance is very different. Steel can be recycled multiple times without losing its mechanical characteristics, and the recycling process is less carbon-intensive than producing steel from raw materials. On the contrary, used concrete is crushed and reduced into inert material (i.e., down-cycled) and aggregate. The carbon emissions related to the crushing process and transportation often offset the ones produced to manufacture new concrete.

Table 2. Strategies and opportunities that arose, along with barriers and how they can be overcome with proposed solutions. BIM— Building Information Modeling.

Strategy	Opportunity	Barrier	Solution
1. Reduction of construction waste and the lean production chain	Integrate a lean production in the prefabrication phase of building components	Complexity and variability of traditional buildings	Increase the use of prefabricated components
2. Integration of scrap, waste, and by-products into new components	The use of concrete fosters the second life of by-products	Strategy limited to the use of concrete, which, by itself, is highly carbon-intensive	Integrate by-products into the concrete production. High potential in traditional buildings, where more concrete is typically used
3. Reuse of replacement parts or entire components	Through reuse of parts, waste can be reduced, giving a second life to building components. Supply chain could be integrated in business planning	Technological barrier of disassembling monolithic building; economic barrier if components are not designed toward reuse. Supply chain for reused components is yet to be developed in the building sector	Design for disassembly facilitates the reuse of components. Preferring visible joints, steel frames, and standard measures, components can be disassembled and reused, fostering the market of reused parts
4. Design toward adaptability (reduction through life extension) during operational stages	Planning of flexible spaces and design of adaptable elements to reduce the waste due to modifications in the operational stage of buildings	The degree of adaptability is proportional to the mobility degree of the building. Traditional buildings are built on-site to be permanent, and thus, are not adaptable	Prefabricated building components could be designed to be movable, increasing the adaptability of both traditional and modular buildings
5. Design toward disassembly of goods into components to be reused	The use of BIM in prefabrication allows for material tracking, identification, and cataloging	Cost effectiveness and technological feasibility hinder the practical application of disassembly	BIM stores instructions on components and their relationship to the structure, enabling methodical deconstruction
6. Design for recycling of construction materials	Steel can be recycled, and concrete is commonly down-cycled. Building with steel would then increase the material saving	Transport of recycling components and the recycling processes themselves are carbon-intensive for both concrete and steel	Whenever possible, the use of recycled concrete and steel should be preferred. Steel in particular maintains its mechanical characteristics
7. Systems to track materials and components within their supply chain	Track materials and components throughout the life cycle of buildings	Location of materials and time when those would become available	Prefabricated buildings designed with BIM could allow the information to be shared on the upcoming deconstruction

In summary, the emergent barriers of the CE of buildings are mainly related to traditional designs, materials, and management. Traditional buildings are monolithic with little degree of disassemblability. The use of concrete complicates the adaptability and reusability of components, and a supply chain of components is not yet implemented.

3.2.2. Proposed Solutions

The CE is a promising framework toward material saving, waste reduction, product life extension, and carbon-emission reduction [8]. Lean and parallel production processes are proven to diminish the generation of waste during the production phase. Through prefabrication of building components it is also possible to overcome the barriers related to design for disassembly, fostering adaptability, and reusability of components. Prefabricated building structures are mainly steel frames that use less concrete, which means that fewer by-products are embodied into new buildings. In contrast, steel is more recyclable than concrete and maintains its characteristics throughout the recycling process. Further, though the supply chain of reused building components has not yet been developed, RFID, distributed ledger, and tracking and tracing devices are promising technologies that would allow buildings to become material banks at their end of lifecycle.

3.2.3. Advantages of Traditional and Prefabricated Buildings toward the CE

Table 3 summarizes the feasibility of the application of the seven proposed strategies to traditional and prefabricated buildings toward the CE. Although prefabrication can enhance most of these strategies, some are also applicable to traditional buildings. The use of by-products in concrete is widely studied and becoming common practice. Reusable components and parts can be used in both traditional and prefabricated buildings as well as some components, such as doors and windows. Movability is still one of the greatest advantages of prefabricated buildings, which makes them more adaptable than their traditional counterparts. Both steel and concrete can be recycled; however, as outlined, concrete is usually down-cycled. Strictly related to design for disassembly, and reuse of components, the use of tracking technology is again an advantage of prefabricated buildings.

Table 3. Feasibility of the application of the strategies to traditional and prefabricated buildings toward the circular economy (CE). Plus (+) means possible to apply that strategy, minus (−) means not possible, and equal (=) means that the strategy could be equally applied to both traditional and prefabricated buildings.

Strategy	Traditional Buildings	Prefabricated Buildings
1. Reduction of construction waste and the lean production chain	−	+
2. Integration of scrap, waste, and by-products into new components	+	−
3. Reuse of replacement parts or entire components	=	=
4. Design toward adaptability (reduction through life extension) during operational stages	−	+
5. Design toward disassembly of goods into components to be reused	=	=
6. Design for recycling of construction materials	−	+
7. Systems to track materials and components within their supply chain	−	+

3.2.4. Proposed Guidelines to Implement the Seven Strategies

From the reviewed literature, we identified the outlined seven strategies. To facilitate the connection between the building industry and theoretical benefits of CE, Table 4 outlines seven guidelines which can be used in either a top-down or bottom-up management approach. The top-down methods include changes to contracting practices that can facilitate the use of the 3Rs, and the bottom-up methods are made through subcontractors proposing the use of recycled components and materials where they meet specified performance criteria. The first guideline promotes levels of prefabrication through the tender process by assigning a higher weighting to contractors. The second guideline suggests that project specifications be written to include the use of recycled materials. The third incorporates changes to traditional "supply and install" contracts, preferring "supply, install, maintain, and remove" contracts for large valuable items within the building. The fourth guideline calls for adaptability of buildings, with the goal of future-proofing, and providing additional service ducts and moveable walls. The fifth guideline suggests the use of BIM models to foster deconstructability of components. Considering recyclability of components, the sixth guideline compares the ability to separate materials to facilitate their recycling processes. Finally, the seventh guideline considers the implementation of inter-organizational systems into building components to help keep track of their characteristics at the end of the buildings' life cycles and to facilitate the vision of buildings as material banks.

Table 4. Seven guidelines which suggest possible applications of CE methods in the building sector.

	Strategy	Guideline
1.	Reduction of construction waste and the lean production chain	Use contractors that are adept with prefabrication and waste-minimization techniques. This can be facilitated by inviting the contractor's proposed lean production chain techniques with their tender submissions, with a higher weighting on the level of lean production proposed than the overall cost in the tender selection process. Examples of subcontractor lean production can include sub-assembly and manufacture of plumbing fixtures, such as water meters, electrical wiring looms, and pre-assembled switchboards, and using casting molds for concrete columns instead of formwork. In addition, reducing the amount of bespoke architectural elements can increase the opportunity for those elements to have a secondary life cycle in the future, as they are more adaptable.
2.	Integration of scrap, waste, and by-products into new components	Produce project specifications which allow recycled materials to be used as replacement for virgin materials. Where specific performance criteria are not needed, recycled materials can replace new materials and reduce the impact of a project. There is a negative view on recycled materials being used in projects, and they are often excluded from specifications due to quality concerns. The acceptance of recycled material in project specifications will increase the demand within the supply chain and grow the industry of project waste, reducing the loop. Examples of recycled waste integration are crushed rock for drainage and civil subgrade work, recycled concrete in driveways and non-load bearing structures, such as basement car-park slabs, and the use of recycled timber for non-structural walls and noggins.
3.	Reuse of replacement parts or entire components	Design a "supply, install, maintain, and remove" contracting approach to large and valuable components of a building. Applying this contract to building components will ensure that the supplier/installer maintains the piece of equipment throughout its life cycle. It will also make contractors design an easy removal method, not only a fast installation method, as retention of ownership remains with the supplier/installer and will become an integral part of design and construct contracting arrangements. This contracting method would be economical for elevators, fire-booster pumps, and water-jacking pumps; all of these items can be remanufactured to create new products with relative ease.
4.	Design toward adaptability (reduction through life extension) during operational stages	Integrating movable lightweight steel-frame walls into the design would increase the adaptability of the internal spaces. Moreover, accessible service risers would further increase the different possibilities of adapting plans to several needs during the operational stage of the buildings.
5.	Design toward disassembly of goods into components to be reused	Projects should be designed using a collaborative BIM model so the interconnectivity of components can be discovered by other people adding information to the model. This will foster methodical deconstruction methods, enabling a faster deconstruction time. Once the timeline for a building's deconstruction becomes close to the timeline needed for demolition, there will be an economical advantage due to the value in salvaged parts being redirected from waste streams. If the model is used correctly, it will become feasible to deconstruct, rather than to demolish. Disassembly processes should be included with the project manual at completion and kept as a working document for the building.
6.	Design for recycling of construction materials	Where materials are not fit for reuse, they must be able to be recycled. The recycling of material is made easier when the building is being disassembled in a specially designed facility to allow for sorting of materials. Traditional construction techniques are dominated by chemical reactions which are used for bonding material components in the building. Once concrete is set, it is permanently joined to reinforcement and unable to be reversed. The same can be said about sealants, glues, and caulking that are used in traditional buildings, making the separation of materials difficult and affecting the recyclability of the materials that are entered into the recycling streams. Through the use of prefabrication, the ability to separate materials into their correct recycling stream can be facilitated.
7.	Systems to track materials and components within their supply chain	The use of barcoded components would enable buildings to become material banks at the end of their life cycle. The implementation would be crucial in adopting and advancing project management tools which could then be linked with integrated barcoded BIM models to create a CE at the end of the life cycle.

4. Contribution and Future Research

This research explores the integration of the CE principles into the building sector. Starting from an exploration of research on CE principles, and how they apply to different industries, opportunities within the building sector were identified. In doing so, several barriers were identified related to both traditional and prefabricated buildings. Finally, solutions and seven strategies are proposed to be implemented into buildings, moving a step closer to the holistic application of the CE principles to buildings.

In identifying the outlined strategies, we make a conceptual contribution. Therefore, future empirical research efforts should be made to test and validate our findings. Similar empirical evidence might determine the CE's contribution toward sustainability by measuring life-cycle assessment and material flow accounting. Research into standardization of material types and sizes could complement the seven strategies as the construction industry increasingly moves toward a closed-loop supply chain. This could provide a list of a building's material components. Distributed ledger technology could provide a framework to facilitate the link between a material passport and a potential buyer through trusted parties and smart contracts, while protecting information surrounding a building's design and protecting public safety. A review of deconstructability is needed to ensure that a closed-loop supply chain is economically viable.

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References

1. Merli, R.; Preziosi, M.; Acampora, A. How do scholars approach the circular economy? A systematic literature review. *J. Clean. Prod.* **2018**, *178*, 703–722. [CrossRef]
2. Ghisellini, P.; Cialani, C.; Ulgiati, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* **2016**, *114*, 11–32. [CrossRef]
3. Shih, P.H.; Chang, J.E.; Lu, H.C.; Chiang, L.C. Reuse of heavy metal-containing sludges in cement production. *Cem. Concr. Res.* **2005**, *35*, 2110–2115. [CrossRef]
4. Haas, W.; Krausmann, F.; Wiedenhofer, D.; Heinz, M. How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. *J. Ind. Ecol.* **2015**, *19*, 765–777. [CrossRef]
5. Siddique, R.; Naik, T.R. Properties of concrete containing scrap-tire rubber—An overview. *Waste Manag.* **2004**, *24*, 563–569. [CrossRef] [PubMed]
6. Di Maria, A.; Eyckmans, J.; Van Acker, K. Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. *Waste Manag.* **2018**, *75*, 3–21. [CrossRef] [PubMed]
7. Allwood, J.M. Squaring the circular economy: The role of recycling within a hierarchy of material management strategies. In *Handbook of Recycling*; Elsevier Science: St. Louis, MO, USA, 2014; pp. 445–477.
8. Stahel, W.R. The circular economy. *Nat. News* **2016**, *531*, 435. [CrossRef] [PubMed]
9. Tingley, D.D.; Cooper, S.; Cullen, J. Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *J. Clean. Prod.* **2017**, *148*, 642–652. [CrossRef]
10. Sparksman, G.; Groak, S.; Gibb, A.; Neale, R. Standardisation and pre-assembly: Adding value to construction projects. *CIRIA Rep.* **1999**, *176*.

11. Gibb, A.G. *Off-Site Fabrication: Prefabrication, Pre-Assembly and Modularisation*; John Wiley & Sons: Hoboken, NJ, USA, 1999.
12. Jackson, M.; Marra, F. Roman Stone Masonry: Volcanic Foundations of the Ancient City. *Am. J. Archaeol.* **2006**, *110*, 403–436. [CrossRef]
13. Condit, C.W. *The Chicago School of Architecture: A History of Commercial and Public Building in the Chicago Area, 1875–1925*; University of Chicago Press: Chicago, IL, USA, 1973.
14. Bruegmann, R.; Zukowsky, J. *Chicago Architecture 1872–1922: Birth of a Metropolis*; Prestel Verlag: Munich, Germany, 1987.
15. Mao, C.; Shen, Q.; Shen, L.; Tang, L. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. *Energy Build.* **2013**, *66*, 165–176. [CrossRef]
16. Fregonara, E.; Giordano, R.; Ferrando, D.G.; Pattono, S. Economic-environmental indicators to support investment decisions: A focus on the buildings' end-of-life stage. *Buildings* **2017**, *7*, 65. [CrossRef]
17. Fercoq, A.; Lamouri, S.; Carbone, V. Lean/Green integration focused on waste reduction techniques. *J. Clean. Prod.* **2016**, *137*, 567–578. [CrossRef]
18. Lin, Y.K.; Chang, P.C.; Chen, J.C. Reliability evaluation for a waste-reduction parallel-line manufacturing system. *J. Clean. Prod.* **2012**, *35*, 93–101. [CrossRef]
19. Van Der Wiel, A.; Bossink, B.; Masurel, E. Reverse logistics for waste reduction in cradle-to-cradle-oriented firms: Waste management strategies in the Dutch metal industry. *Int. J. Technol. Manag.* **2012**, *60*, 96–113. [CrossRef]
20. Scherrer-Rathje, M.; Boyle, T.A.; Deflorin, P. Lean, take two! Reflections from the second attempt at lean implementation. *Bus. Horiz.* **2009**, *52*, 79–88. [CrossRef]
21. Browning, T.R.; Heath, R.D. Reconceptualizing the effects of lean on production costs with evidence from the F-22 program. *J. Oper. Manag.* **2009**, *27*, 23–44. [CrossRef]
22. Brown, M.T.; Buranakarn, V. Emergy indices and ratios for sustainable material cycles and recycle options. *Resour. Conserv. Recycl.* **2003**, *38*, 1–22. [CrossRef]
23. Elia, V.; Gnoni, M.G.; Tornese, F. Measuring circular economy strategies through index methods: A critical analysis. *J. Clean. Prod.* **2017**, *142*, 2741–2751. [CrossRef]
24. Formoso, C.T.; Soibelman, L.; De Cesare, C.; Isatto, E.L. Material waste in building industry: Main causes and prevention. *J. Constr. Eng. Manag.* **2002**, *128*, 316–325. [CrossRef]
25. Myhre, M.; Mackillop, D.A. Rubber recycling. *Rubber Chem. Technol.* **2002**, *75*, 429–474. [CrossRef]
26. Pollard, S.J.T.; Fowler, G.D.; Sollars, C.J.; Perry, R. Low-cost adsorbents for waste and wastewater treatment: A review. *Sci. Total. Environ.* **1992**, *116*, 31–52. [CrossRef]
27. Al-Obaidi, K.M.; Wei, S.L.; Ismail, M.A.; Kam, K.J. Sustainable building assessment of colonial shophouses after adaptive reuse in Kuala Lumpur. *Buildings* **2017**, *7*, 87. [CrossRef]
28. Bocken, N.M.P.; Olivetti, E.A.; Cullen, J.M.; Potting, J.; Lifset, R. Taking the Circularity to the Next Level: A Special Issue on the Circular Economy. *J. Ind. Ecol.* **2017**, *21*, 476–482. [CrossRef]
29. Galle, W.; de Temmerman, N.; Meyer, R.D. Integrating scenarios into life cycle assessment: Understanding the value and financial feasibility of a demountable building. *Buildings* **2017**, *7*, 64. [CrossRef]
30. Mok, H.S.; Kim, H.J.; Moon, K.S. Disassemblability of mechanical parts in automobile for recycling. *Comput. Ind. Eng.* **1997**, *33*, 621–624. [CrossRef]
31. Adams, K.T.; Osmani, M.; Thorpe, T.; Thornback, J. Circular economy in construction: Current awareness, challenges and enablers. *Proc. Inst. Civ. Eng. Waste Resour. Manag.* **2017**, *170*, 15–24. [CrossRef]
32. Bakker, C.; Wang, F.; Huisman, J.; Den Hollander, M. Products that go round: Exploring product life extension through design. *J. Clean. Prod.* **2014**, *69*, 10–16. [CrossRef]
33. Hirschl, B.; Konrad, W.; Scholl, G. New concepts in product use for sustainable consumption. *J. Clean. Prod.* **2003**, *11*, 873–881. [CrossRef]
34. Sanchez, B.; Haas, C. Capital project planning for a circular economy. *Constr. Manag. Econ.* **2018**, *36*, 303–312. [CrossRef]
35. Truttmann, N.; Rechberger, H. Contribution to resource conservation by reuse of electrical and electronic household appliances. *Resour. Conserv. Recycl.* **2006**, *48*, 249–262. [CrossRef]
36. Merrild, H.; Jensen, K.G.; Sommer, J. *Building a Circular Future*; GXN Innovation: Copenhagen, Denmark, 2016.

37. Catalli, V.; Williams, M. Designing for disassembly [An innovative strategy for attaining environmental goals and building adaptability] [Mountain Equipment Co-op Ottawa store case study]. *Can. Arch.* **2001**, *46*, 27–29.
38. Ashcraft, H.W. Building information modeling: A framework for collaboration. *Constr. Law* **2008**, *28*, 5.
39. Desai, A.; Mital, A. Incorporating work factors in design for disassembly in product design. *J. Manuf. Technol. Manag.* **2005**, *16*, 712–732. [CrossRef]
40. Blengini, G.A. Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. *Build. Environ.* **2009**, *44*, 319–330. [CrossRef]
41. Knoeri, C.; Sanyé-Mengual, E.; Althaus, H.-J. Comparative LCA of recycled and conventional concrete for structural applications. *Int. J. Life Cycle Assess.* **2013**, *18*, 909–918. [CrossRef]
42. Tam, V.W.Y. Economic comparison of concrete recycling: A case study approach. *Resour. Conserv. Recycl.* **2008**, *52*, 821–828. [CrossRef]
43. Yellishetty, M.; Mudd, G.M.; Ranjith, P.G.; Tharumarajah, A. Environmental life-cycle comparisons of steel production and recycling: Sustainability issues, problems and prospects. *Environ. Sci. Policy* **2011**, *14*, 650–663. [CrossRef]
44. Ahmadian FF, A.; Rashidi, T.H.; Akbarnezhad, A.; Waller, S.T. BIM-enabled sustainability assessment of material supply decisions. *Eng. Constr. Arch. Manag.* **2017**, *24*, 668–695. [CrossRef]
45. Akadiri, P.O.; Olomolaiye, P.O. Development of sustainable assessment criteria for building materials selection. *Eng. Constr. Arch. Manag.* **2012**, *19*, 666–687. [CrossRef]
46. Power, D.; Gruner, R.L. Variable use of standards-based IOS enabling technologies in Australian SMEs: An examination of deliberate and emergent decision making processes. *Eur. J. Inf. Syst.* **2017**, *26*, 164–184. [CrossRef]
47. Pearce, D.W.; Turner, R.K. *Economics of Natural Resources and the Environment*; JHU Press: Baltimore, MD, USA, 1990.
48. Lan, C.H. The design of multiple production lines under deadline constraint. *Int. J. Prod. Econ.* **2007**, *106*, 191–203. [CrossRef]
49. Sacks, R.; Radosavljevic, M.; Barak, R. Requirements for building information modeling based lean production management systems for construction. *Autom. Constr.* **2010**, *19*, 641–655. [CrossRef]
50. Yu, H.; Tweed, T.; Al-Hussein, M.; Nasseri, R. Development of lean model for house construction using value stream mapping. *J. Constr. Eng. Manag.* **2009**, *135*, 782–790. [CrossRef]
51. Höök, M.; Stehn, L. Applicability of lean principles and practices in industrialized housing production. *Constr. Manag. Econ.* **2008**, *26*, 1091–1100. [CrossRef]
52. Allwood, J.M.; Cullen, J.M.; Carruth, M.A.; Cooper, D.R.; McBrien, M.; Milford, R.L.; Moynihan, M.C.; Patel, A.C. *Sustainable Materials: With Both Eyes Open*; UIT Cambridge: Cambridge, UK, 2012.
53. Allwood, J.M.; Ashby, M.F.; Gutowski, T.G.; Worrell, E. Material efficiency: A white paper. *Resour. Conserv. Recycl.* **2011**, *55*, 362–381. [CrossRef]
54. Steinhilper, R.; Hieber, M. Remanufacturing-the key solution for transforming "downcycling" into "upcycling" of electronics. In Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment, Denver, CO, USA, 9 May 2001; pp. 161–166.
55. Tabsh, S.W.; Abdelfatah, A.S. Influence of recycled concrete aggregates on strength properties of concrete. *Constr. Build. Mater.* **2009**, *23*, 1163–1167. [CrossRef]
56. Penteado, C.S.G.; Viviani De Carvalho, E.; Lintz, R.C.C. Reusing ceramic tile polishing waste in paving block manufacturing. *J. Clean. Prod.* **2016**, *112*, 514–520. [CrossRef]
57. Demir, I.; Orhan, M. Reuse of waste bricks in the production line. *Build. Environ.* **2003**, *38*, 1451–1455. [CrossRef]
58. Junak, J.; Sicakova, A. Effect of surface modifications of recycled concrete aggregate on concrete properties. *Buildings* **2017**, *8*, 2. [CrossRef]
59. Meyer, C. The greening of the concrete industry. *Cem. Concr. Compos.* **2009**, *31*, 601–605. [CrossRef]
60. Teixeira, E.R.; Mateus, R.; Camõesa, A.F.; Bragança, L.; Branco, F.G. Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material. *J. Clean. Prod.* **2016**, *112*, 2221–2230. [CrossRef]
61. Imbabi, M.S.; Carrigan, C.; McKenna, S. Trends and developments in green cement and concrete technology. *Int. J. Sustain. Built Environ.* **2012**, *1*, 194–216. [CrossRef]

62. Omran, A.; Tagnit-Hamou, A. Performance of glass-powder concrete in field applications. *Constr. Build. Mater.* **2016**, *109*, 84–95. [CrossRef]
63. Aye, L.; Ngo, T.; Crawford, R.H.; Gammampila, R.; Mendis, P. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy Build.* **2012**, *47*, 159–168. [CrossRef]
64. Cullen, J.M. Circular Economy: Theoretical Benchmark or Perpetual Motion Machine? *J. Ind. Ecol.* **2017**, *21*, 483–486. [CrossRef]
65. Desai, A.; Mital, A. Evaluation of disassemblability to enable design for disassembly in mass production. *Int. J. Ind. Ergon.* **2003**, *32*, 265–281. [CrossRef]
66. De Ron, A.; Penev, K. Disassembly and recycling of electronic consumer products: An overview. *Technovation* **1995**, *15*, 363–374. [CrossRef]
67. Go, T.F.; Wahab, D.A.; Rahman, M.N.A.; Ramli, R.; Azhari, C.H. Disassemblability of end-of-life vehicle: A critical review of evaluation methods. *J. Clean. Prod.* **2011**, *19*, 1536–1546. [CrossRef]
68. Langerak, E. To shred or to disassemble? Recycling of plastics in mass consumer goods. In Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment, San Francisco, CA, USA, 5–7 May 1997; pp. 63–68.
69. Gorgolewski, M. Designing with reused building components: Some challenges. *Build. Res. Inf.* **2008**, *36*, 175–188. [CrossRef]
70. Oguchi, M.; Tasaki, T.; Moriguchi, Y. Decomposition analysis of waste generation from stocks in a dynamic system: Factors in the generation of waste consumer durables. *J. Ind. Ecol.* **2010**, *14*, 627–640. [CrossRef]
71. Woods, L.; Bakshi, B.R. Reusable vs. disposable cups revisited: Guidance in life cycle comparisons addressing scenario, model, and parameter uncertainties for the US consumer. *Int. J. Life Cycle Assess.* **2014**, *19*, 931–940. [CrossRef]
72. Arge, K. Adaptable office buildings: Theory and practice. *Facilities* **2005**, *23*, 119–127. [CrossRef]
73. Sanchez, B.; Haas, C. A novel selective disassembly sequence planning method for adaptive reuse of buildings. *J. Clean. Prod.* **2018**, *183*, 998–1010. [CrossRef]
74. Wheaton, W.G. Designing for Disassembly in the Built Environment. Master's Thesis, Univesrity of Washington, Seattle, WA, USA, 2017.
75. Crowther, P. Developing Guidelines for Designing for Deconstruction. In *Deconstruction—Closing the Loop*; BRE Group: Garston, UK, 18 May 2000.
76. Wu, S.-H. Use BIM and Prefabrication to Reduce Construction Waste. Master's Thesis, Univesrity of Washington, Seattle, WA, USA, March 2017.
77. Braungart, M.; McDonough, W.; Bollinger, A. Cradle-to-cradle design: Creating healthy emissions–a strategy for eco-effective product and system design. *J. Clean. Prod.* **2007**, *15*, 1337–1348. [CrossRef]
78. Van Erp, G.; Rogers, D. A highly sustainable fibre composite building panel. In Proceedings of the International Workshop on Fibre Composites in Civil Infrastructure–Past, Present and Future, Toowoomba, Queensland, Australia, 1–2 December 2008.
79. Sri Ravindrarajah, R.; Tam, C.T. Recycling concrete as fine aggregate in concrete. *Int. J. Cem. Compos. Lightweight Concr.* **1987**, *9*, 235–241. [CrossRef]
80. Noguchi, T.; Tamura, M. Concrete design towards complete recycling. *Struct. Concr.* **2001**, *2*, 155–167. [CrossRef]
81. Evangelista, L.; de Brito, J. Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cem. Concr. Compos.* **2007**, *29*, 397–401. [CrossRef]
82. Park, J.Y.; Chertow, M.R. Establishing and testing the "reuse potential" indicator for managing wastes as resources. *J. Environ. Manag.* **2014**, *137*, 45–53. [CrossRef] [PubMed]

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Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building

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A B S T R A C T

Recent research indicates that circular economy practices have the potential to provide significant environmental benefits. In particular, recycling has been associated with reductions of greenhouse gas emissions. However, in this study, the authors posit that in a building context, environmental benefits of reuse practices could far surpass recycling. To test this, we evaluated the environmental benefits of a prototype and purpose-built, modular building designed for disassembly and reuse through a life cycle assessment of its components. We then compared the results of our life cycle assessment with the results of a contemporary construction approach with a focus on the recyclability of materials. Our results indicate that, compared to recycling, designing and building for reuse components offsets greenhouse gas emissions by 88% while also benefiting several other tested environmental indicators. Our findings help guide the judicious adoption of practices to reduce buildings' waste production and greenhouse gas emissions.

1. Introduction

The practice of taking, using, and disposing products in a linear fashion is common in the building sector (Campbell-Johnston et al., 2019) and is the main cause of material depletion and waste production associated with environmentally unsustainable operations (Brambilla et al., 2019; Jimenez-Rivero and Garcia-Navarro, 2017a). Across most developed countries, around one third of all generated waste originates from the building sector (Eckelman et al., 2018; Martín-Morales et al., 2017). To test the extent to which it is possible to limit the building sector's adverse environmental impact, this study employs a circular economy (CE) approach in this context (Eberhardt et al., 2019b; Jimenez-Rivero and Garcia-Navarro, 2017a; Minunno et al., 2018). We define CE as aiming to increase material efficiency through the adoption of the 3R's: reduce, reuse and recycle (Kirchherr et al., 2017; Lieder and Rashid, 2016; Zaman, 2014).

We hypothesize that a CE of building materials can be achieved through a combination of reuse and recycle practices. We conducted a systematic review of the literature, which revealed that recycling is considered the most applied practice toward a CE (Haas et al., 2015; Kirchherr et al., 2017). However, significant research evidence suggests that recycling is the least beneficial of the 3R's, as some recyclable materials are invariably wasted or contaminated in the process (Jimenez-Rivero and Garcia-Navarro, 2017b; Lawson et al., 2001).

Conversely, components which are designed for disassembly from the outset, enable reuse practices to be optimized at the end of the buildings' useful life, thereby minimizing demolition waste (Guy et al., 2006; Kibert et al., 2000). Amongst non-structural components, for example, windows can be easily disassembled and reused (Eberhardt et al., 2019a; Krikke et al., 2004; Schultmann and Sunke, 2007). Further, technological innovation fosters the disassemblability of structural components, such as concrete columns, floor systems and roof structures (Brambilla et al., 2019; Eberhardt et al., 2019a). Design for disassembly and reuse is gaining traction despite many obstacles, in particular, the lack of marketability of reuse components and the competitiveness of material recycling (e.g. Akanbi et al. (2019), Hopkinson et al. (2018) and Tingley et al. (2017)). However, little research tests the combined approach of reuse and recycle and how they differentially impact environmental metrics, such as material saving and the reduction of greenhouse gas emissions (Corona et al., 2019).

To test the environmental benefits of design for disassembly and reuse, we have designed and constructed a modular building, which is called the Legacy Living Lab (L3). Doing so represents an opportunity to foster the application of design for disassembly through prefabrication of building components and modular building technology (Allwood, 2014). Although the LCA method has been applied to a number of other buildings to calculate their environmental impact (Cabeza et al., 2014; Eberhardt et al., 2019b; Guinée et al., 2011), and to investigate the benefits of reusing building components

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(Eberhardt et al., 2019a; Eckelman et al., 2018), to our knowledge, a comparative assessment of the benefits of reuse over recycle has not been carried out for a whole building.

We posit that, apart from material savings, reusing products and components can lead to improved environmental performance when compared to recycling alone. We test this notion empirically through a life cycle assessment (LCA)—a method commonly applied to calculate the environmental impact of buildings throughout their life cycle (Bribián et al., 2009; Westin et al., 2019)—that measures the greenhouse gas emissions and other environmental indicators of L3's materials and components. Further, we compare the results with an LCA of the same building assuming that it had been built in a traditional manner, i.e. not designed to be disassembled and reused.

Our objective is to explore the environmental benefits of the following three practices: (1) integration of reused materials in the building's production stage; (2) implementation of adaptable design to eliminate waste during the operation stage; (3) design for disassembly and reuse, which enables components' second life. Our study explores the environmental benefits of reuse over recycle in the context of a full-scale modular building, using a purposely built prototype. This approach allows us to make a number of practical and theoretical contributions that help offset the building sector's adverse environmental impact.

2. Methodology

Allwood (2014) refers to the 3R's as a synonym for CE. From this perspective, the 3R's can be considered as a hierarchy of practices, ordered by effectiveness of material saving and environmental benefits. The focus of this paper is the application of reuse and recycle practices. In this paper we consider the underexplored practice of reusing building components, and apply an LCA to a building that has been prototyped with the purpose of studying the feasibility of creating a CE construction. We then compare reuse and recycle, to investigate which practice produces greater environmental benefits.

2.1. The legacy living lab prototype

The case study presented in this paper is the L3, a modular building that the authors designed and built in an industrial consortium following the principles of CE, 3R's and Cradle-to-Cradle (McDonough and Braungart, 2010). The L3 was built at a dedicated modular facility in Perth, Western Australia. It is comprised of eight modules (five on the ground floor and three on the first floor). L3 has a floor area of 251 m^2, and includes a meeting area and café space on the ground floor, and an open office area with shared kitchenette on the first floor. The ground floor and first floor of the prototype L3 are specifically designed for adaptability (Fig. 1). The structure is built using a heavy gauge steel chassis and columns, light gauge steel wall frames and particle board floors. The external cladding is pressed recycled timber on the ground floor and corrugated steel sheeting on the first floor and roof. Internal cladding is composed of plywood sheets and plaster board. Fig. 2 shows the first floor of the prototype building L3. The ceiling and internal cladding were designed to be fully disassemblable, granting access to the insulation and electrical systems, without creating any waste. To increase the reusability of buildings, we designed the prototype including open plan spaces.

We compared the environmental impact of this disassemblable building, namely the circular L3 (C), with a variation designed as a linear (traditional) version (L). The linear version is based on the modular builder's typical *modus operandi*, which assumed design without considering the CE features. In summary:

Circular approach, C. The built prototype, L3 was designed and built following the CE of buildings. The bolted connections are accessible, providing fast installation and complexing from safe working positions. Balcony waterproofing over module splits was designed to be non-destructive, ensuring that only minimal repairs or patching will be needed between lifecycles.

Linear approach, L. The hypothetical case study used for comparison, was typical of a build by the same modular builder, in its production facility. The linear case study would use traditional modular building practices. These buildings are typically made to be moved only once, and their materials landfilled or recycled upon demolition.

Hereafter, we refer to the circular version as C, and to the linear version as L, both as regular text or as subscripts.

2.2. Systematic literature review methodology

An important feature of this paper is a systematic review of the literature and analysis of research findings on deconstruction, reuse of components within the construction industry, CE practices and environmental assessment methods. We reviewed the literature by adopting a systematic approach to ensure replicability and decrease the risk of biases (Siddaway et al., 2019). Additionally, the systematic literature review method allowed us to gather the extensive literature that has been produced on this topic and helped position this research in the literature (Merli et al., 2018; Tranfield et al., 2003). In selecting the relevant articles, we applied five main steps (Khan et al., 2003). First, we selected the search keywords that form the search phrase circular economy AND (reuse OR reduce OR recycle) AND building; we searched the phrase in Scopus, and extracted the results into EndNote X9. Second, in EndNote we identified 34 relevant studies. Third, we identified two main focuses of the shortlisted articles: circular economy practices and design for disassembly. Fourth, we summarized the key insights of the selected articles in Table 1 and employed them as background studies as well as to consolidate our findings.

2.3. Life cycle assessment methodology

The LCA methodology enables quantification of the environmental impact of products' life, from production to disposal and next product systems, including material recycle and reuse (International Organization for Standardization, 2006). Buildings have an impact on the environment during their life cycle stages, from construction to disposal, and further, to their next product system (Sharma et al., 2011a).LCAs have been extensively applied to buildings, evaluating their environmental impact across all these stages (Singh et al., 2010). Several applications of the LCA to buildings have focused on the production and operation phases, but with the advent of building disassembly and reuse, LCA is considered a key approach to evaluating environmental benefits of reused building components (Blengini and Di Carlo, 2010; Eberhardt et al., 2019b). Although the literature on LCA and CE practices for buildings is still fragmented, it is clear that a great reduction of environmental impact could be achieved by implementing the reuse of building components (Zink and Geyer, 2017).

This comparative LCA was performed using SimaPro 9.0 and the database Ecoinvent 3.5. This is in accordance with the European international standards 14040 and 14044 (Chomkhamsri et al., 2011).

2.3.1. Goal and scope definition

The goal of this LCA is to calculate the environmental impact of a modular building designed following the CE principles of design for disassembly and reuse, and compare it to the same modular building, constructed without considering the disassembly phase. Hence, this research aims to quantify the potential environmental benefits of building for disassembly and reuse. The focus of this research is the environmental impact due to materials alone. The LCA method is divided into four main stages (Junnila et al., 2006): production, operation, end of life and next product system (Table 2) (Cabeza et al., 2014). The transport of raw materials (A2) and transport of modules (A4) stages were excluded from this research, whereas refurbishment and repair or components damaged during the operation stage were

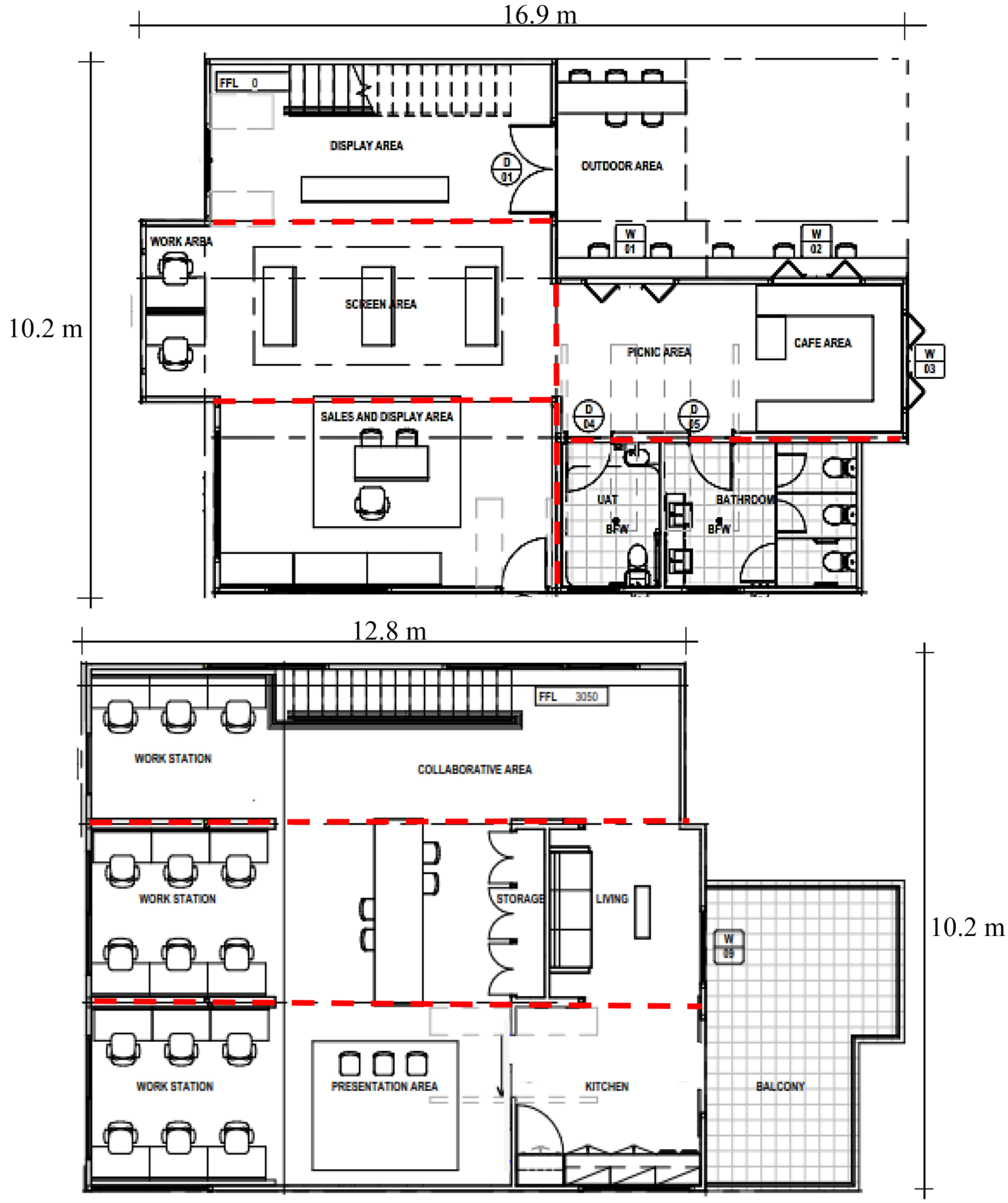

Fig. 1. – Plans of the prototype L3. The ground floor (top, 117m^2) and the first floor (bottom, 129m^2) were designed for adaptability of spaces. The red dashed lines highlight where the eight modules can be detached to disassemble the L3.

included (B1). The energy and water consumption related to the operational stage was not considered (LCA stage B2). The end of life and next product system stages (C and D) are included, with the exclusion of transport to disposal and recycling facilities (C2).

The functional unit expresses the function of the analyzed products and is used in LCAs as the basis of calculations of the quantities of materials studied (Baumann and Tillman, 2004). The functional unit chosen in this LCA is the whole building.

An attributional LCA was adopted in this study, allowing the determination of the environmental impact related to the product system (the building itself), as opposed to the consequential methodology, which focuses on the broader environmental impact of system changes, i.e. the building and its interactions with the environment (Baumann and Tillman, 2004; Cabeza et al., 2014).

The characterization method adopted in this study is the CML-IA (Centrum voor Milieuwetenschappen Leiden Impact Assessment) baseline. The impact categories and analysis in this LCA were selected amongst the most commonly used in other similar studies (Green Building Council of Australia, 2014; Khasreen et al., 2009; Sharma et al., 2011b; Stocker et al., 2013; Yellishetty et al., 2011). We quantified global warming potential (GWP, measured in t CO_2 eq), ozone depletion potential (ODP, measured in kg CFC-11 eq *10^4), acidification potential (AP, measured in kg SO_2 eq), eutrophication potential (EP, measured in kg PO_4 eq), abiotic depletion of non-fossil resources (AD, measured in kg Sb eq *10^2), and abiotic depletion of fossil fuels (ADFF, measured in MJ*10^2).

Fig. 2. – First floor of the prototype building L3. The wall and roof cladding is disassemblable, showing the frames granting access to insulation and systems. This feature allows low waste and low environmental impact during the operation stage of the L3.

2.3.2. Life cycle inventory analysis

The data for the life cycle inventory analysis typically include the material input and output, transport, waste generated, material recycle and reuse, and assembling processes (Crawford, 2011). In our case, these materials were meticulously measured in the construction phase of the building, therefore we could gather exact measures and produced the accurate primary data listed in Table 3.

The life cycle inventory analysis defines system boundaries, the link between production, use and disposal phases and material flow. Further, the life cycle inventory analysis is the LCA stage where the data is collected and evaluated. Fig. 3 highlights the difference between the LCA of approaches C and L. The material inflow in case C is lower than the materials necessary to build case L, considering that some components (i.e. steel frame, carpet and timber staircase) are already in their second life. In case L, the material flows from the off-site production phase to landfill or recycling of the building. When the first life cycle of the circular approach ends, the building is refurbished and reused (eventually relocated), starting a second life cycle, and has the potential to be reused multiple times without creating any waste. When the building reaches the end of its final life cycle, most materials are reused into the construction industry. The remaining components that cannot be reused are recycled or sent to landfill. Furthermore, the building is designed to reduce any waste during the refurbishment/repair/renew stage (operation stage, B) of the circular L3 alone (B_C). Typically, the building components that are replaced during the operation stage are finishes. Often finishes need to be replaced to access walls and ceilings, and in the case of traditional constructions, to do so requires destroying or cutting wall finishes (Ghose et al., 2017; Hossain and Ng, 2018). To avoid this issue, we employed resilient finishing materials, such as plywood or steel sheets, which, due to their flexibility, are virtually unbreakable. Additionally, we avoided chemically bonding connections (i.e. by gluing or welding). Instead, we opted for disassemblable connections for all module joints and most wall and ceiling spaces. Thus, the stage B_C is expected to contribute insignificant or virtually zero environmental impact. In contrast, a traditional installation of a plywood wall finish would use a nail fixing and adhesive to connect the plywood to the stud wall. This method is used for installation speed and to hide the fixings. Due to the fixings being nails and the glued connection to the wall frame, the plywood must be destroyed to be removed. Consequently, during the operational stage of the comparison case L (B_L), some materials are assumed to be wasted for maintenance (see Section 0, Dixit et al. (2013), Kamali and Hewage (2016)). Fig. 3 reflects this assumption in showing that—during the operations stage of the circular design (B_C)—we expect virtually no inflow or outflow of materials whereas during the operation stage of the linear design (B_L) some materials are needed to renovate the building.

2.4. Sensitivity analysis

When performing an LCA, it is typically difficult to collect precise data, therefore often there is a need to assume and even speculate about the amounts of some materials. This data uncertainty usually derives from secondary data (Brogaard et al., 2014), and can affect the LCA results significantly. The incidence of the uncertainty needs to be evaluated by means of sensitivity analysis (Hu, 2019; Wang and Shen, 2013). For example, a sensitivity analysis was necessary in both Hossain et al. (2016) and Brambilla et al. (2019), as they had elements of uncertainty when evaluating unknown material transport distance; in addition, Jain et al. (2020) carried out a sensitivity analysis to quantify the uncertainty due to recycling plants efficiency and electricity mix production. Conversely, a sensitivity analysis is not necessary when only primary data is used (see Toniolo et al. (2017), Wei et al. (2015)). In this study, however, we carried out an LCA of a building that has been purposely designed and built so that all the materials in this inventory are calculated directly from field measurements and using primary data only. Consequentially, as we eliminated all possible uncertainties, a sensitivity analysis was not necessary.

3. Results – Life cycle impact assessment

3.1. Life cycle assessment of the L3 designed for disassembly

The L3 was designed for disassembly and reuse. The environmental impact of the circular design of L3 accounts for its materials (as listed above in Table 3), however, the majority of the steel structure was reused from previous buildings (a total of 16 139 kg of steel out of the overall 22 070 kg). We salvaged these structures which otherwise would have been recycled. Other elements, such as carpet tiles or

Table 1.
Selected studies pertaining to the material focus and circular economy practice.

Studies	Research design	Study purpose	Key insights
Focus on circular economy practices			
Hopkinson et al. (2018)	Comprehensive literature review approach.	Understanding how the CE has been applied to which materials and building components.	• Reusing building components can overtake the environmental benefits of recycling processes. • Studies on the environmental benefits of reuse of building components is fragmented.
Honic et al. (2019)	Creating a methodology to compile the Material Passport of building, through the use of BIM.	Building a new tool (Material Passport) to foster the recyclability of building materials. The authors test the tool on a case study designed in timber vs concrete.	• Whereas concrete is typically more recyclable than timber, recycling concrete also produces more waste. • Integrate circular economy thinking in the design phase of buildings allows greater environmental benefits.
Jimenez-Rivero and Garcia-Navarro (2017a)	Survey and literature review.	The aim of this paper is to collect the practices of recycling gypsum waste, and define under which circumstances it is landfilled.	Not all countries have regulations on recycling gypsum waste in Europe, but other factors that limits its recycling are: ○ Difficult on site segregation. ○ Workers experience and skills. ○ Lacking of design for disassembly (which makes more difficult segregation without contamination)
Verbinnen et al. (2017)	General review.	Summarizing the possibilities, limits and barriers of using MSWI fly-ashes as by-product into new materials.	The integration of by-products into new materials (i.e. MSWI fly-ashes into concrete) can hide secondary consequences, such as excessive heavy metals concentrations.
Parron-Rubio et al. (2018)	Testing different types of slag as by-products to substitute concrete.	Integration of by-products into concrete as a way to reuse waste.	• Cross-industry reuse of waste as new resource can be successful and open new opportunities toward a circular economy. • Integrating slag into concrete has the double benefit of reusing waste and diminish cement needed for concrete.
Rose et al. (2018)	Empirical research on integrating used timber into cross laminated secondary timber (CLST).	Comparing the structural characteristic of CLT with a similar product made out of reused timber.	• Used timber is conventionally down-cycled into chipboard or similar products, and can be down-cycled only once before disposal or incineration. • In the EU reuse of timber in CLT is not allowed, however, CLST has proven to be structurally similar to CLT.
Focus on design for disassembly			
Brambilla et al. (2019)	LCA of different concrete/steel floor structure technologies designed for disassemble (case studies).	Evaluate the environmental impact of different structural components, to understand which technology allows greater benefits in terms of GWP and other indicators.	Through DfD, structural components can be used multiple times, providing great benefits for the environment.
Eberhardt et al. (2019)	LCA of a building designed for disassembly, case study in Denmark. Four different structural materials are compared to traditional buildings.	Highlighting the potential environmental saving owed to DfD practices. To do so, the authors assess the life cycle of reusable concrete structure, steel, timber and concrete/bricks.	• Material choice, DfD and buildings service life are amongst the most important parameters that influence the LCA of buildings. • Up to 60% of saving (weighted amount of different environmental indicators) can be achieved when reusing building components three times.
Tingley et al. (2017)	Semi-structured interviews and literature study.	Discover the barriers toward reuse of steel components in the UK and propose framework to overcome these barriers.	• There is not yet demand for reused components, and until steel components reuse is regulated, their reintegration in the market is unachievable. • Disassembling steel structure can often be more expensive than the preferred demolishing practices. • Governments could implement regulations that force new buildings to be scanned for potentially reusable materials, during their design phase.
Akanbi et al. (2018)	BIM and case study evaluation.	Quantify reusable and recyclable materials in building structures, through the use of BIM.	Buildings that are designed to be disassembled, using the BIM tool, can provide up to 93% of reusable components.
Nußholz et al. (2019)	Surveys. Comparative case studies of three producers of circular materials for the built environment.	The authors examine the case studies business models to facilitate the application of the circular economy on building materials and components.	• Existing companies that close the material loop find difficulties in gathering uncontaminated, high quality materials. • Design for disassembly helps providing components and materials that can be reused. • Modular design is one strategy to upscale the availability of reusable building components.

plywood boards for internal finishes, can be completely disassembled and replaced after each life cycle. In prototyping this building, we used lightweight, pile driven steel foundations instead of typical concrete foundations. Additionally, we designed and constructed the building with the comparative linear building (see section 0 below), the LCA stage B_C is considered but has no impact. The life cycle stages of the circular L3 are characterized by:

- A_C: reused materials, addition of some raw materials, and assembly of the building.
- B_C: refurbishment and renewal of internal and external finishes. This LCA stage has minimal impact in the circular L3, as all glued and welded connections were replaced by screwed connections, making walls and ceilings accessible without having to destroy or cut wall finishes.
- C_C: disposal of the materials that are not reusable or recyclable.
- D_C: discount of CO_2 equivalent emissions attributed to reuse and recycle of components (e.g. steel components, aluminum, plasterboard).

Table 2.
Life cycle stages included in this study.

Material input	LCA stage	Process	Code	Included
	Production (A)	Raw materials input	A1	Yes
		Transport of raw materials	A2	No
		Production	A3	Yes
		Transport of modules to site	A4	No
		Craning	A5	Yes
	Operation (B)	Refurbishment/repair	B1	Yes
		Energy and water consumption for operation	B2	No
Material output	End of life (C)	Deconstruction/ demolition	C1	Yes
		Transport to landfill	C2	No
		Waste recovery	C3	Yes
		Landfill disposal	C4	Yes
	Next product system (D)	Reuse, recovery or recycle	D	Yes

Fig. 4 shows the environmental impact of the building during its four life cycle stages (Balasbaneh et al., 2019; Fufa et al., 2018; Hoxha et al., 2017). The production stage is when most of the impact is generated, however, refurbishing the L3 allows the building to be reused across multiple life cycles (Table 4). When the building reaches the end of life, it is disassembled and its components reused, recycled or disposed.

Production (A_C). The production life cycle stage (A_C) accounts for the impact of all the materials involved in the production stage. Following the CE principles, the L3 was built reusing 16 139 kg of salvaged steel, which would otherwise have been recycled. Recycling steel has a potential positive environmental impact, and because that potential was not realized, it was accounted for as an adverse impact. For this reason, steel is the most negative impacting material in the production stage of the circular L3 (A_C). A total of about 62% of the mass of the building is steel (all the frames, foundations, floors and roof structures, and second level external cladding and roof cover), and its environmental impact is around 70% of the total impact of L3 in most categories (e.g. 30.6 t CO_2 eq in terms of global warming potential, 9.4 kg CFC-11 eq $*10^4$ in terms of ozone depletion potential, 123.7 kg SO_2 eq in terms of acidification potential, and 29.5 kg PO_4 eq in terms of eutrophication potential), and almost 90% of abiotic depletion (equivalent to 24.8 kg Sb eq $*10^2$). Timber, however, is the second most impacting material. Timber represents about 27% of the mass of the building, and was used as floor structure and first level partial internal and external cladding; its impact ranges from about 20% (or 3.3 kg CFC-11 eq $*10^4$) of ozone depletion potential, to 5% (or 20.3 kg SO_2 eq) of abiotic depletion. The impact of other materials, i.e. carpet tiles, vinyl and insulation, is also important, as it sums up to about 20% of the total global warming potential.

End of life and next product (C_C and D_C). Most materials of the C version of L3 are reused or recyclable, leaving only timber, floor covering and insulation to contribute to the disposal stage (C_C). For this reason, the reduction of global warming potential across the LCA is due to the D_C stage, dropping from about 47.2 t CO_2 eq to the final value of 5.4 t CO_2 eq. The reuse and recycle of steel are the main positive contributors for all environmental impact categories, decreasing the impact by up to about 88% of global warming potential, ozone depletion potential and acidification potential. All structural steel components are designed to be reused, for a total of about 20 t. The joints are fastened with nuts and bolts and positioned to be easy to reach, the two main requirements for reusability of building components (Allwood, 2014; Dunant et al., 2017; Eberhardt et al., 2019b; Gorgolewski, 2008). Another important requirement to move toward a CE is standardization of components, which contributes to their reuse. In our case, the dimensions of the internal steel wall frame sections are consistent within the whole building, with a width of 1200 mm, aligned with standard construction sheet sizes (e.g. plywood boards). Despite our efforts in making most components disassemblable and reusable, 1.6 t of steel cannot be reused (i.e. the steel sheets used for external cladding and roofing). Instead, this non-reusable steel will be recycled. Timber is another material whose environmental impact is not negligible. We calculated that the 9.5 t of timber used in L3 (or, as mentioned above, its 27% by mass), will be disposed to landfill when decommissioning the L3. Disposing this amount of timber has the detrimental effect of increasing the eutrophication potential by 40%.

3.2. Life cycle assessment of the linear L3

The linear version of L3 differs from the circular one in the way it has been conceptualized. The linear version does not include any reused materials; it has not been designed for disassembly; and the foundations are concrete, as it has been designed as a traditional modular building. As a consequence, all the materials are new, the joints are welded, instead of bolted, and at the end of the life cycle it cannot be disassembled, but most materials (e.g. steel and concrete) might be recycled. The life cycle stages of the linear L3 are characterized by:

- A_L: entirely new components, and assembly of the building.
- B_L: refurbishment and renewal of internal and external finishes.
- C_L: disposal of the materials that are not recyclable.
- D_L: discount of CO_2 equivalent emissions due to recycling of materials (e.g. steel, aluminum, plasterboard).

In each impact category, the production stage (A_L) accounts for most of the impact generated. At the end of life of the linear case study, some materials are recycled (e.g. steel and concrete), and all the non-recyclable materials are disposed to landfill (Table 5 and Fig. 5).

Production (A_L). The production stage accounts for all the materials and components used in the building, and the assembly processes. All the components are new and produced from raw materials. The 21 t of steel that have been used in the building represent about 70% (or 43.9 t

Table 3.
Life cycle inventory, materials input involved in the production of L3.

Material	**Description**	**Amount (kg)**
Steel	Chassis and load bearing structure, internal walls structure, and external cladding.	21 335
Timber	Stairway steps, cladding plywood, flooring pressed timber and external cladding pressed timber.	9 406
Concrete foundations	Concrete foundations composed of concrete discs and footings[1].	19 848
Steel foundations	Pile driven lightweight steel foundations[2].	735
Plasterboard	Plasterboard cladding, used in kitchen/bathroom areas and ground floor ceiling.	140
Others (carpet, vinyl and insulation)	Floor covering and insulation.	3 413
Openings	Aluminum windows and glazed doors, and internal timber doors.	63 (m^2)

[1] Concrete foundations are only used in the linear version. Its impact is evaluated in section 0.
[2] Steel foundations are included as an alternative design choice in the prototype only.

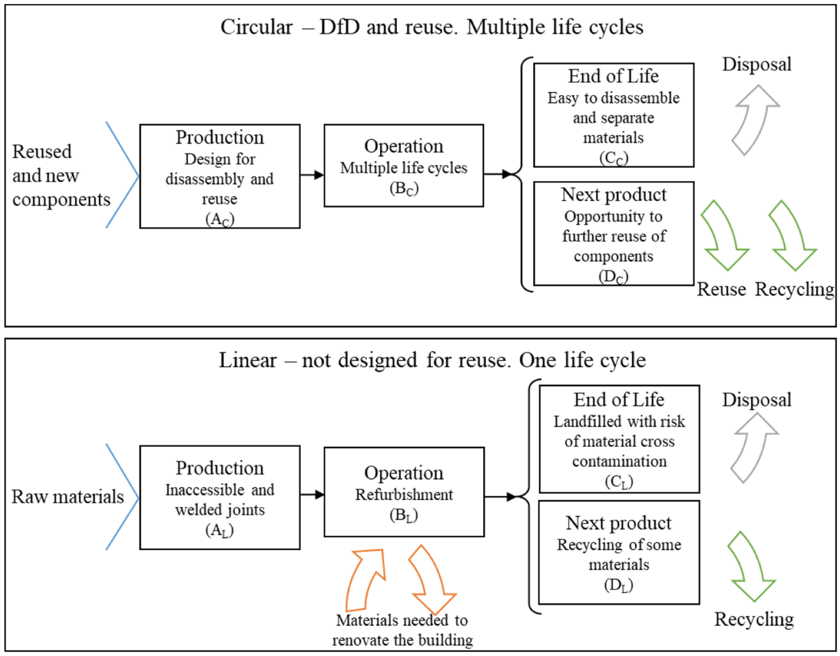

Fig. 3. – Life cycle assessment phases and flows of materials of the four life cycles studied: the linear approach, or traditional offsite manufacturing, L, and the circular approach, offsite manufacturing designed towards disassembly and reuse, C.

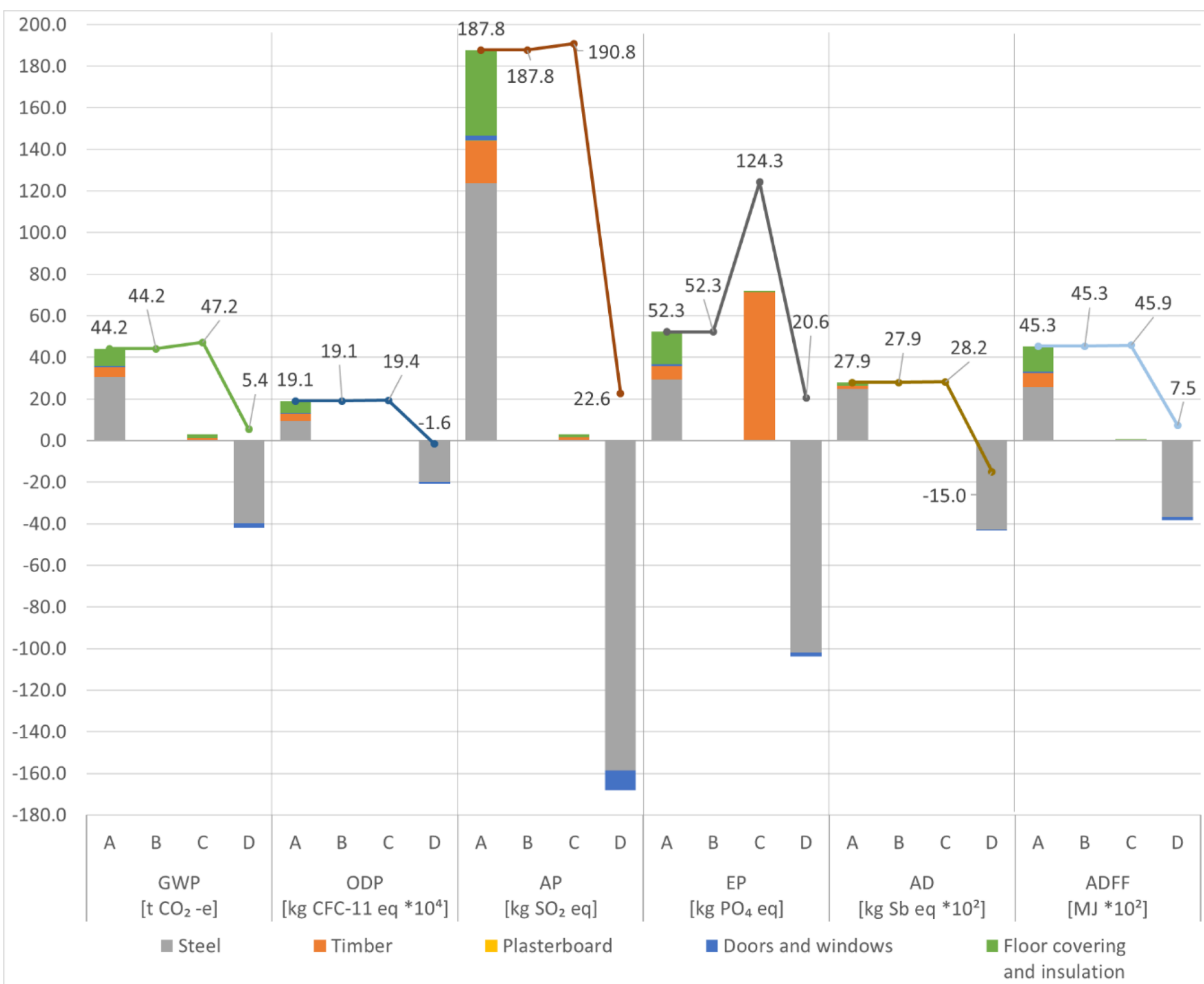

Fig. 4. – LCA of the L3 in its circular version. A = production stage, B = operation stage, C = end of life, and D = next product system. The chart includes the main materials that compose the building, and the cumulative lines to demonstrate how the LCA varies across its four stages.

Table 4.
Life cycle impact assessment of the circular, design for disassembly and reuse L3 (C), divided in the four LCA stages: A_C, production; B_C, refurbishment (considered null); C_C, end of life; D_C next product system.

	GWP (t CO_2 eq)	ODP (kg CFC-11 eq *10^4)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	AD (kg Sb eq *10^2)	ADFF (10^3 MJ *10^2)
A_C	44.2	19.1	187.8	52.3	27.9	45.3
B_C	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0
C_C	3.0	0.3	3.0	72.0	0.2	0.6
D_C	−41.9	−21.0	−168.2	−103.7	−43.1	−38.4
TOTAL	5.4	−1.6	22.6	20.6	−15.0	7.5

Table 5.
Life cycle impact assessment of the linear case study (L), divided in the four LCA stages: A_L, production; B_L, refurbishment; C_L, end of life; D_L, next product system.

	GWP (t CO_2 eq)	ODP (kg CFC-11 eq *10^4)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	AD (kg Sb eq *10^2)	ADFF (10^3 MJ *10^2)
A_L	61.2	33.7	253.0	139.7	62.0	63.7
B_L	6.6	3.2	28.9	8.7	3.2	10.0
C_L	3.0	0.3	3.0	72.0	0.2	0.6
D_L	−26.2	−4.8	−106.3	−10.4	−0.3	−19.6
TOTAL	44.5	32.5	178.6	210.1	65.2	54.6

CO_2 eq) of the global warming potential, ozone depletion potential and acidification potential (22.7 kg CFC-11 eq *10^4 and 178.1 kg SO^2 eq respectively), about 80% (or 113.7 kg PO_4 eq) of the eutrophication potential, almost the total of the abiotic depletion and more than 60% (or 40.7 MJ *10^2) of abiotic depletion of fossil fuels. Overall, concrete and plasterboard have a minor impact, partly because of the limited use of these two materials (in total 19.8 t of concrete and 140 kg of plasterboard).

Refurbishment (B_L). To maintain and refurbish the linear case study, we consider entirely new internal finishes (plywood and plasterboard cladding, carpet and vinyl floor covering), and a partial external cladding and roof covering (20% pressed wood covering, 20% wall steel sheet, 10% roof sheet). The used materials are disposed of or recycled at the end of the first and second life cycles, and substituted with new materials. As shown in Table 5, the impact of the refurbishment process (B_L) accounts for about 11% of the production stage of the building (A_L). Overall, the refurbishment stage increases the impact of the L3 drastically: it accounts for about 15% of global warming potential, acidification potential, and abiotic depletion of fossil fuels (6.6 t CO_2 eq, 3.2 kg Sb eq *10^2 and 10.0 MJ *10^2 respectively), and about 10% (or 3.2 kg CFC-11 eq *10^4) in terms of ozone depletion potential. Timber accounts for the majority of these materials (Table 6), and for most of the environmental impact, ranging from 26% of abiotic depletion to about 83% of ozone depletion potential.

End of life and next product (C_L and D_L). At the end of its life cycle, the linear building is assumed to be demolished, and its components recycled or landfilled. All steel (21 335 kg), concrete (19 848 kg), plasterboard components (140 kg), and doors and windows are recycled, and carpet, insulation, vinyl (3 413 kg) and timber (9 406 kg) disposed to landfill. Recycling steel alone is the most beneficial practice to diminish the impact of the linear building in all impact categories except eutrophication potential and abiotic depletion, where recycling steel is almost negligible. In terms of eutrophication potential, disposing timber creates a peak of PO_4 equivalent emissions. The glass component of windows and doors allows a decrease of about 50% of abiotic depletion, and the disposal of vinyl increases the abiotic depletion of about 47% at the end of life of the building. Owing to recycling practices, the impact of the linear L3 reduces 60% of global warming potential and acidification potential, more than 35% of abiotic depletion of fossil fuels, 15% and 5% in terms of ozone depletion potential and eutrophication potential respectively, but does not result in any saving in terms of abiotic depletion (Table 5).

4. Discussion – Interpretation of results

4.1. Comparison of the L3: circular vs linear design

Fig. 6 illustrates the incremental global warming potential of the circular L3 prototype in comparison with the linear case study building. The overall impact of the circular L3 is 5.4 t CO_2 eq versus 44.5 t CO_2 eq emitted by the linear L3. The environmental benefits of design for disassembly and reuse are apparent from this comparative LCA. The avoidance of recycling, and planning a building that can be reused multiple times resulted in a circular building that impacts much less than its linear counterpart. This finding is valid across all considered impact categories. Indeed, by adopting the CE strategies, the circular L3 proves that it is possible to save about 5% of ozone layer depletion and 23% in terms of abiotic depletion. This translates to a drop from 32.5×10^{-4} kg CFC-11 eq emitted by the linear L3 to -1.6×10^{-4} kg CFC-11 eq, and from 65.2×10^2 kg Sb eq of the linear L3 to -15×10^2 kg Sb eq absorbed by the circular L3 owing mainly to its disassembly and reuse features. In terms of both acidification potential and abiotic depletion of fossil fuels, the circular L3 embodies only around 13% of the linear L3 (or 22.6 kg SO_2 eq compared to the 178.6 kg SO_2 eq emitted by the linear L3 and 750 MJ compared to 5460 MJ embodied by the linear L3). The circular L3 also contributes via diminished environmental impact of buildings in terms of eutrophication potential, resulting in a fall from 210.1 kg PO_4 eq released by the linear L3, to 20.6 kg PO_4 eq released by the circular L3 (Fig. 7).

By zooming-in at the initial and end stages of the circular and linear L3 it is possible to separate the life cycle stages, and therefore unveil the savings of reuse of components and design for disassembly. These savings are analyzed in terms of global warming potential only for simplicity, but more complete results are provided in Table 4 and Table 5.

4.2. Prodution stage: reuse vs virgin materials

The circular L3 was built with several reused components (i.e. chassis and load bearing structure, internal walls structure), while the linear L3 would have been built with components manufactured using virgin materials. The saving due to the adoption of the circular economy strategy of reuse of second hand components can be deduced by calculating the difference between the global warming potential of the production stage of the circular L3 (A_C) and the linear L3 (A_L). This results in a saving of 17.0 t CO_2 eq in terms of global warming potential

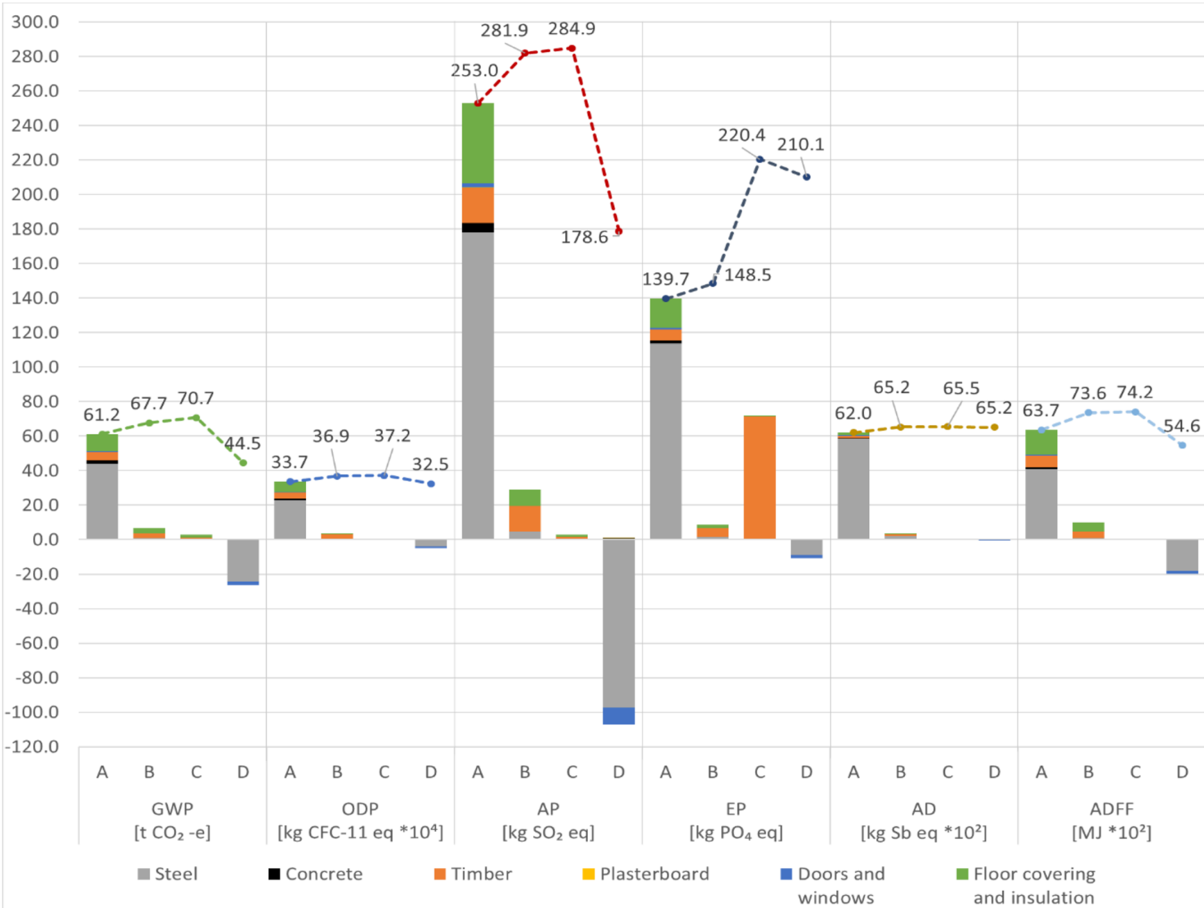

Fig. 5. – LCA of the L3 in its traditional version. A = production stage, B = operation stage, C= end of life, and D = next product system. The chart includes the main materials that compose the building, and the cumulative lines to demonstrate how the LCA varies across its four stages.

Table 6.
Materials replaced during refurbishment stages (B_L) in percentage of the initial amount used in new building.

Material	Description	Amount (kg)
Steel	Steel sheet cladding (20%). Roof cladding (10%).	184
Timber	Plywood, internal cladding (100%). External cladding (20%).	3 690
Plasterboard	Plasterboard cladding (100%).	140
Others (carpet and vinyl)	Carpet and vinyl, floor covering (100%)	897

(44.2 t CO_2 eq – 61.2 t CO_2 eq, see Tables 4 and 5). In summary, producing the L3 with reused components allows a saving of about 28% in terms of global warming potential, when compared to a linear approach of construction.

4.2.1. End of life stages: design for disassembly vs recycle

In designing the circular L3 for disassembly and reuse, it features disassemblability of most of its structural and non-structural components (i.e. chassis and load bearing structure, internal walls structure). Conversely, the linear L3 has been designed with non-disassemblable components, inaccessible and welded joints, therefore its materials that cannot be disassembled are demolished and recycled. This difference in design approaches translates to the difference between the last life cycle stage of the circular L3 (D_C) and the linear L3 (D_L). In terms of global warming potential, this difference equals to a saving of 15.7 t CO_2 eq (–41.9 t CO_2 eq + 26.2 t CO_2 eq, see Tables 4 and 5). In essence, designing for disassembly and reuse could enable a saving of about 60% of global warming potential, when compared to demolishing and recycling building materials.

4.3. Reuse vs recycle

The LCA stage D accounts for the next product system, and includes reuse and recycle practices. Recycling of steel and other materials, such as concrete and plasterboard is highly beneficial, as demonstrated above. Interestingly, material recycling has been researched more extensively than reuse (1 404 articles mention the keywords "buildings and recycling" in their abstracts versus 227 only that mention "buildings and reuse"; source: Scopus, October 2019). Furthermore, recycling procedures are regulated by policies in several countries globally (Ma and Hipel, 2016), providing guidelines for practitioners on the adoption of these procedures. However, despite the known benefits of recycling, we posit that reuse is a more beneficial practice toward a CE. Considerable research has been done to advance knowledge on the reintegration of material waste. An example is the integration of by-products, e.g. as fly-ash, into new concrete (Bocken et al., 2016). Despite fly-ash being successfully integrated with concrete (Costa and Marques, 2018) or building components such as bricks (Karayannis, 2016), two main issues have been related to this practice: in some cases heavy metals can leach from concrete incorporating fly-ash (Lederer et al., 2017), and that concrete can only be down-cycled after the buildings' service life (Adams et al., 2017). However, this research enhances knowledge of the reuse of entire components, enabled by design for disassembly. Design for disassembly is an emerging innovative practice that carries several benefits, including material separation (which also limits the risk of cross-contamination) (Jimenez-

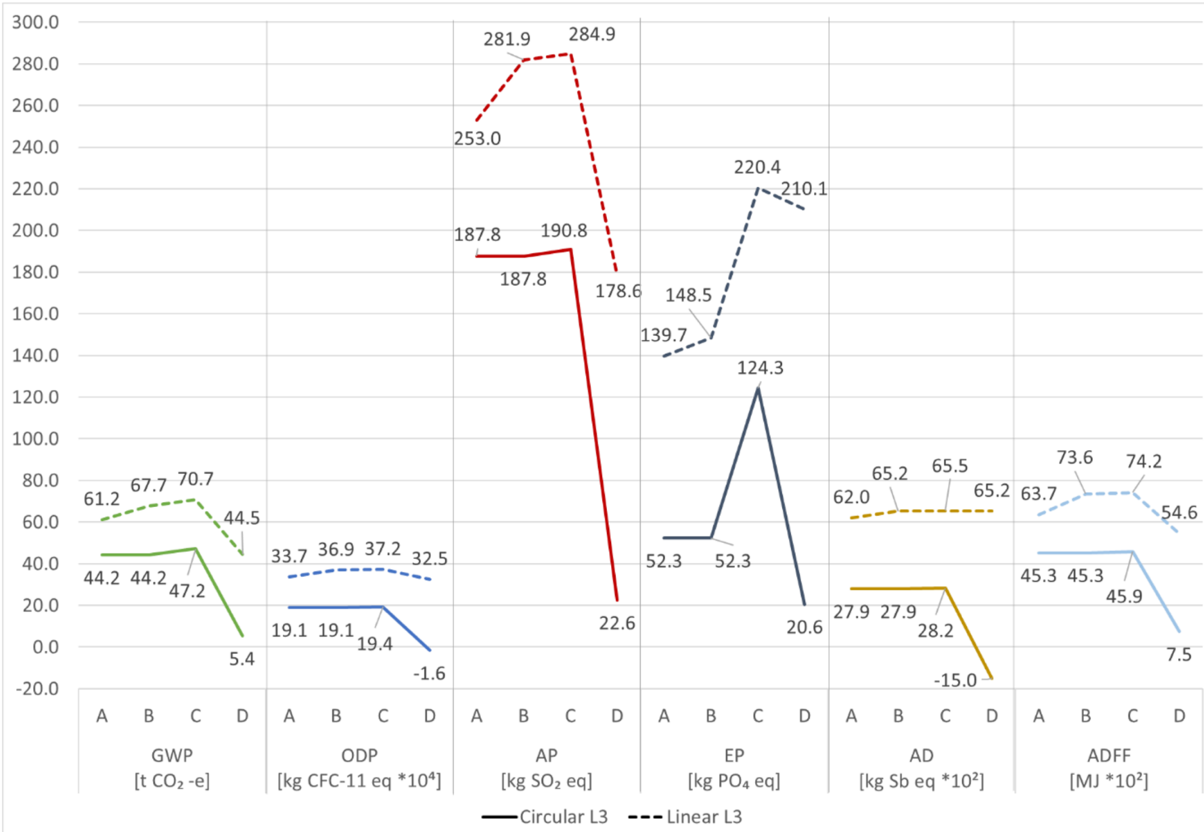

Fig. 6. – Comparison of the LCA of the circular and the linear versions of the L3. Continuous lines represent the circular L3, dashed lines represent the linear L3.

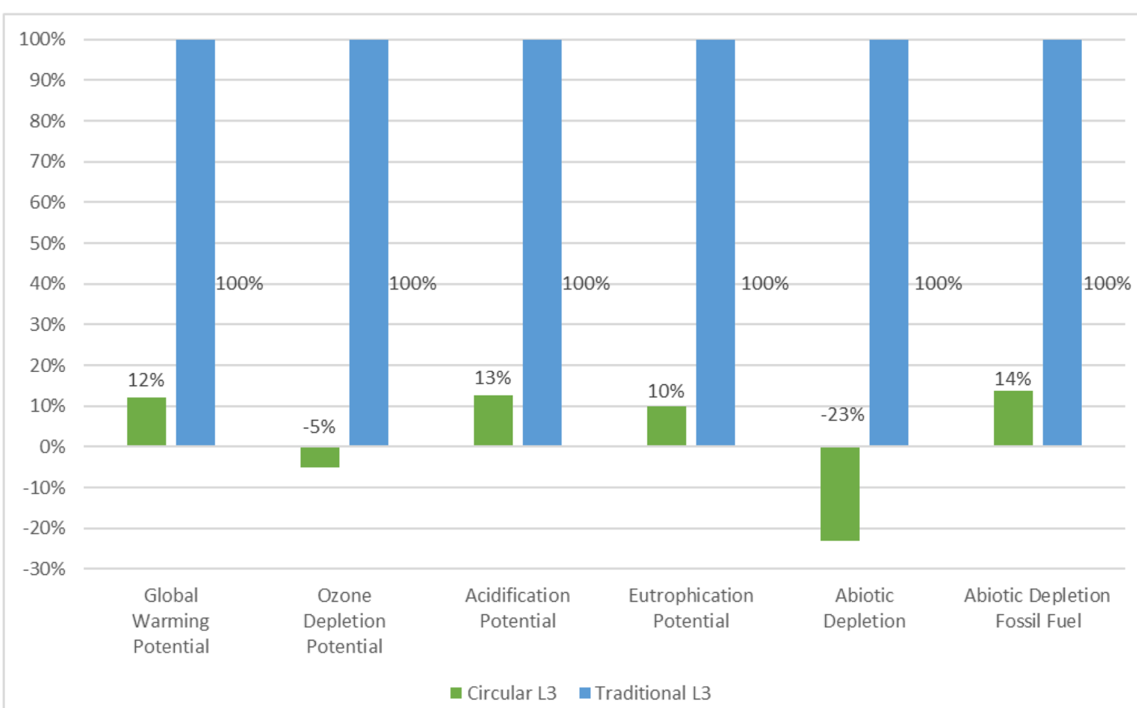

Fig. 7. – Environmental impact of the circular L3 compared to the linear L3 in terms of the six environmental indicators studied in this LCA. Overall, the circular L3 impacts only a fraction of the linear L3 (e.g. between 10–14% in terms of EP, GWP, AP and ADFF).

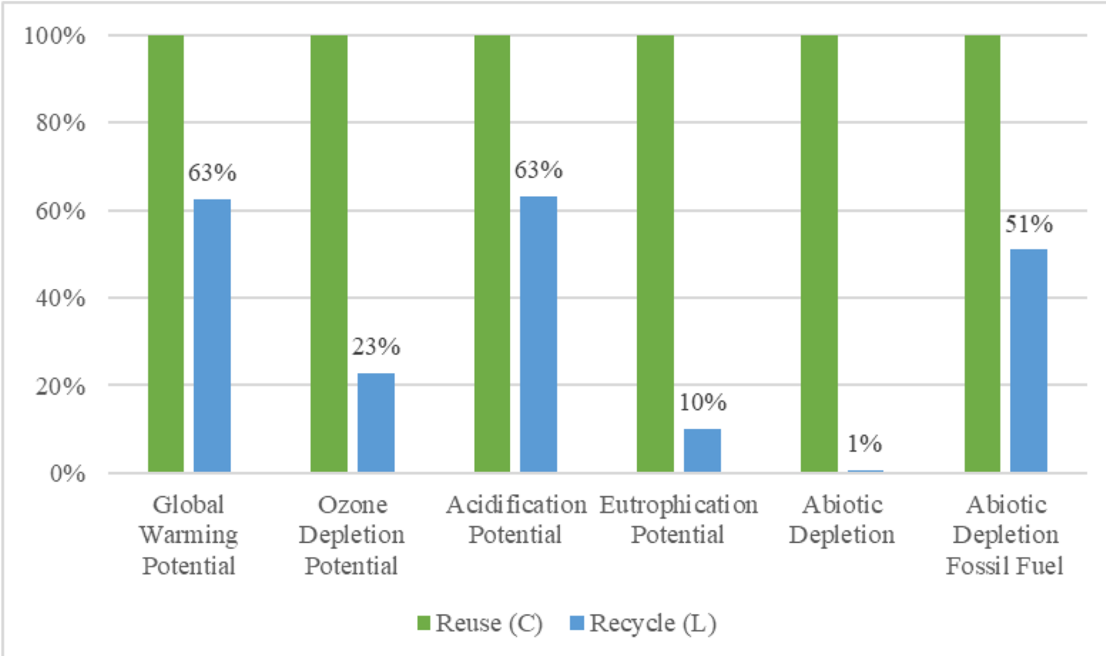

Fig. 8. – Environmental savings of reuse vs recycle practices in terms of the six environmental indicators included in this LCA (e.g. reuse allows about 39% savings in terms of global warming potential when compared to recycle, about 77% in terms of ozone layer depletion, etc.).

Rivero and Garcia-Navarro, 2017b; Nakamura and Kondo, 2018) and reuse of components (da Rocha and Sattler, 2009). Only components that have been designed for disassembly can be reused, and disassembly of entire buildings is often regarded as a dangerous practice that requires skilled labor (Galvez-Martos et al., 2018; Pauliuk et al., 2012). Despite these barriers, up to 95% of reusable building components could be returned to the market at the end of their previous service life (Galvez-Martos et al., 2018), with greater environmental benefits in contrast to the recycling of materials. According to our results, compared to reuse, recycle allows only 64% of global warming potential savings, 23% in terms of ozone depletion potential, 10% in terms of eutrophication potential and just 1% in terms of abiotic depletion (Fig. 8).

4.4. Comparison of components and materials

The L3 is designed and built as an example of what can be achieved by applying the CE principles to modular buildings. Between the linear and the circular version, there is no difference in terms of materials above foundations, only in the way the circular L3 prototype was built. There is no difference in timber, insulation and floor covering, however their impact should not be neglected.

Foundations. Traditionally, buildings consume significant amounts of concrete (Rahman et al., 2014), resulting in material depletion and other adverse consequences for the environment, i.e. excessive emissions of detrimental greenhouse gas (Gan et al., 2019; Parron-Rubio et al., 2018). Although concrete is a recyclable material, it usually produces materials of rather inferior quality; for this reason, the term down-cycling is often preferred over recycling (Minunno et al., 2018). To avoid using concrete, we built the L3 using only 735 kg of pile driven steel foundations *in lieu* of 19 848 kg of concrete plinths. As a result, we drastically decreased material consumption and related environmental savings in most of the LCA categories studied (e.g. recyclable steel foundations allow a saving of −0.14 t CO_2 eq, compared to the 2.14 t CO_2 eq of concrete foundations; similar proportions were found in terms of acidification potential and eutrophication potential; Table 7).

Timber. After steel, timber is the third highest material by mass used in the L3 prototype. Timber is used for floor structures, cladding and some internal doors, it accounts for 27% of the mass of the circular L3 prototype and 17% of the total mass of the linear building (the difference is the mass percentage due to the weight of the concrete foundations, not used in the circular L3). The floor structure is particle board, internal cladding is plywood and the external cladding is a pressed timber pulp and wax composite. Two of the three products of timber used in the L3 prototype are not recyclable, and as a consequence, the disposal of timber produces a slightly negative impact, ranging from 3% of global warming potential to 0.2% of abiotic depletion of fossil fuels. A peak of emissions is however registered in terms of eutrophication potential of timber disposal, emitting about 71 kg of PO_4 eq (for reference, recycling of steel allows a saving of about −101 kg of PO_4 eq).

Floor covering and insulation. Accounting for about 6% of the overall mass of the linear building, and 10% of the circular L3, carpet, insulation and vinyl produce an environmental impact which is considerably elevated, ranging from 6% of abiotic depletion to 30% of ozone depletion potential. This impact is mainly due to the 2.5 t of insulation. In addition, one limitation of the SimaPro software is that carpet and vinyl are planned to be disposed of during the refurbishment of the circular L3, increasing the adverse environmental impact of the circular L3 prototype. In actual fact the vinyl and carpet tiles used can

Table 7.
Comparison of the two foundation types adopted in the circular L3 prototype (735 kg of steel) versus the 20 t of concrete used in the linear L3 version.

	GWP (t CO_2 eq)	ODP (kg CFC-11 eq)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	AD (kg Sb eq)	ADFF (10^3 MJ)
Steel foundations - Circular L3	−0.14	1.6E-05	−1.64	−0.17	9.1E-03	0.36
Concrete foundations - Linear L3	2.14	1.4E-04	6.12	1.91	2.9E-03	14.37

be reintroduced in the manufacturing process as both the carpet tiles and vinyl companies have closed loop material take back options. At the end of life of the linear building, floor covering and insulation are conservatively assumed as not recyclable, adding negative impact to the environment.

Doors and windows. Aluminum doors and windows represent a minimal portion of the building in terms of mass (about 2% by mass). In the production process their impact does not exceed 1% in each impact category, the saving due to recycling of glass and aluminum at the end of life stage is about 5% in all categories.

5. Conclusions

5.1. Summary

According to the literature, several barriers stand in the way of applying the 3R's and the circularity of building materials and components. Two of these barriers include monolith building structures (which means that the structures cannot be disassembled), and non-standardized building measures (which means that building components do not align with the design of other buildings). Scholars have applied many strategies to get closer to a CE (e.g. through integrating by-products in construction materials). Amongst these strategies, the most applied relate to recycling building materials, such as concrete and steel. However, whilst these practices reduce landfill, and decrease the amount of greenhouse gas emissions (together with other environmental indicators), we hypothesized that a CE of building materials can be achieved by following reuse principles. We tested this hypothesis by performing a comparative LCA of a circular building, designed for disassembly and reuse, and its traditional (linear) modular building, which is not designed for disassembly and whose materials are recycled or disposed to landfill. Our findings show that, by adopting the CE framework of design for disassembly and reuse, we can reuse the entire steel structure of the L3, which accounts for 62% of the mass of the building. We demonstrated that building for deconstruction and reuse enables a saving of up to 88% of global warming potential and eutrophication potential, about 87% in terms of acidification potential and abiotic depletion of fossil fuels and a positive environmental contribution in terms of ozone depletion potential and abiotic depletion when compared to recycling. In so doing, we make significant theoretical and practical contributions, which we outline in more detail in the following sub-section.

5.2. Main contributions

We make four main contributions toward understanding the potential of CE practices in the sustainable buildings sector. First, we prototyped a CE building built with reused frames, designed to be disassemblable and movable. The prototype is a practical exploration of applying the CE principles to buildings. Similar applications have so far received scant research attention; for example, the environmental benefits of reusing buildings parts of an entire modular building is missing (Cabeza et al., 2014; Nwodo and Anumba, 2019; Pomponi and Moncaster, 2017; Sanchez et al., 2020). By applying CE practices, such as design for disassembly and reuse of building components, our study challenges traditional (linear) construction industry practices, where recycling and integrating by-products in construction materials remain the most adopted strategies to diminish the environmental impact of buildings.

Second, we validated the CE applications in the building context (see Junnila et al. (2006), Cabeza et al. (2014), Kamali and Hewage (2016), and Gálvez-Martos et al. (2018)), and, in doing so, our LCA of the L3 revealed that these practices offset the environmental outcomes of recycling. The greater environmental outcomes are due to the reusability of L3 prototype across several life cycles; it can be disassembled and moved to other locations. Its components could be reused in other buildings, resulting not only in environmental benefits, but in potential operating cost savings, opening the horizons to innovative new operations in the building sector (e.g. design for disassembly, markets of reused components).

Third, our findings can guide policy makers to end-of-life best practices by regulating the re-certification of reused steel components. By establishing guidelines on how to maintain building components into the material loop, construction industries could be incentivized to design reusable components that can be disassembled and reused. Our study could thus help lead the way toward a new market for reusable building components. Establishing such a market could provide one possible solution to the many barriers that hinder the adoption of CE practices and facilitate the implementation of take-back practices.

Our final contribution relates to showing that LCAs can help quantify the benefits of CE practices. The LCA method adopted in this study was first established in the 1970s (Guinée et al., 2011), but remains only loosely integrated with CE practices. Our study, however, demonstrates that an LCA can be used to validate the benefits of adopting and implementing the CE. Although previous work has associated CE principles with an LCA in the building sector, most studies either focus on parts of buildings or lack the comparison between reuse and recycle practices (Brambilla et al., 2019; Buyle et al., 2019; Cruz Rios et al., 2019). Our study fills this gap by advancing knowledge through a prototype constructed by applying CE practices to each life cycle stage.

6. Further research

Our research opens up three main future research opportunities. First, although we evaluated the environmental benefits of material reuse, we did not consider the potential reduction of operational energy and water consumption in our case study. Further research should extend our study to empirically assess the benefits of applying strategies that aim to reduce energy (e.g. by integrating socio-technical dynamics such as CO_2 sensor devices to sensitize the household users (Hansen et al., 2019)) and water (e.g. through water-recycling systems (Zhijun and Nailing, 2007)) use.

Second, it would be beneficial to explore the marketability of reused building components and end of life management. Specifically, research should study whether second hand steel parts are re-sellable, or whether they are more expensive to produce, re-certify and re-sell than new parts. To answer this research question, studies on closed-loop supply chain of second hand steel parts for buildings are needed. Further, it is necessary to understand how to standardize steel components that can be reused in different buildings.

Third, our study measures the environmental benefits of applying CE practices of reuse and recycle, but does not investigate the economic and social dimensions of sustainability. Regarding economic sustainability, further research can provide insight into how a CE can maximize the economic benefits by optimizing the material efficiency through the 3R's. Regarding social sustainability, applying a CE requires highly-skilled labor and technicians; further studies can help advance knowledge on how applying a CE promotes education (D'Amato et al., 2017).

CRediT authorship contribution statement

Roberto Minunno: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft. **Timothy O'Grady:** Conceptualization, Methodology, Investigation. **Gregory M. Morrison:** Conceptualization, Writing - review & editing, Supervision. **Richard L. Gruner:** Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Akanbi, L., Oyedele, L., Delgado, J.M.D., Bilal, M., Akinade, O., Ajayi, A., Mohammed-Yakub, N., 2019. Reusability analytics tool for end-of-life assessment of building materials in a circular economy. World J. Sci. Technol. Sustain. Dev. 16, 40–55. https://doi.org/10.1108/wjstsd-05-2018-0041.

Adams, K.T., Osmani, M., Thorpe, T., Thornback, J., 2017. Circular economy in construction: current awareness, challenges and enablers. In: Proceedings of the Institution of Civil Engineers-Waste and Resource Management. 170. Thomas Telford Ltd., pp. 15–24. https://doi.org/10.1680/jwarm.16.00011.

Akanbi, L.A., Oyedele, L.O., Akinade, O.O., Ajayi, A.O., Davila Delgado, M., Bilal, M., Bello, S.A., 2018. Salvaging building materials in a circular economy: a BIM-based whole-life performance estimator. Resour. Conserv. Recycl. 129, 175–186. https://doi.org/10.1016/j.resconrec.2017.10.026.

Allwood, J.M., 2014. Squaring the circular economy: the role of recycling within a hierarchy of material management strategies. Handbook of Recycling. Elsevier, pp. 445–477.

Balasbaneh, A.T., Bin Marsono, A.K., Gohari, A., 2019. Sustainable materials selection based on flood damage assessment for a building using LCA and LCC. J. Clean. Prod. 222, 844–855. https://doi.org/10.1016/j.jclepro.2019.03.005.

Baumann, H., Tillman, A.-.M., 2004. The hitch hiker's guide to LCA. ISBN 13, 978–9144023649.

Blengini, G.A., Di Carlo, T., 2010. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energy Build. 42, 869–880. https://doi.org/10.1016/j.enbuild.2009.12.009.

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Brambilla, G., Lavagna, M., Vasdravellis, G., Castiglioni, C.A., 2019. Environmental benefits arising from demountable steel-concrete composite floor systems in buildings. Resour. Conserv. Recycl. 141, 133–142. https://doi.org/10.1016/j.resconrec.2018.10.014.

Bribián, I.Z., Usón, A.A., Scarpellini, S., 2009. Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification. Build. Environ. 44, 2510–2520. https://doi.org/10.1016/j.buildenv.2009.05.001.

Brogaard, L.K., Damgaard, A., Jensen, M.B., Barlaz, M., Christensen, T.H., 2014. Evaluation of life cycle inventory data for recycling systems. Resour. Conserv. Recycl. 87, 30–45. https://doi.org/10.1016/j.resconrec.2014.03.011.

Buyle, M., Galle, W., Debacker, W., Audenaert, A., 2019. Sustainability assessment of circular building alternatives: consequential lca and lcc for internal wall assemblies as a case study in a Belgian context. J. Clean. Prod. 218, 141–156. https://doi.org/10.1016/j.jclepro.2019.01.306.

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector:a review. Renew. Sustain. Energy Rev. 29, 394–416. https://doi.org/10.1016/j.rser.2013.08.037.

Campbell-Johnston, K., Cate, J.T., Elfering-Petrovic, M., Gupta, J., 2019. City level circular transitions: barriers and limits in Amsterdam, Utrecht and The Hague. J. Clean. Prod. 235, 1232–1239. https://doi.org/10.1016/j.jclepro.2019.06.106.

Chomkhamsri, K., Wolf, M.-.A., Pant, R., 2011. International reference life cycle data system (ILCD) handbook: review schemes for life cycle assessment. Towards Life Cycle Sustainability Management. Springer, pp. 107–117.

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., Worrell, E., 2019. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. 151, 104498. https://doi.org/10.1016/j.resconrec.2019.104498.

Costa, C., Marques, J.C., 2018. Feasibility of eco-friendly binary and ternary blended binders made of fly-ash and oil-refinery spent catalyst in ready-mixed concrete production. Sustainability (Switzerland) 10. https://doi.org/10.3390/su10093136.

Crawford, R.H., 2011. Life Cycle Assessment in the Built Environment. Routledge.

Cruz Rios, F., Grau, D., Chong, W.K., 2019. Reusing exterior wall framing systems: a cradle-to-cradle comparative life cycle assessment. Waste Manag. 94, 120–135. https://doi.org/10.1016/j.wasman.2019.05.040.

D'Amato, D., Droste, N., Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J., Leskinen, P., Matthies, B.D., Toppinen, A., 2017. Green, circular, bio economy: a comparative analysis of sustainability avenues. J. Clean. Prod. 168, 716–734. https://doi.org/10.1016/j.jclepro.2017.09.053.

da Rocha, C.G., Sattler, M.A., 2009. A discussion on the reuse of building components in Brazil: an analysis of major social, economical and legalfactors. Resour. Conserv. Recycl. 54, 104–112. https://doi.org/10.1016/j.resconrec.2009.07.004.

Dixit, M.K., Culp, C.H., Fernández-Solís, J.L., 2013. System boundary for embodied energy in buildings: a conceptual model for definition. Renew. Sustain. Energy Rev. 21, 153–164. https://doi.org/10.1016/j.rser.2012.12.037.

Dunant, C.F., Drewniok, M.P., Sansom, M., Corbey, S., Allwood, J.M., Cullen, J.M., 2017. Real and perceived barriers to steel reuse across the UK construction value chain. Resour. Conserv. Recycl. 126, 118–131. https://doi.org/10.1016/j.resconrec.2017.07.036.

Eberhardt, L., Birgisdottir, H., Birkved, M., 2019a. Comparing life cycle assessment modelling of linear vs. circular building components. Iop Conference Series: Earth and Environmental Science. IOP Publishing, 012039.

Eberhardt, L., Birgisdóttir, H., Birkved, M., 2019b. Life cycle assessment of a Danish office building designed for disassembly. Build. Res. Inf. 47, 666–680. https://doi.org/10.1080/09613218.2018.1517458.

Eberhardt, L.C.M., Birgisdottir, H., Birkved, M., 2019. Life cycle assessment of a Danish office building designed for disassembly. Build. Res. Inf. 47, 666–680. https://doi.org/10.1080/09613218.2018.1517458.

Eckelman, M.J., Brown, C., Troup, L.N., Wang, L., Webster, M.D., Hajjar, J.F., 2018. Life cycle energy and environmental benefits of novel design-for-deconstruction structural systems in steelbuildings. Build. Environ. 143, 421–430. https://doi.org/10.1016/j.buildenv.2018.07.017.

Fufa, S.M., Skaar, C., Gradeci, K., Labonnote, N., 2018. Assessment of greenhouse gas emissions of ventilated timber wall constructions based on parametric LCA. J. Clean. Prod. 197, 34–46. https://doi.org/10.1016/j.jclepro.2018.06.006.

Gálvez-Martos, J.-.L., Styles, D., Schoenberger, H., Zeschmar-Lahl, B., 2018. Construction and demolition waste best management practice in Europe. Resour. Conserv. Recycl. 136, 166–178. https://doi.org/10.1016/j.resconrec.2018.04.016.

Galvez-Martos, J.L., Styles, D., Schoenberger, H., Zeschmar-Lahl, B., 2018. Construction and demolition waste best management practice in Europe. Resour. Conserv. Recycl. 136, 166–178. https://doi.org/10.1016/j.resconrec.2018.04.016.

Gan, V.J.L., Cheng, J.C.P., Lo, I.M.C., 2019. A comprehensive approach to mitigation of embodied carbon in reinforced concrete buildings. J. Clean. Prod. 229, 582–597. https://doi.org/10.1016/j.jclepro.2019.05.035.

Ghose, A., Pizzol, M., McLaren, S.J., 2017. Consequential LCA modelling of building refurbishment in New Zealand- an evaluation of resource and waste management scenarios. J. Clean. Prod. 165, 119–133. https://doi.org/10.1016/j.jclepro.2017.07.099.

Gorgolewski, M., 2008. Designing with reused building components: some challenges. Build. Res. Inf. 36, 175–188. https://doi.org/10.1080/09613210701559499.

Green Building Council of Australia, 2014. Materials Life Cycle Impacts. https://www.gbca.org.au/uploads/78/34894/Materials_Life_Cycle%20Impacts_FINAL_JUNE2014.pdf. (Accessed December 2019).

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life cycle assessment: past, present, and future. Environ. Sci. Technol. 45, 90–96. https://doi.org/10.1021/es101316v.

Guy, B., Shell, S., Esherick, H., 2006. Design for deconstruction and materials reuse. Proc. CIB Task Group 39, 189–209.

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005. J. Ind. Ecol. 19, 765–777. https://doi.org/10.1111/jiec.12244.

Hansen, P., Liu, X., Morrison, G.M., 2019. Agent-based modelling and socio-technical energy transitions: a systematic literature review. Energy Res. Soc. Sci. 49, 41–52. https://doi.org/10.1016/j.erss.2018.10.021.

Honic, M., Kovacic, I., Rechberger, H., 2019. Improving the recycling potential of buildings through material passports (MP): an Austrian case study. J. Clean. Prod. 217, 787–797. https://doi.org/10.1016/j.jclepro.2019.01.212.

Hopkinson, P.C., H-M.; Zhou, K.; Wang, Y.; Lam, D., 2018. Recovery and reuse of structural products from end-of-life buildings. Proc. Inst. Civ. Eng.. 172, 119–128. 18. 00007.

Hossain, M.U., Ng, S.T., 2018. Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: an analytical review. J. Clean. Prod. 205, 763–780. https://doi.org/10.1016/j.jclepro.2018.09.120.

Hossain, M.U., Poon, C.S., Lo, I.M.C., Cheng, J.C.P., 2016. Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources bylca. Resour. Conserv. Recycl. 109, 67–77. https://doi.org/10.1016/j.resconrec.2016.02.009.

Hoxha, E., Habert, G., Lasvaux, S., Chevalier, J., Le Roy, R., 2017. Influence of construction material uncertainties on residential building LCA reliability. J. Clean. Prod.

144, 33–47. https://doi.org/10.1016/j.jclepro.2016.12.068.
Hu, M., 2019. Building impact assessment—A combined life cycle assessment and multi-criteria decision analysisframework. Resour. Conserv. Recycl. 150, 104410. https://doi.org/10.1016/j.resconrec.2019.104410.
International Organization for Standardization, 2006. Environmental Management: Life Cycle Assessment; Principles and Framework. ISO.
Jain, S., Singhal, S., Pandey, S., 2020. Environmental life cycle assessment of construction and demolition waste recycling: a case of urbanIndia. Resour. Conserv. Recycl. 155, 104642. https://doi.org/10.1016/j.resconrec.2019.104642.
Jimenez-Rivero, A., Garcia-Navarro, J., 2017a. Best practices for the management of end-of-life gypsum in a circular economy. J. Clean. Prod. 167, 1335–1344. https://doi.org/10.1016/j.jclepro.2017.05.068.
Jimenez-Rivero, A., Garcia-Navarro, J., 2017b. Exploring factors influencing post-consumer gypsum recycling and landfilling in the European Union. Resour. Conserv. Recycl. 116, 116–123. https://doi.org/10.1016/j.resconrec.2016.09.014.
Junnila, S., Horvath, A., Guggemos, A.A., 2006. Life-cycle assessment of office buildings in Europe and the United States. J. Infrastruct. Syst. 12, 10–17 10.1061/(ASCE)1076-0342(2006)12:1(10).
Kamali, M., Hewage, K., 2016. Life cycle performance of modular buildings: a critical review. Renew. Sustain. Energy Rev. 62, 1171–1183. https://doi.org/10.1016/j.rser.2016.05.031.
Karayannis, V.G., 2016. Development of extruded and fired bricks with steel industry byproduct towards circular economy. J. Build. Eng. 7, 382–387. https://doi.org/10.1016/j.jobe.2016.08.003.
Khan, K.S., Kunz, R., Kleijnen, J., Antes, G., 2003. Five steps to conducting a systematic review. J. R. Soc. Med. 96, 118–121.
Khasreen, M.M., Banfill, P.F.G., Menzies, G.F., 2009. Life-Cycle assessment and the environmental impact of buildings: a review. Sustainability 1, 674–701. https://doi.org/10.3390/su1030674.
Kibert, C.J., Chini, A.R., Languell, J., 2000. Deconstruction as an essential component of sustainable construction. In: Proceedings of the Second Southern African Conference on Sustainable Development in the Built Environment, Pretoria, pp. 1–5.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.
Krikke, H., Blanc, I.l., van de Velde, S., 2004. Product modularity and the design of closed-loop supply chains. Calif Manage Rev 46, 23–39. https://doi.org/10.2307/41166208.
Lawson, N., Douglas, I., Garvin, S., McGrath, C., Manning, D., Vetterlein, J., 2001. Recycling construction and demolition wastes–a UK perspective. Environ. Manag. Health 12, 146–157. https://doi.org/10.1108/09566160110389898.
Lederer, J., Trinkel, V., Fellner, J., 2017. Wide-scale utilization of mswi fly ashes in cement production and its impact on average heavy metal contents in cements: the case of Austria. Waste Manag. 60, 247–258. https://doi.org/10.1016/j.wasman.2016.10.022.
Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. J. Clean. Prod. 115, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042.
Ma, J., Hipel, K.W., 2016. Exploring social dimensions of municipal solid waste management around the globe–A systematic literaturereview. Waste Manag. 56, 3–12. https://doi.org/10.1016/j.wasman.2016.06.041.
Martín-Morales, M., Cuenca-Moyano, G.M., Valverde-Espinosa, I., Valverde-Palacios, I., 2017. Effect of recycled aggregate on physical-mechanical properties and durability of vibro-compacted dry-mixed concrete hollow blocks. Construct. Build. Mater. 145, 303–310. https://doi.org/10.1016/j.conbuildmat.2017.04.013.
McDonough, W., Braungart, M., 2010. Cradle to Cradle: Remaking the Way We Make Things. North Point Press.
Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. J. Clean. Prod. 178, 703–722. https://doi.org/10.1016/j.jclepro.2017.12.112.
Minunno, R., O'Grady, T., Morrison, G., Gruner, R., Colling, M., 2018. Strategies for applying the circular economy to prefabricated buildings. Buildings 8, 125. https://doi.org/10.3390/buildings8090125.
Nakamura, S., Kondo, Y., 2018. Toward an integrated model of the circular economy: dynamic waste input-output. Resour. Conserv. Recycl. 139, 326–332. https://doi.org/10.1016/j.resconrec.2018.07.016.
Nußholz, J.L.K., Nygaard Rasmussen, F., Milios, L., 2019. Circular building materials: carbon saving potential and the role of business model innovation and publicpolicy. Resour. Conserv. Recycl. 141, 308–316. https://doi.org/10.1016/j.resconrec.2018.10.036.
Nwodo, M.N., Anumba, C.J., 2019. A review of life cycle assessment of buildings using a systematic approach. Build. Environ.. 162. https://doi.org/10.1016/j.buildenv.2019.106290.
Parron-Rubio, M.E., Perez-Garcia, F., Gonzalez-Herrera, A., Rubio-Cintas, M.D., 2018. Concrete properties comparison when substituting a 25% cement with slag from differentprovenances. Materials. 11. https://doi.org/10.3390/ma11061029.
Pauliuk, S., Wang, T., Müller, D.B., 2012. Moving toward the circular economy: the role of stocks in the Chinese steel cycle. Environ. Sci. Technol. 46, 148–154. https://doi.org/10.1021/es201904c.
Pomponi, F., Moncaster, A., 2017. Circular economy for the built environment: a research framework. J. Clean. Prod. 143, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055.
Rahman, M.E., Muntohar, A.S., Pakrashi, V., Nagaratnam, B., Sujan, D., 2014. Self compacting concrete from uncontrolled burning of rice husk and blended fine aggregate. Mater. Des. 55, 410–415. https://doi.org/10.1016/j.matdes.2013.10.007.
Rose, C.M., Bergsagel, D., Dufresne, T., Unubreme, E., Lyu, T.Y., Duffour, P., Stegemann, J.A., 2018. Cross-Laminated secondary timber: experimental testing and modelling the effect of defects and reduced feedstock properties. Sustainability 10. https://doi.org/10.3390/su10114118.
Sanchez, B., Rausch, C., Haas, C., Saari, R., 2020. A selective disassembly multi-objective optimization approach for adaptive reuse of buildingcomponents. Resour. Conserv. Recycl. 154, 104605. https://doi.org/10.1016/j.resconrec.2019.104605.
Schultmann, F., Sunke, N., 2007. Organisation of reverse logistics tasks in the construction industry. Portugal SB07: Sustainable Construction, Materials and Practices. 577–584.
Sharma, A., Saxena, A., Sethi, M., Shree, V., 2011a. Life cycle assessment of buildings: a review. Renew. Sustain. Energy Rev. 15, 871–875. https://doi.org/10.1016/j.rser.2010.09.008.
Sharma, A., Saxena, A., Sethi, M., Shree, V., Varun, 2011b. Life cycle assessment of buildings: a review. Renew. Sustain. Energy Rev. 15, 871–875. https://doi.org/10.1016/j.rser.2010.09.008.
Siddaway, A.P., Wood, A.M., Hedges, L.V., 2019. How to do a systematic review: a best practice guide for conducting and reporting narrative reviews, meta-analyses, and meta-syntheses. Annu. Rev. Psychol. 70, 747–770. https://doi.org/10.1146/annurev-psych-010418-102803.
Singh, A., Berghorn, G., Joshi, S., Syal, M., 2010. Review of life-cycle assessment applications in building construction. J. Archit. Eng. 17, 15–23. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000026.
Stocker, T.F., Qin, D., Plattner, G.-.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., 2013. Climate Change 2013: The Physical Science Basis. Cambridge University Press, Cambridge.
Tingley, D.D., Cooper, S., Cullen, J., 2017. Understanding and overcoming the barriers to structural steel reuse, a UK perspective. J. Clean. Prod. 148, 642–652. https://doi.org/10.1016/j.jclepro.2017.02.006.
Toniolo, S., Mazzi, A., Pieretto, C., Scipioni, A., 2017. Allocation strategies in comparative life cycle assessment for recycling: considerations from casestudies. Resour. Conserv. Recycl. 117, 249–261. https://doi.org/10.1016/j.resconrec.2016.10.011.
Tranfield, D., Denyer, D., Smart, P., 2003. Towards a methodology for developing evidence-informed management knowledge by means of systematicreview. Br. J. Manag. 14, 207–222. https://doi.org/10.1111/1467-8551.00375.
Verbinnen, B., Billen, P., Van Caneghem, J., Vandecasteele, C., 2017. Recycling of mswi bottom ash: a review of chemical barriers, engineering applications and treatment-technologies. Waste and Biomass Valorization 8, 1453–1466. https://doi.org/10.1007/s12649-016-9704-0.
Wang, E., Shen, Z., 2013. A hybrid data quality indicator and statistical method for improving uncertainty analysis in LCA of complex system – application to the whole-building embodied energy analysis. J. Clean. Prod. 43, 166–173. https://doi.org/10.1016/j.jclepro.2012.12.010.
Wei, W., Larrey-Lassalle, P., Faure, T., Dumoulin, N., Roux, P., Mathias, J.-.D., 2015. How to conduct a proper sensitivity analysis in life cycle assessment: taking into account correlations within LCI data and interactions within the LCA calculation model. Environ. Sci. Technol. 49, 377–385. https://doi.org/10.1021/es502128k.
Westin, A.L., Kalmykova, Y., Rosado, L., Oliveira, F., Laurenti, R., Rydberg, T., 2019. Combining material flow analysis with life cycle assessment to identify environmental hotspots of urbanconsumption. J. Clean. Prod. 226, 526–539. https://doi.org/10.1016/j.jclepro.2019.04.036.
Yellishetty, M., Mudd, G.M., Ranjith, P.G., 2011. The steel industry, abiotic resource depletion and life cycle assessment: a real or perceived issue? J. Clean. Prod. 19, 78–90. https://doi.org/10.1016/j.jclepro.2010.08.020.
Zaman, A.U., 2014. Identification of key assessment indicators of the zero waste management systems. Ecol. Indic. 36, 682–693. https://doi.org/10.1016/j.ecolind.2013.09.024.
Zhijun, F., Nailing, Y., 2007. Putting a circular economy into practice in China. Sustain. Sci. 2, 95–101. https://doi.org/10.1007/s11625-006-0018-1.
Zink, T., Geyer, R., 2017. Circular economy rebound. J. Ind. Ecol. 21, 593–602. https://doi.org/10.1111/jiec.12545.

Design for disassembly, deconstruction and resilience: A circular economy index for the built environment

Abstract.

In this paper we present a new circular economy based approach for the built environment: design for disassembly, deconstruction and resilience (D^3R)[1]. This approach has been prototyped in our purpose built disassemblable modular building, named Legacy Living Lab (L3)[2]. The D^3R method illustrates the steps and operations that, if applied during design, production, maintenance and end of life, would enable a closure of the building materials loop. We designed and built the prototype to evaluate the benefits of the D^3R method. Furthermore, the material flow of the building was analysed and a comparison made of the amount of new material that was required to produce the case study, to the amount of reusable material that can be reintroduced to sustain the circularity once the building is disassembled. The benefits of applying the D^3R method are proven for and during each life cycle stage. During the operation phase, building refurbishment is possible through the 83% of walls and ceilings that can be disassembled. The prototype building can be relocated, in the process producing less than 1% of the buildings mass in waste. At end of life up to 46% by mass (16.1 tonnes) of steel can be recycled. A circular economy approach implies the conversion of building waste into new resources, our method advances the aims of the circular economy, embedding D^3R principles into refurbishment and end of life disassembly and thereby reducing construction waste.

Keywords: Circular Economy; Modular Construction; Design; Disassembly; Deconstruction; Resilience

[1] D^3R – Design for Disassembly, Deconstruction and Resiliency

[2] L3 – Legacy Living Lab (The name of the case study)

LCA – Life Cycle Assessment

1. Introduction

The building sector generates the largest percentage of waste globally (Ajayi et al., 2015; Solís-Guzmán et al., 2009). Construction and demolition waste is believed to be the single most adversely impacting industry sector on the environment in developed countries (Ajayi et al., 2015). Although construction waste is generated during all the stages of buildings' life cycles, most is generated during building demolition. While building material waste continues to be disposed to landfill, a growing percentage of building waste is maintained in the material loop through recycling (Vefago and Avellaneda, 2013), especially materials such as concrete and steel (Oikonomou, 2005; Tam and Tam, 2006). Despite its popularity, many problems make recycling difficult or not optimized. Concrete recycling, for example, is often limited by factors, such as material contamination (concrete is typically contaminated by steel, while concrete mixed with fly-ash might be contaminated with heavy metals ; see Abid et al. (2018) and Verian et al. (2018)). Consequently, the term down-cycling is used to imply the decreased quality of recycled concrete (Adams et al., 2017). However, in the case of steel, this can be recycled while maintaining its original mechanical qualities, although this process is both carbon and energy intensive (Jiang et al., 2018). For these reasons, the circular economy approach signifies the direct reuse of building components as an alternative to recycling, which might be related to improved environmental benefits through the creation of new resources out of waste (Allwood, 2014; Allwood et al., 2011). Materials and components reuse is less carbon and energy intensive when compared to recycling (Zaman et al., 2018a), and modularity, closed-loop supply chain, reverse logistics and design for deconstruction are practices that are gaining traction between both academics and practitioners. Reuse promises not only environmental benefits, but related economic profit (Chileshe et al., 2018; Stahel, 2016). Attempts have been made to create reusable building components and to understand the benefits of reusing materials and components (Eckelman et al., 2018).

Systems analysis tools help researchers and practitioners quantify the environmental impact of buildings. For example, the life cycle assessment method allows the quantification of greenhouse gas emissions (and other environmental indicators) related to buildings (Ghisellini et al., 2018), thereby allowing the validation of the application of processes of reuse or recycling. In addition, a material flow accounting method helps us understand the amount of material used by the construction industry in a defined boundary (Winans et al., 2017). Nevertheless, a method or approach to quantify and measure the level of reusability of a building in relation to its materials and connections does not exist (Buyle et al., 2019). In this paper, we propose the D^3R method which enables the calculation of the degree of disassemblability and reusability of a building. The method is based on design assumptions, such as connection details, flashing design, material selection and dimension and construction type.

The methodology that we propose in this paper is an experimental research approach, which is based on circular economy principles for the aspects of design, disassembly, deconstruction and material resiliency. A case study of a modular building was used to test the above-mentioned ideas for their materials and components reuse. In grouping the decisions made in accordance with these considerations, the D^3R methodology allows us to quantify the circular economy index of a building in its design stage. This research enables a circular economy design index of the built environment. The D^3R method can be employed through all stages of the lifecycle of a building, promoting circular economy with the ability of influenced weighting. This could potentially transform the construction industry leading to a reduction of its substantial environmental impact.

2. The Principles of Circular Economy and D^3R

The aim of this research was straightforward: design and build a circular economy building. The principles drawn upon were from past examples of the automotive industry. One question arising from this knowledge is; can building elements be easily removed, rebuilt, interchanged or relocated? A second question arising is; will there be spare parts at the end of life or just rubble? The design of the building was heavily influenced by the early automotive industry, where car parts were rebuilt, and wrecking yards held a firm position in the supply chain when compared to new alternatives. These principles, were adapted to design a construction project where a majority of the building elements could be removed, replaced, improved, relocated, or eventually recycled.

The 10 years of trade experience of one of the authors enabled the iteration of the functional design of the prototype which enabled the building to be funded and built. The circular economy of the building was hypothesised through the D^3R methodology and this allowed us to provide a proof of concept.

The following outlines the *modus operandi* of D^3R methodology for the circular economy approach.

Design in the context of circular economy buildings.

The design stage of a building is considered the most important toward achieving a circular economy (Van den Berghe and Vos, 2019). It is during the design stage that decisions, such as materials, types of connections, and components specifications are made (Eckelman et al., 2018). The circular economy approach and its principles can be utilized to ensure that waste and components are properly managed. For example, it is agreed that by selecting a material or a modern construction method, such as volumetric prefabrication, a decrease in concomitant waste generation can be achieved (Esa et al., 2017). In the design stage, efforts should be made to integrate reused and reusable materials (eg preferring steel over concrete), assess the existence of a market of specific reused components and even definition of the building site, leaving room for adequate deconstruction processes to take place, including the correct lifting plant and waste sorting on-site (Ghisellini et al., 2018). Finally, during the design process, team design and collaboration between experts in multiple disciplines is fundamental to the development of a vision of closing the material loop (Leising et al., 2018). Collaboration between architects, engineers and tradespeople will help facilitate harmonic and sustainable solutions towards a circular economy for buildings (Sieffert et al., 2014). Despite the importance of diminishing construction and demolition waste, in many countries the adoption of circular design is limited to "on-site cleanliness and the ordering of, correct storage of raw materials, and prioritization of the nearest authorized waste managers" (see Gangolells et al. (2014)).

Consequently, we define buildings in the context of circular economy as the process of aiming to construct a building where components and materials can be taken apart in a safe and feasible manner, without the need for particularly skilled workers and at a similar price to that of a traditional building.

Disassembly in the context of circular economy of buildings.

Disassembly refers to the individual parts that make up the finished building fabric. This includes the wall cladding, flooring, kitchen and internal finishes. This will extend to panelised, non-structural walls and components of a building.

Deconstruction in the context of circular economy of buildings.

Deconstruction can be defined by the removal of structural elements of the building and relocation of parts of or the whole of the building which can be for either volumetric frames or the whole building. In a volumetric building, this would refer to the modules, however this might also be used for the removal of a panelised or precast prefabrication system. This can be frames, beams, walls or whole modules

Resiliency in the context of circular economy of buildings.

Resilience in construction can be described as a variation to Holling's (Schulze and Engineering, 1996) static engineering definition as, the ability to reduce the lasting result of a disruptive event, for example dismantlement and relocation of a structure. The (NIAC, 2009) explains that resilience can be characterised by the following; Robustness, resourcefulness, rapid recovery and redundancy, all of which can be adapted to define construction resilience. A structure must be robust enough to withstand the forces that will be imposed on it through the disassembly and relocation process. The structure must be correctly resourced with correct documentation to assist with material provenance, structural load and lifting manuals and safe disassembly procedures to enable a practical and safe transition into its second lifecycle. Rapid recovery of materials ensures economic viability whilst redundancy ensures there are latent features within the structure which will enable it to be renovated as needed without the need for additional waste (Tatiya et al 2018). Resiliency is the ability to anticipate, absorb, adapt and rapidly recover from a disruptive event and in order to accommodate the circular economy framework, a resilient building must be dismantled with its materials kept in a reusable and saleable condition throughout the process (NIAC, 2009).

2.1. Circularity indexing

We propose the D^{3}R method to calculate the circular economy index of a building based on the considerations made during the design stage of a building, meaning the disassembly, deconstruction and resilience of the buildings structural fabric, finishes and components. These considerations will be influenced by the materials second life opportunities of re-use, recycling, down-cycling or disposal and the difficulty by which the materials can be separated from each other and the tools needed to complete the process. The circularity indexing of buildings should help industry prioritise circular economy over the traditional demolition techniques and reduce the environmental impact during refurbishment and end of lifecycle stages.

3. Methodology – Experimental Research

The overall methodology of the experimental research has been designed into five stages as identified in Figure 1. It commenced with a systematic literature review to define and make clear the principles of the D^{3}R method. Subsequently, the D^{3}R methodology was developed to bridge the gap in the literature to include that which was needed to practically implement the circular economy index to the built environment. The D^{3}R equations were developed to enable a potential dissemination of D^{3}R method throughout the construction industry. The methodology was tested in a full size, built case study, the Legacy Living Lab. Design typologies were identified and material analysis was conducted to validate the methodology and consolidate the theory.

3.1. Systematic literature review methodology

Following established guidelines on systematic literature reviews (Denyer and Tranfield, 2009; Siddaway et al., 2019), we positioned this research in the literature and analysed research through the terms used to define the D^{3}R method. The research question that we attempted to answer through this systematic literature review was; how can the terms design, disassembly, deconstruction and material resiliency be defined in the context of the circular economy of buildings? To address this question, we shortlisted 496 articles from three academic databases (i.e., Scopus, ScienceDirect, Web of Science) using relevant keywords including design, deconstruction, disassembly, resiliency, circular economy, buildings. We grouped the shortlisted articles into four categories: design towards a circular economy

(412 references, e.g., Nunez-Cacho et al. (2018), Leising et al. (2018), Akanbi et al. (2018)), building disassembly in parts or component (17 references, e.g., Diyamandoglu and Fortuna (2015), Brambilla et al. (2019), (Diyamandoglu and Fortuna, 2015); Eberhardt et al. (2019)), moving or repurposing of buildings through deconstruction (16 references, e.g., Diyamandoglu and Fortuna (2015), Akinade et al. (2017); (Diyamandoglu and Fortuna, 2015; Eberhardt et al., 2019)), and material resiliency in the context of circular economy (51 references, e.g., Gaustad et al. (2018)). Furthermore, the shortlisted articles were used to define the D^3R variables (see section 3.3) and referenced through the remainder of the paper (Merli et al., 2018).

3.2. The D^3R method

The D^3R method is based on the definitions of design for disassembly, deconstruction and resiliency in the context of the circular economy of buildings that emerged from our systematic literature review (see section **Error! Reference source not found.**). We hypothesize that the degree of reusability of buildings depends on a limited number of parameters, such as the tools needed to disassemble and move them, and whether the components can be reused, recycled, down-cycled or disposed (Jimenez-Rivero and Garcia-Navarro (2017), Akanbi, L. A. et al. (2019)). The D^3R method unfolds in four steps. In the first step, the case study and the scope of the analysis is defined. In doing so, the assessors should answer the question; is the analysed building planned for decommission after its service life, or moved and repurposed? Although most buildings are typically designed in a linear fashion, to be used and then disposed (Allwood, 2014), the circular economy of buildings is gaining traction and increasingly buildings are designed to be reused or easily refurbished (Celadyn, 2019; Nordby et al., 2009; Rodrigues and Freire, 2017). The second step consists of analysing the components and connections, focusing attention on how the components can be detached and the building or its parts can be taken apart. Accessible and disassemblable connections, such as visible bolted steel columns, make a disassembly more feasible; conversely, monolithic connections, such as concrete columns and beams, are not readily disassemblable or reusable (with the exception of bolted modular systems). In this step, the weights of building components are collected; further, a numeric value is assigned to all the building components, depending on the feasibility of their reuse (see section 3.3). The third step consists of the solution of the D^{3}R equation to calculate the D^{3}R index. Finally, the results are interpreted in step four, to understand the improvement that can be implemented to increase the D^{3}R index and design a more reusable building.

Through our systematic literature review, two main scenarios were identified, characterising the decommissioning of a building (Figure 2). A first, more typical scenario represents the end of life of the building, where it is taken apart and its materials are either recycled, disposed to landfill or reused (see Huang, B. et al. (2018), Babu et al. (2019)).

The operations that take place in this scenario are related to building disassembly, and they depend on the level of disassemblability of the structure that has been implemented in the design phases(s) (Akanbi, L. A. et al., 2019; Eberhardt et al., 2019). The three main actions identified in the deconstruction and disassembly of a building are turning forces, impact forces and lifting forces. For example, the typical disassembly and removal actions consist of the following: manual connections (bolts and screws), chemically bonded connections (concrete, glues and plasterboard) and lifting forces (removal and transport around the site to the relevant waste and material reuse streams. Once the components are disassembled, or the materials separated, they can be recirculated in the market for reuse (Zaman et al., 2018b), recycling or down-cycling (Jin et al., 2017) or disposal (Huang, B.J. et al., 2018). A second scenario is deconstruction of the building for the reuse of its parts or

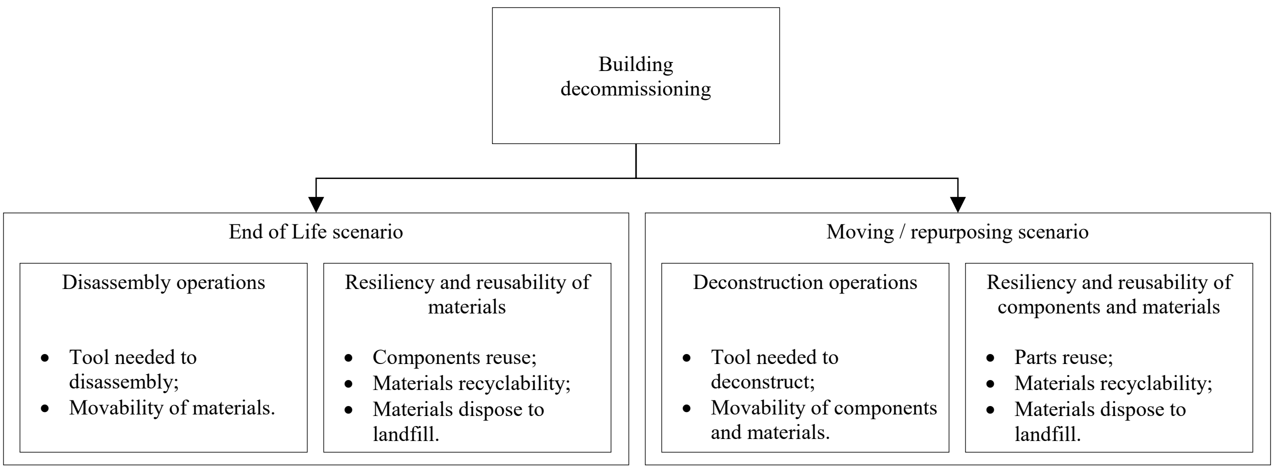


Figure 2 – End of life and moving / repurposing scenarios in the circular economy context.

components, where buildings maintain their shape, and can be moved to another site and repurposed or adapted (see Sanchez and Haas (2018)). The intent of deconstruction is to maintain most of the parts as they are, leaving a minimum of debris to be recycled (or down-cycled) and disposed to landfill (Akinade et al., 2017; Tatiya et al., 2018). This is typical for volumetric prefabrication where mining camps are positioned in place for a short-term period and relocated to the next site. Tools that are needed to deconstruct a building range from hand tools to tower cranes. Once the building is deconstructed, its material could be reused, or waste generated could be recycled or disposed (Diyamandoglu and Fortuna, 2015; Gorgolewski et al., 2008; Jiménez-Rivero and García-Navarro, 2017).

3.3. D^3R equations

The proposed method is based on the formulation and resolution of one equation that can be applied to building operations in planning and designing the building and according to the two scenarios described above (see section 3.2 and Figure 2). Equation 1 provides a calculation of the D^3R normalized index as the sum of the degree of disassembly (DI), deconstruction (DE) and resiliency (R) (equation 1):

1. $$D^3R = DI \times a + DE \times b + R \times c$$

A D^3R equal to zero means that the structure is fully linear: it cannot be disassembled, reused, or recycled. Conversely, a D^3R equal to one, means that the building can be fully disassembled and reused multiple times.

The influencers a, b and c account for the relevance of these operations in relation to the end of life scenario or moving/repurposing scenario (Figure 2). For the end of life scenario, the building is fully disassembled, as opposed to the moving/repurposing scenario, where the building is fully deconstructed. Therefore $b = 0$ in the former case, and $a = 0$ in the latter. The sum of the remaining variables (a and c in the first scenario, b and c in the second) is in both cases one. Although we suggest to assign a value of 0.5 to the two non-zero variables, the user can decide to change them to increase the weight of disassembly/deconstruction over resiliency, therefore emphasizing the importance of one or the other aspect. The three other values in equation 1 are revealed in equations 2, 3 and 4:

2. $$DI = \sum_{i=1}^{n}(DIt_i \times DIm_i \times w_i) \times \frac{1}{w_T}$$

3. $$DE = \sum_{j=1}^{m}\left(DEt_j \times DEm_j \times w_j\right) \times \frac{1}{w_T}$$

4. $$R = \sum_{k=1}^{t}(Re_k \times w_k) \times \frac{1}{w_T}$$

The variables of these equations depend on the disassembly, deconstruction and resiliency of the parts, components and materials of the building. We adapted the Likert scale to assign numeric values to these practices (see Tables 1, 2 and 3 below), giving a value of one to the practice that is close to fully circular economy (e.g., disassembly without power tools, or reusability an infinite number of times) and 0.2 to the practice that is considered less circular (e.g., dispose to landfill). We divided this 1 to 0.2 range in appropriate weighting, in order for the five scales to reflect the best practice, as suggested by Likert (Ekanayake and Ofori, 2004).

Disassembly: equation 2. The level of disassemblability of a building at the end of its life depends on the tools required to disassemble the specific component *i*. (Machado et al., 2018) entered the variable DIt_i, and the people or plant needed to move the components and materials (this is limited to on-site material movement, as accounting for transportation would be too broad and unpredictable) (Ganiron Jr and Almarwae, 2014; Musa et al., 2016), entered the variable DIm_i (Table 1). The symbol w_i represents the weight of the *i* component, while w_T is the total weight of the building. *n* represents the total number of components of the building.

Table 1 – Values of the variables DIt and DIm used in equation 2, that define the degree of disassemblability of a building.

	Operation & tools required		Value
DIt	Parameter that depends on the availability of tools, dimensions, manual, power tool etc.	No tool	1
		Hand tool	0.9
		Power tool	0.8
		Gas/pneumatic tool	0.5
		Hydraulic plant	0.2

DIm	Possibility of being disassembled and moved in up to two people, more than two people, need for a fork-lift or a crane.	1 person < 25kg	1
		2 people < 42kg	0.9
		Hand trolley < 50kg	0.7
		Fork-lift < 2000 kg	0.4
		Crane > 2000kg	0.1

Deconstruction: equation 3. Similarly, the extent that a building can be deconstructed at the end of its life depends on the tools required to deconstruct the project (the project can be defined as entire modules, panels, materials or components) j, entered as the variable DEt_j, and the people or plant needed to move the parts, components or materials on-site, entered as the variable DEm_j (Table 2). The symbol w_j represents the weight of the j component. w_T is the total weight of the building. m represents the total number of components in the building.

Table 2 – Values of the variables DEt and DEm used in equation 3, that define the degree of deconstructability of a building.

	Description		***Value***
DEt	Parameter that depends on the availability of tools, dimensions, manual, power tool etc.	No tool	1
		Hand tool	0.9
		Power tool	0.8
		Gas/pneumatic tool	0.5
		Hydraulic plant	0.2
DEm	Possibility of being disassembled and moved in up to two people, more than two people, need for a fork-lift or a crane.	1 person < 25kg	1
		2 people < 42kg	0.9
		Hand trolley < 50kg	0.7
		Fork-lift < 2000 kg	0.4
		Crane > 2000kg	0.1

Resiliency: equation 4. Once the parts, components and materials are dismantled, they can be reused an infinite number of times, a limited number of times, are recyclable (or down-cyclable) or disposed to landfill (Cuellar-Franca and Azapagic, 2012). The symbol Re_k takes this variability into account (Table 3). The symbol w_k represents the weight of the k component. w_T is the total weight of the building. t represents the last component of the building.

Table 3 – Values of the variable Re used in equation 4 that define the degree of resiliency of a part, component or material.

Description	***Value of Re***
Reusable infinite times	1
Reusable up to 3 times	0.9
Reusable only once	0.7

Recyclable	0.6
Down-cyclable	0.2
Disposable	0

To refine the D^{3}R method, we tested it through circular and linear examples, and finally, to validate it we applied it to the L3 and a comparative building constructed with the same materials, with the same dimensions, but in a linear fashion (i.e., without applying the circular economy approach).

3.4. Case study and scope definition: the Legacy Living Lab (L3)

Enabled by a number of industry partners, we designed and built a modular building prototype to study several aspects of the circular economy. The Legacy Living Lab (L3), built in Perth, Western Australia[3], is a two story volumetric modular building with a floor area of 251 m^2. The building comprises eight modules (five on the ground floor and three on the first floor). L3 is a research facility and commercial space, located on a new sustainable development named East Village at Knutsford, Fremantle, Western Australia. The D^{3}R method was incorporated in the building with an attempt set as an example and showcase the feasibility of circular economy to the Western Australian construction industry. For example, reused steel frames from a failed building project were reused; internal ceiling panels were made to be accessible, wall cladding was disassemblable plywood panels; recycled and recyclable materials were used where available; bolted connections were used in favour of welded connections; steel micro-pile foundations substituted concrete footings (the preferred foundations material in linear constructions). We compare the D^{3}R index of L3, namely the circular L3 (C), with a variation designed as a linear (traditional) version (L). The linear version has the same amount of materials, but most connections would be welded, making the building nearly impossible to

[3] 29-27 Blinco St, Fremantle WA 6160 Latitude: -32° 02' 17.63" S Longitude: 115° 46' 3.36" E

disassemble, and the foundations would be in concrete strip footings weighing 19.9 tons from engineered drawings.

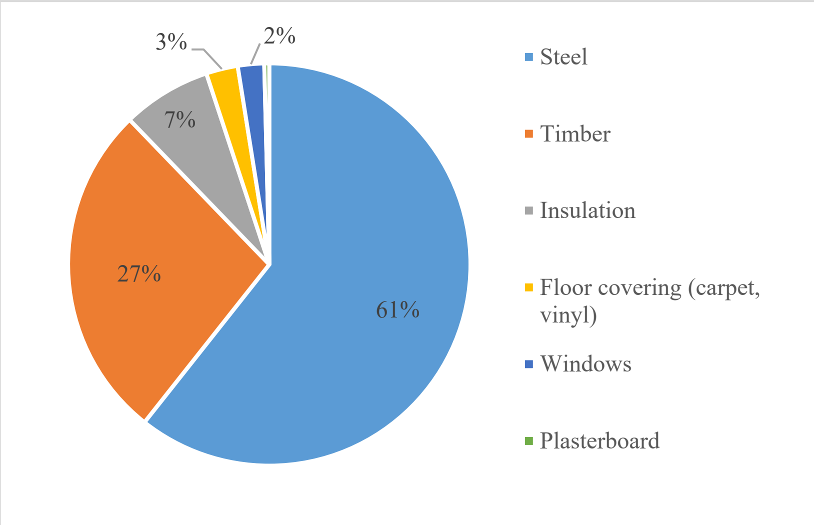


Figure 3 – The materials that compose the circular version of the L3.

The circular L3 weighs 35.9 tons, and its materials include steel (61% by mass), timber (27% by mass), insulation (7% by mass) and others (i.e., plasterboard, windows, etc.; see Figure and Table 4).

When prototyping the circular L3 we sourced whenever possible, second lifecycle material, although some new components had to be crafted such as the new columns needed on the ground floor to lift the ceiling height to suit the building's new purpose. Finally, other components, such as the external steel cladding, or the vinyl floor covering are not reusable. These materials, once the circular L3 is decommissioned, will be recycled.

Table 4 – Materials used in the Legacy Living Lab in its circular and linear versions

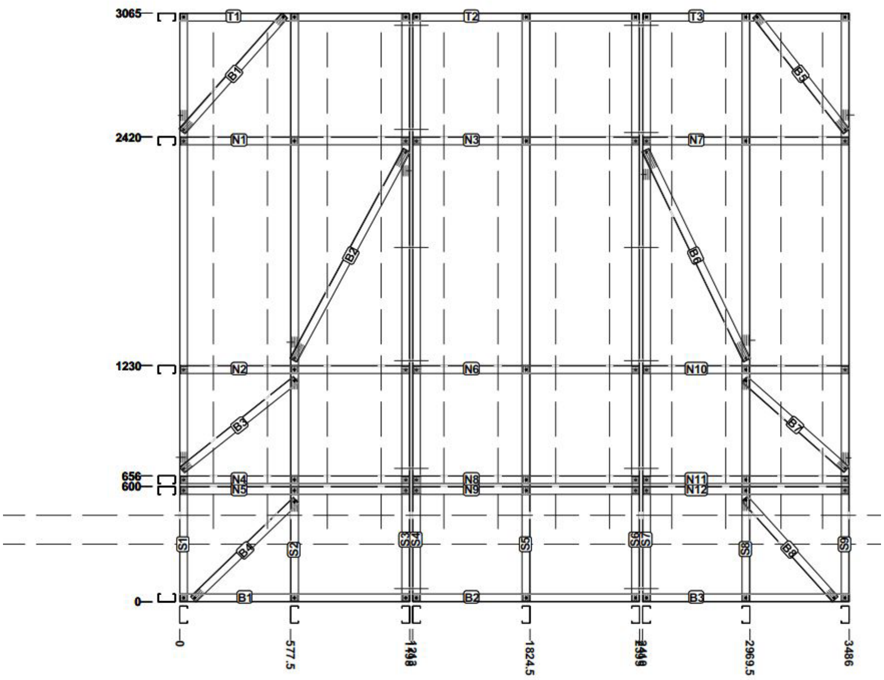
Material	***Description***	***Amount [kg]***
Steel – load bearing	Steel chassis and load bearing structure.	16 138.9
Timber – stairway	Salvaged timber composing the stairway steps.	164.0
Internal cladding – plywood	Plywood covering internal walls and the first floor ceiling.	3 328.0
Floor covering – carpet	Carpet covering 193m2 of internal floors.	183.4
Steel – stairway	Stairway steel structure.	422.8

Steel – internal walls structure	Lightweight steel structure, internal walls.	3 590.3
External cladding – pressed timber	Pressed timber used as ground floor external cladding.	1 811.7
External cladding – steel sheet	Steel sheets used at the first floor for external cladding.	652.1
Roof cladding – steel sheets	Steel sheets used for roof covering.	531.3
Floor covering – vinyl	Vinyl covering floors in wet areas.	714.0
Windows and glazed doors	Aluminum windows and glazed doors.	744.0
Timber doors	Internal timber doors.	138.0
Internal cladding – acoustic felt	Felt ceiling.	333.7
Internal cladding – plasterboard	Plasterboard cladding, used in kitchen/bathroom areas and ground floor ceiling.	140.2
Floor structure – particle board	Pressed fiber particle board used as floor structure.	4 102.6
Insulation	Glass wool used in all external walls, ceilings and roof.	2 516.0
Steel foundations (circular L3 only)	Screw pile lightweight steel foundations.	735.0
Concrete foundations (linear L3 only)	Concrete foundations composed by concrete discs and footings.	19 848.0
	Total weight	***35 551.0 (C)*** ***55 359.0 (L)***

3.5. The L3 connections and material analysis.

In this section we assess the main materials that make up the buildings structure and envelope. 4 main types of connections were used in the circular L3: bolted, screwed, magnetic, and welded. The main structural connections between modules were bolted. This includes the connections between the 8 modules and also the 5 ground floor modules connections to the footings. Structural steel frame connections were welded with this being standard practice for the builder responsible for the construction. This was required to comply with engineering standards as the modules were designed to be lifted by crane multiple times.

Figures 3 and 4 show how the wall frames were designed and built in 1200mm sections, keeping in line with the industry standard sheet sizes for wall cladding. The wall section was cut into three, reducing the elements weight from 60.6kg to three sections that weigh only 20.2kg. This facilitates a safe, 1 person lift if walls are to be replaced or removed easily by one person if and when the building is decommissioned. The Frame-Cad walls were built with screwed connections and the



plastic packer connecting the sections of wall frame throughout the building is also a screwed connection, enabling wall frames to be disassembled down to their initial forms at end of life.

Figure 4 – Frame-Cad plan of a wall section typically built in a single piece, was split into three sections to decrease the section weight of the element from 60.6kg to 20.2kg each.

Figure 5 – Photograph of the packing between the two frame sections making them accessible and disassemblable.

The internal cladding is mainly composed of plywood sheets 2400 x 1200mm, which have been screwed to the steel frames. The plywood sits on an aluminium negative detail to add aesthetic value, but also to provide tradespeople with a working edge when removing and re-installing the panels, thereby making them easy to disassemble, and reducing the impact of overhead movement by installers (Figure 5). The plywood was selected as the internal wall lining because of the resilient properties of plywood when compared to brittle gypsum board or cement sheeting. The panels were designed to line up with the windows and set out specifically to maximise the use of standardised industry measures.

A new ceiling fixing method was tested for the acoustic ceiling panels, which were used in the ground floor ceiling and apartment display space (Figure 5). Pressed felt boards were held in place by pot magnets. Each 2400 x 1200mm panel had a thin steel "C" channel glued to the back. Magnets were positioned in-line with the channel to support the weight of the sheet. Both the acoustic felt ceiling and plywood wall detailing can be seen below (Figure 5).

Figure 5 – Magnetic acoustic felt ceiling, plywood walls (disassembable and resilient) and windows are all standard measures of 2400 x 1200mm to promote standard measurements.

The building sits on galvanised steel micro-piles which are comprised of two main parts, a base plate which the buildings stumps were bolted to, and a series of steel tubes that were driven into the earth with a jackhammer at different angles to deflect the buildings load into the bearing strata. These footing plates were screwed to the micro-piles and bolted to the main structure. The manufacturer of the steel micro-pile foundations used in the circular version claimed that the footings can be reused, however these foundations were omitted from the results due to this new technology had not been structurally tested, and the foundations were assigned to be recycled at the end of life.

However, the concrete foundations used in the linear version cannot be disassembled or transported. A large excavator with a demolition breaker is required to split them apart, in order for them to be removed from the ground, and the broken concrete can only be down-cycled (Adams et al., 2017).

4. Results

The D^3R method has considered the machinery needed to disassemble or deconstruct a structure, the reusability or recyclability and weight of its components. In doing so, the method applies equations 2, 3 and 4 to calculate the D^3R index. The D^3R index measures the level of disassemblability, deconstructability and resiliency of a building, in a range from zero (which means that the building is entirely demolished and landfilled) to one (which means that every component is easy to disassemble and is reusable infinite times). To validate the D^3R method, we applied its equations to calculate the D^3R index of the L3 modular building (called circular prototype, C), and compared the results with the D^3R index of a traditionally built modular building (called linear case study, L).

4.1. D^3R of the circular L3

To calculate the D^3R index of the L3 it is important to consider that the circular L3 is a disassemblable structure. Therefore, the parameter *b* of equation 1 is equal to zero. Further, the remaining parameters *a* and *c* are arbitrarily chosen as being equal to 0.5. That means that the disassemblability of the L3 and the reusability of its components are considered of equal relevance. In considering these parameters, equation 1 becomes:

$$D^3R = 0.5 \times DI + DE \times 0 + 0.5 \times R$$

To calculate the values of *DI* and *R* we used the parameters listed in Table 5, have been referred for the mass of the components of the circular L3, and the tools needed to disassemble and transport them.

Table 5 – Values of the parameters DIt, DIm and Ri of the circular L3.

Description	***Mass (kg)***	***DI tools needed***	***DIt***	***DI moving tool description***	***DIm***	***Resiliency description***	***Ri***
Steel chassis and load bearing structure.	16 138.9	Gas/pneumatic tool	0.5	Fork-lift	0.4	Reusable infinite times	1
Salvaged timber composing the stairway steps.	164.0	Power tool	0.8	Fork-lift	0.4	Reusable up to 3 times	0.9
Plywood covering internal walls and the first floor's ceiling.	3 328.0	Power tool	0.8	2 people > 25kg	0.9	Reusable up to 3 times	0.9
Carpet covering 193m2 of internal floors.	183.4	No tool	1	1 person < 25kg	1	Reusable up to 3 times	0.9
Stairway steel structure.	422.8	Gas/pneumatic tool	0.5	Fork-lift	0.4	Recyclable	0.6
Lightweight steel structure, internal walls.	3 590.3	Power tool	0.8	2 people > 25kg	0.9	Reusable infinite times	1
Pressed timber used as ground floor external cladding.	1 811.7	Power tool	0.8	1 person < 25kg	1	Reusable up to 3 times	0.9
Steel sheets used at the first floor for external cladding.	652.1	Power tool	0.8	2 people > 25kg	0.9	Reusable infinite times	1
Steel sheets used for roof covering.	531.3	Power tool	0.8	2 people > 25kg	0.9	Reusable infinite times	1
Vinyl covering floors in wet areas.	714.0	No power tool	1	1 person < 25kg	1	Reusable 1 time	0.7
Aluminium windows and glazed doors.	744.0	Hand tool	0.9	2 people > 25kg	0.9	Reusable up to 3 times	0.9
Internal timber doors.	138.0	Power tool	0.8	1 person < 25kg	1	Reusable infinite times	1
Magnetic felt ceiling	333.7	No tool	1	1 person < 25kg	1	Reusable up to 3 times	0.7
Plasterboard cladding, used in kitchen/bathroom areas and ground floor ceiling.	140.2	Power tool	0.8	1 person < 25kg	1	Disposable	0
Pressed fibre particle board	4 102.6	Power tool	0.8	2 people > 25kg	0.9	Down-cyclable	0.2

used as floor structure.							
Insulation	2 516.0	No tool	1	1 person < 25kg	1	Recyclable	0.6
Screw pile lightweight steel foundations.	735	Hydraulic plant	0.2	1 person < 25kg	1	Recyclable	0.6

These parameters allow the calculation of the values of DI_C and R_C of the circular L3. DI_C = *0.52*, and R_C = *0.86*. Therefore, the D^3R_C of the circular L3 is calculated in equation 2.

$$D^3R_C = 0.5 \times 0.52 + 0.5 \times 0.86 = 0.69$$

This means that, in considering the connections that form the building, the level of reusability and recyclability of its components, the tools and machineries necessary to disassemble and transport them, 69% of the mass of the L3 has been designed following the circular economy framework.

4.2. D^3R of the linear case study

The same procedure can be adopted to calculate the D^3R index of a linear building—built without considering the circular economy framework in its design stage. To be able to compare the D^3R index of the linear building with the D^3R index of the circular L3, we assume that this linear building is similarly a steel-framed modular building, whose connections are welded, panels are glued and with a concrete foundation. Additionally, a traditionally built modular building would employ a concrete foundation. In considering these features of the linear building, Table 6 summarizes the *DIt*, *Dim* and *Ri* values of the components of the linear version of the L3.

Table 6 – Values of the parameters DIt, DIm and Ri of the linear version of the L3.

Description	***Mass (kg)***	***DI tools needed***	***DIt***	***DI moving tool description***	***DIm***	***Resiliency description***	***Ri***
Steel chassis and load bearing structure.	16 138.9	Gas/pneumatic tool	0.5	Fork-lift	0.4	Recyclable	0.6
Salvaged timber composing the stairway steps.	164.0	Power tool	0.8	Fork-lift	0.4	Reusable up to 3 times	0.9
Plywood covering internal walls and the first floor's ceiling.	3 328.0	Power tool	0.8	2 people > 25kg	0.9	Down-cyclable	0.2

Carpet covering 193m2 of internal floors.	183.4	No tool	1	1 person < 25kg	1	Reusable up to 3 times	0.9
Stairway steel structure.	422.8	Gas/pneumatic tool	0.5	Fork-lift	0.4	Recyclable	0.6
Lightweight steel structure, internal walls.	3 590.3	Power tool	0.8	2 people > 25kg	0.9	Recyclable	0.6
Pressed timber used as ground floor external cladding.	1 811.7	Power tool	0.8	1 person < 25kg	1	Down-cyclable	0.2
Steel sheets used at the first floor for external cladding.	652.1	Power tool	0.8	2 people > 25kg	0.9	Recyclable	0.6
Steel sheets used for roof covering.	531.3	Power tool	0.8	2 people > 25kg	0.9	Recyclable	0.6
Vinyl covering floors in wet areas.	714.0	No tool	1	1 person < 25kg	1	Reusable 1 time	0.7
Aluminium windows and glazed doors.	744.0	Power tool	0.8	2 people > 25kg	0.9	Disposable	0
Internal timber doors.	138.0	Power tool	0.8	1 person < 25kg	1	Disposable	0
Glued felt ceiling	333.7	Hand tool	0.9	1 person < 25kg	1	Recyclable	0.6
Plasterboard cladding, used in kitchen/bathroom areas and ground floor ceiling.	140.2	Power tool	0.8	1 person < 25kg	1	Disposable	0
Pressed fibre particle board used as floor structure.	4 102.6	Power tool	0.8	2 people > 25kg	0.9	Down-cyclable	0.2
Insulation	2 516.0	No tool	1	1 person < 25kg	1	Recyclable	0.6
Concrete foundations composed by concrete discs and footings.	19 848.0	Hydraulic plant	0.2	Fork-lift	0.4	Down-cyclable	0.2

These parameters allow the calculation of the values of DI_L and R_L for the linear version of the L3. This results in values for $DI_L = 0.35$, and $R_L = 0.38$. Therefore, the D^3R_L of the circular L3 is:

$$D^3R_L = 0.5 \times 0.35 + 0.5 \times 0.38 = 0.37$$

That means that, in considering that the connections that form the building are mainly welded, most components are not reusable, but are recyclable, the tools and machineries necessary to disassemble and transport them, 37% of the mass of the linear version of the L3 can be considered circular.

5. Discussion and improvements

Conventionally, LCA is an established tool for calculating the environmental savings of products, to our knowledge a tool to calculate the circularity of buildings was a noticeable literature gap, with the exception of the material circularity indicator (Akanbi, Lukman A. et al., 2019). To bridge this gap, this research proposes the D^3R method, which is the main contribution of this research. It can guide practitioners in calculating the D^3R index. The D^3R index allows the quantification of the circularity index of any building. The D^3R index is decoupled from environmental impacts and therefore has the potential to give a perspective on buildings' circularity separated from their environmental saving (Linder et al., 2020). The calculation of the D^3R index allows an evaluation of the degree to which the circular economy framework has been applied in designing a building. Also, using a table template such as Table 5 or Table 6 allows the designer to evaluate which components provide an increased D^3R index and to which extent. For example, despite the efforts made to design the L3 by following the circular economy strategies and framework, the use of disposable or down-cyclable materials such as plasterboard or particle board, or the necessity of large power tools or mechanical plant contribute to reducing the D^3R index of the circular L3. When considering the linear version of the L3, it is clear from Table 6 that the reason why its D^3R index is low is the restriction of reusing components such as steel frames, which will instead be recycled, or the use of concrete foundations, which require a large mechanical plant to be broken-out and removed before being down-cycled.

5.1. Comparison of the results

The D^3R index varies between 0 and 1, with higher values associated with a higher level of circularity. To test the D^3R method, this was applied to the materials, assembly and disassembly operations of the L3, obtaining a $D^3R = 0.69$. When the same index was calculated for the L3 version built as a traditional modular building (i.e. not designed for circularity disassembly, but with most of its materials recyclable), the D^3R index was 0.37. Therefore, the results show that a building designed by following the circular economy framework can be related to higher values of a D^3R index. The comparison between the two indices, one calculated for the disassemblable building, and the other calculated for the recyclable building, demonstrates that the D^3R index can be effectively employed to calculate the circularity level of a building.

6. Conclusions

In this research we propose a method to calculate the level of disassemblability, deconstructability, and resiliency of buildings and their components made possible by accurate design for second life. The D^3R method takes into account the people and tools needed to disassemble or deconstruct a building, and to move its components. The Legacy Living Lab case study was used to validate the proposed method. It is demonstrated that the Legacy Living Lab, a building which has been designed for disassembly, has a D^3R index equal to 0.69. The D^3R method can be used for multiple purposes: it can demonstrate the level of circularity of different designs by comparing the reusability of buildings and their components; can guide the design stages of new buildings to help reduce material consumption and waste in the construction industry, and their related greenhouse gas emissions; and can be used to assess the circularity of existing buildings.

The use of second hand components relies heavily on the quality of components that are available in the market place. If the builder or client has direct control of this process, then it is easy to recover materials. The supply chain for second hand material will require significant improvement for circular economy to become a feasible practice in Australia, given the work that was needed to procure materials for the L3 project. With proper design, the ease by which buildings can be disassembled will increase and the quality of second hand materials will be reflected in these small changes.

The magnetic acoustic felt ceiling panels present well as a product offering, having both recycled content (60%) and, with the magnetic fixing method, they were thought to be a highlight as an example of a circular economy material. However, we encountered issues with tradespeople changing their practices because the ceiling panels were so easy to remove. This caused them to be removed more often than planned and the soft felt showed signs of wear after being incorrectly stored or stood on whilst laying on the floor. The case study was built by a company accustomed to building mining camps and not all new technology was fully embraced, resulting in sub-optimal finishes. This is an example of a number of practical learnings that are of use for the building industry in a transition to circular economy based construction.

Currently the link between high quality building materials recovered from the construction industry is under-developed. The normal industry practice is to recover timber for down-cycling, with masonry products being crushed into road base. Demolition companies recover historic features and these are sold for a higher price than other recoverable items that are not seen to be as valuable. Education and skills training would help promote the importance of the recovered materials and the role they have in sustainable construction. Demolition crews are not properly trained to remove or extract the materials as they were installed, often force is used instead of removing the material correctly, causing its worth to be removed instantaneously. With a correct marketplace established qualified trades people can deconstruct buildings in reverse order, sorting and separating the extracted parts for future use, and thereby maximising the material recovery.

7. Future research

Future research into the D^3R method will integrate D^3R with the LCA method to increase the depth of study into circular economy indexing and their relationship to environmental impact factors. Linking LCA to the D^3R method will allow the next stage of the study to determine the relevance of the influencers *a, b* and *c.* In this paper we have given the influencers an equal value of 0.5 to see the circular index as a baseline. Integration of the LCA method will allow designers to make changes based on circular economy principles with quantifiable benefits to the environment which will change the values given to indicators based on desired emissions reductions in upcoming projects. This will provide building designers with the complete set of tools required to design sustainable buildings for the future.

Circular economy is still in its early stage of development in the building industry and there is a need to facilitate the efficient recovery and reuse of materials in the construction industry. We have been fortunate to design the L3 case study and have the proof of concept that a circular economy building can be delivered, but scaling will require translation of practice into the construction demolition and material recovery sector. Future research is needed into the process of demolition and material recovery in order to establish a market supply chain of second hand building materials.

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8. References

Abid, S.R., Nahhab, A.H., Al-aayedi, H.K.H., Nuhair, A.M., 2018. Expansion and strength properties of concrete containing contaminated recycled concrete aggregate. Case Studies in Construction Materials 9, e00201.

Adams, K.T., Osmani, M., Thorpe, T., Thornback, J., 2017. Circular economy in construction: current awareness, challenges and enablers. Proceedings of the Institution of Civil Engineers - Waste and Resource Management 170(1), 15-24.

Ajayi, S.O., Oyedele, L.O., Bilal, M., Akinade, O.O., Alaka, H.A., Owolabi, H.A., Kadiri, K.O., 2015. Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements. Resources Conservation and Recycling 102, 101-112.

Akanbi, L.A., Oyedele, L.O., Akinade, O.O., Ajayi, A.O., Davila Delgado, M., Bilal, M., Bello, S.A., 2018. Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. Resources, Conservation and Recycling 129, 175-186.

Akanbi, L.A., Oyedele, L.O., Omoteso, K., Bilal, M., Akinade, O.O., Ajayi, A.O., Davila Delgado, J.M., Owolabi, H.A., 2019. Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. Journal of Cleaner Production 223, 386-396.

Akanbi, L.A., Oyedele, L.O., Omoteso, K., Bilal, M., Akinade, O.O., Ajayi, A.O., Delgado, J.M.D., Owolabi, H.A., 2019. Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. Journal of Cleaner Production 223, 386-396.

Akinade, O.O., Oyedele, L.O., Ajayi, S.O., Bilal, M., Alaka, H.A., Owolabi, H.A., Bello, S.A., Jaiyeoba, B.E., Kadiri, K.O., 2017. Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. Waste Management 60, 3-13.

Allwood, J.M., 2014. Squaring the circular economy: the role of recycling within a hierarchy of material management strategies, Handbook of recycling. Elsevier, pp. 445-477.

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2011. Material efficiency: A white paper. Resources Conservation and Recycling 55(3), 362-381.

Babu, S., Zhou, J., Wan, M.P., Lamano, A.S., Sarvaiya, J.N., Zhang, Z., Kumar, D.E.V.S.K., Gao, C.P., Valliappan, S., Goh, A., Seoh, A., 2019. Investigation of an integrated automated blinds and dimmable lighting system for tropical climate in a rotatable testbed facility. Energy and Buildings 183, 356-376.

Brambilla, G., Lavagna, M., Vasdravellis, G., Castiglioni, C.A., 2019. Environmental benefits arising from demountable steel-concrete composite floor systems in buildings. Resources Conservation and Recycling 141, 133-142.

Buyle, M., Galle, W., Debacker, W., Audenaert, A., 2019. Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. Journal of Cleaner Production 218, 141-156.

Celadyn, M., 2019. Interior Architectural Design for Adaptive Reuse in Application of Environmental Sustainability Principles. Sustainability 11(14).

Chileshe, N., Rameezdeen, R., Hosseini, M.R., Martek, I., Li, H.X., Panjehbashi-Aghdam, P., 2018. Factors driving the implementation of reverse logistics: A quantified model for the construction industry. Waste Management 79, 48-57.

Cuellar-Franca, R.M., Azapagic, A., 2012. Environmental impacts of the UK residential sector: Life cycle assessment of houses. Building and Environment 54, 86-99.

Denyer, D., Tranfield, D., 2009. Producing a systematic review.

Diyamandoglu, V., Fortuna, L.M., 2015. Deconstruction of wood-framed houses: Material recovery and environmental impact. Resources, Conservation and Recycling 100, 21-30.

Eberhardt, L.C.M., Birgisdóttir, H., Birkved, M., 2019. Life cycle assessment of a Danish office building designed for disassembly. Building Research and Information 47(6), 666-680.

Eckelman, M.J., Brown, C., Troup, L.N., Wang, L.Z., Webster, M.D., Hajjar, J.F., 2018. Life cycle energy and environmental benefits of novel design-for-deconstruction structural systems in steel buildings. Building and Environment 143, 421-430.

Ekanayake, L.L., Ofori, G., 2004. Building waste assessment score: design-based tool. Building and Environment 39(7), 851-861.

Esa, M.R., Halog, A., Rigamonti, L., 2017. Strategies for minimizing construction and demolition wastes in Malaysia. Resources Conservation and Recycling 120, 219-229.

Gangolells, M., Casals, M., Forcada, N., Macarulla, M., 2014. Analysis of the implementation of effective waste management practices in construction projects and sites. Resources Conservation and Recycling 93, 99-111.

Ganiron Jr, T.U., Almarwae, M., 2014. Prefabricated technology in a modular house. International Journal of Advanced Science and Technology 73, 51-74.

Gaustad, G., Krystofik, M., Bustamante, M., Badami, K., 2018. Circular economy strategies for mitigating critical material supply issues. Resources, Conservation and Recycling 135, 24-33.

Ghisellini, P., Ripa, M., Ulgiati, S., 2018. Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. Journal of Cleaner Production 178, 618-643.

Gorgolewski, M., Straka, V., Edmonds, J., Sergio-Dzoutzidis, C., 2008. Designing buildings using reclaimed steel components. Journal of Green Building 3(3), 97-107.

Huang, B., Wang, X., Kua, H., Geng, Y., Bleischwitz, R., Ren, J., 2018. Construction and demolition waste management in China through the 3R principle. Resources, Conservation and Recycling 129, 36-44.

Huang, B.J., Wang, X.Y., Kua, H.W., Geng, Y., Bleischwitz, R., Ren, J.Z., 2018. Construction and demolition waste management in China through the 3R principle. Resources Conservation and Recycling 129, 36-44.

Jiang, Y., Ling, T.-C., Shi, C., Pan, S.-Y., 2018. Characteristics of steel slags and their use in cement and concrete—A review. Resources, Conservation and Recycling 136, 187-197.

Jimenez-Rivero, A., Garcia-Navarro, J., 2017. Exploring factors influencing post-consumer gypsum recycling and landfilling in the European Union. Resources Conservation and Recycling 116, 116-123.

Jiménez-Rivero, A., García-Navarro, J., 2017. Best practices for the management of end-of-life gypsum in a circular economy. Journal of Cleaner Production 167, 1335-1344.

Jin, R.Y., Li, B., Zhou, T.Y., Wanatowski, D., Piroozfar, P., 2017. An empirical study of perceptions towards construction and demolition waste recycling and reuse in China. Resources Conservation and Recycling 126, 86-98.

Leising, E., Quist, J., Bocken, N., 2018. Circular Economy in the building sector: Three cases and a collaboration tool. Journal of Cleaner Production 176, 976-989.

Linder, M., Boyer, R.H., Dahllöf, L., Vanacore, E., Hunka, A., 2020. Product-level inherent circularity and its relationship to environmental impact. Journal of Cleaner Production, 121096.

Machado, R.C., de Souza, H.A., Verissimo, G.D., 2018. Analysis of Guidelines and Identification of Characteristics Influencing the Deconstruction Potential of Buildings. Sustainability 10(8).

Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. Journal of Cleaner Production 178, 703-722.

Musa, M.F., Yusof, M.R., Mohammad, M.F., Samsudin, N., 2016. Towards the adoption of modular construction and prefabrication in the construction environment: A case study in Malaysia. Journal of Engineering and Applied Sciences 11(13), 8122-8131.

NIAC, 2009. Critical Infrastructure Resilience Final Report and Recommendations by National Infrastructure Advisory Council

Nordby, A.S., Berge, B., Hakonsen, F., Hestnes, A.G., 2009. Criteria for salvageability: The reuse of bricks. Building Research and Information 37(1), 55-67.

Nunez-Cacho, P., Gorecki, J., Molina-Moreno, V., Corpas-Iglesias, F.A., 2018. What Gets Measured, Gets Done: Development of a Circular Economy Measurement Scale for Building Industry. Sustainability 10(7).

Oikonomou, N.D., 2005. Recycled concrete aggregates. Cement and Concrete Composites 27(2), 315-318.

Rodrigues, C., Freire, F., 2017. Adaptive reuse of buildings: Eco-efficiency assessment of retrofit strategies for alternative uses of an historic building. Journal of Cleaner Production 157, 94-105.

Sanchez, B., Haas, C., 2018. A novel selective disassembly sequence planning method for adaptive reuse of buildings. Journal of Cleaner Production 183, 998-1010.

Schulze, P., Engineering, N.A., 1996. Engineering Within Ecological Constraints. National Academies Press.

Siddaway, A.P., Wood, A.M., Hedges, L.V., 2019. How to do a systematic review: a best practice guide for conducting and reporting narrative reviews, meta-analyses, and meta-syntheses. Annual review of psychology 70, 747-770.

Sieffert, Y., Huygen, J.M., Daudon, D., 2014. Sustainable construction with repurposed materials in the context of a civil engineering-architecture collaboration. Journal of Cleaner Production 67, 125-138.

Solís-Guzmán, J., Marrero, M., Montes-Delgado, M.V., Ramírez-de-Arellano, A., 2009. A Spanish model for quantification and management of construction waste. Waste Management 29(9), 2542-2548.

Stahel, W.R., 2016. The circular economy. Nature 531(7595), 435-438.

Tam, V.W.Y., Tam, C.M., 2006. A review on the viable technology for construction waste recycling. Resources, Conservation and Recycling 47(3), 209-221.

Tatiya, A., Zhao, D., Syal, M., Berghorn, G.H., LaMore, R., 2018. Cost prediction model for building deconstruction in urban areas. Journal of Cleaner Production 195, 1572-1580.

Van den Berghe, K., Vos, M., 2019. Circular area design or circular area functioning? A discourse-institutional analysis of circular area developments in Amsterdam and Utrecht, The Netherlands. Sustainability (Switzerland) 11(18).

Vefago, L.H.M., Avellaneda, J., 2013. Recycling concepts and the index of recyclability for building materials. Resources, Conservation and Recycling 72, 127-135.

Verian, K.P., Ashraf, W., Cao, Y., 2018. Properties of recycled concrete aggregate and their influence in new concrete production. Resources, Conservation and Recycling 133, 30-49.

Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. Renewable and Sustainable Energy Reviews 68, 825-833.

Zaman, A.U., Arnott, J., McLntyre, K., Hannon, J., 2018a. Resource Harvesting through a Systematic Deconstruction of the Residential House: A Case Study of the 'Whole House Reuse' Project in Christchurch, New Zealand. Sustainability 10(10).

Zaman, A.U., Arnott, J., McLntyre, K., Hannon, J., 2018b. Resource harvesting through a systematic deconstruction of the residential house: A case study of the 'Whole House Reuse' project in Christchurch, New Zealand. Sustainability (Switzerland) 10(10).

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The project network approach for Living Laboratories

Abstract

While the value of innovation is recognized within knowledge intensive contexts as requiring inter-organizational cooperation, one particular form gaining increasing attention in industry, Living Laboratories (Living Labs), is comparatively less understood. This paper analyzes the management of the different stages of two complex projects related to the construction of a Living Lab platform with a focus on sustainability, in particular overcoming the potential conflict between the goal of the project (the macro goal) and the goals of the actors (micro goal). The need for a new form of coordination of Living Labs, going beyond the top down (lead firm centricity) and the bottom up (user centricity) approaches is identified. Furthermore, we contribute to the understanding of the relevance of a new role, a transdisciplinary coach, in the network overcoming the conservatism of the traditional lead actors. In addition, the case depicted the relevance of Peer-to-Peer (P2P) business relationships overcoming the traditional top down and bottom up perspective.

Keywords

Sustainable Living, Circular Economy, Living Lab, Projects, Platform, Goals Alignment, Committed Goals

1. Introduction

Originating from the notion of long-term field experiments (1980s and 1990s), the concept of the Living Laboratory (Living Lab) evolved to laboratory style infrastructures aimed at testing innovations in settings where real-life conditions were recreated (1990s and 2000s) through to an innovation approach based on user co-creation and real-life experimentation (2000s and 2010s) (Schuurman and Protic, 2018). Living Labs have often, but not always, been generated by the cooperation of universities, industry, and community, working together to co-create, explore, experiment and foster innovation for mutually beneficial outcomes (ENoLL, 2014). Even if the open innovation perspective was adopted to investigate Living Labs (Westerlund and Svahn 2008, Leminen, Westerlund & Nyström, 2012; Nyström, Leminen, Westerlund and Kortelainen, 2014), the full innovation potential continues to be underutilized due to the complexity of the Living Lab at the three system levels: the organizational level, the project level, and the individual user interactions level (Schuurman, 2015).

The overall aim of Living Labs is to learn and experiment, by integrating processes of research and innovation (ASC, 2016; ENoLL, 2016; Stten and van Bueren, 2017). If indeed many Living Lab projects miss full innovation exploitation then there is a need to identify the key drivers that enable the management of Living Lab complexity and the development of the innovation platform. Traditionally the lead firm that can orchestrate and control the strategic net defines the goals for the Living Lab platform (Nambisan & Sawhney, 2011). As stated by Protic & Schuurman (2018) who focused on the ownership and the business model of Living Labs, we observe a lack of clarity. In particular, other actors can take a key role in platform evolution and coordination and must therefore be considered across all stages of the project. Given different actors assume roles in these networks, in line with Industrial Marketing and Purchasing (IMP) research, the alignment between heterogeneous goals is founded on their interaction. The extensive cooperation between multi-sectoral actors and collaboration processes are considered to take into account diverse approaches and strategic objectives (Håkansson & Waluszewski, 2007; Aarikka-Stenroos et al., 2017; Baraldi & Strömsten, 2009).

Considering that the main approach to managing company innovation has been through the project concept (Giard and Midler, 1997) as the vehicle for strategic implementation, we focus attention on how the projects of this platform can be managed in order to pursue sustainability-orientated goals. Given the relative nascent state of sustainability-focused innovation in practice, actors seeking to internalize these principles may have to radically change their business models, including through new partnerships and innovation processes (Ünal and Shao, 2019). In examining these change processes, we seek to identify the collaboration patterns of the heterogeneous actors involved, the evolution of individual goals and the role of actors (Nyström et al 2014).

This paper analyzes the management of the different stages of a complex project related to the construction of a Living Lab platform with a focus on sustainability. The main aim of this paper is to investigate the project nature of a Living Lab, and the management of complexity generated by attempting to achieve the goal of the project (macro goal) together with the individual actors goals (micro goal). We address a key research question in identifying how the management of the project can provide value to heterogeneous actor goals while sustaining the evolution of the project. Furthermore, the research seeks to characterise a new form of coordination of Living Labs which enables it to go beyond the top down (lead firm centricity) and the bottom up (user centricity) approaches.

This research applies a case study design to investigate two interrelated Living Lab projects focusing on sustainability related issues, with an emphasis on outcomes relevant to the construction industry. We present two Living Labs at different stages of development – a Swedish Living Lab with a focus on sustainable living and an Australian Living Lab with a focus on the circular economy of the building and its occupancy. Data has been collected from interviews with the key stakeholders involved in the development of these projects, including individuals that have experience with both cases. Secondary data has also been collected from available internal documentation, publications and media during the study timeframe. The case provides insights into the relevance of a new coordination approach, with a foundation in peer-to-peer business relationships. It follows that a new role is required to manage the alignment of the goal of actor (micro goal), goal of the project (macro goal) and the committed goals (pursued by the individual actor).

In the next section, we introduce the traditional coordination approach of the Living Lab. Then we present the project network perspective, focusing on the goals and the commitment. Next the research approach is explained. Subsequently we describe the case and the findings. Finally we present the theoretical and managerial implications of our findings and answer our research questions.

2. Managing Living Lab projects: a sustainability orientation

2.1 Living Lab: the coordination approach

Across different iterations, Living Labs have been considered relevant tools for organizing innovation activities between companies (Leminen et al., 2016, Steen and van Bueren, 2017).
Three generations of Living Lab have been identified (Leminen et al., 2018). The first generation of living labs focused on creating real-life environments intertwined with users and stakeholder activities. The second generation considered the Living Lab methodology as innovation activities in the real-life environment. The third generation of Living Labs focused on a wider perspective of collaborative innovation, emphasizing that different stakeholder and particularly users have crucial roles in innovation on platforms (Leminen et al., 2018, Nyström et al., 2014; Schuurman et al., 2016). Starting from this last perspective, scholars have sought to clarify how Living Labs contribute to open innovation outcomes through managing multiple actor contributions (Nyström et al., 2014). While combining multiple

actors generates value, at the same time, divergent interests increases the complexity of collective decision making.

Considering the managerial configuration and coordination approaches used to realize third generation of Living Labs, these ones can be broadly characterized as either consortium based or as service organizations (Schuurman et al., 2018). As a service organization, projects are carried out for customers of the Living Lab and thus have a clear project owner, whereas in consortium-based Living Labs, the diverse interests of consortium partners generate less clear ownership and emergent roles (Schuurman et al., 2016). These management and ownership structure are strictly related to the coordination approaches, classified by Leminen (2013) into top down and bottom up approaches. The top down approach (Tang et al., 2012) is led or coordinated in accordance with centralized, official targets, whereas a bottom up approach (Schuurman et al., 2011) focuses on local needs and operates at the grassroots level to realize a platform. Understanding managerial and intra-organizational dynamics involves the analysis of leadership, monovocal top down approach and autocratic leadership style (Venselaar et al., 2015) as well as the approach oriented to customer/user involvement (Rust et al., 2016) well emphasized by the business service network approach (Ramos et al., 2012). While firms are pursuing both top down and bottom-up approaches, a blend of the two approaches bodes well for firms (Gupta et al., 2019, Birkinshaw et al., 2011).

Literature on platforms suggests that the platform is managed by the lead firm that devises and implements architectures to enable novel offerings and coordinate network actors (Eloranta & Turunen, 2016; Nambisan & Sawhney, 2011). The lead firm supports the value platform development and the network-centric reconfiguration (Möller & Svahn, 2009). Similarly, network orchestration perspectives assume that central actors can purposefully influence and manage the development of a value network (Müller-Seitz, 2012, Laczko et al., 2019). A key part of the central actors' role is to manage and/or avoid conflict between other participating actors. Conflict can include clashes between divergent perspectives, interests, objectives, or behaviours, defined by Wall and Callister (1995, p. 517) as "a process in which one party perceives that interests are being opposed or negatively affected by another party". Some forms of conflict can be useful because they foster creativity and debate (Vaaland & Håkansson, 2003), however, whether conflicts are perceived as positive or negative depends upon the outcome (Mele, 2011).

In a bottom up approach, platforms are co-created with the involvement of users. It follows that network actors enhance, change and redirect the value platform over time (Eloranta & Turunen, 2016, Perks et al., 2017). Opening a platform up to third parties can enhance the diversity of complementors and positively contribute to the innovations produced (Gawer, 2014). This aligns with perspectives which assume no actor can control the network (Ford & Håkansson 2002), and that interdependent entities in the relationship control each other as a result of the resources which they possess (Ford et al., 2008). Emergent, bottom up approaches focus on the networking capabilities of actors which enable them to perform certain roles which can influence networks to achieve collective goals (Mitrega et al., 2017). The goals are the starting point of a project aimed at the development of a platform.

2.2 Project Networks: sustainable goals and commitment

From a network perspective, project networks are "structures of exchange relationships among business actors—firms as well as individuals—structures which emerge, evolve and dissolve over time in a continuous and interactive process" (Halinen & Törnroos, 1998, p. 189). The project marketing approach views projects as typically occurring in the networked business environment referred to as the milieu (Cova et al., 1996). Business relationships with the other actors in the milieu are crucial for the functional position and the relational position of the firm in the project business (Ahola, Kujala, Laaksonen, & Aaltonen, 2013). "Contrasting with the idea of market which refers to a group of companies, competitors, customers clearly operating in business, the idea of milieu puts the emphasis on the environment and on the formal and informal links existing between business and non-business actors (set of implicit rules)" (Cova et al., 1994, p. 36). The management of project business involves two levels, the management of projects or project portfolios and, in a traditional way, the management of customer relationships (Mainela and Ulkuniemi, 2013). To bridge these distances and diminish the differences, personal interaction is a necessity (Mainela and Ulkuniemi, 2013). In addition, the context of the relationships seems to influence the customer's selection of partnering and partners (Crespin-Mazet et al., 2016).

The starting point of different projects is the definition of the project goal (Jalkala et al., 2010). In a relational perspective, broad engagement of external stakeholders in early stages allows for the inclusion of multiple perspectives into a goal definition (Missonier & Loufrani-Fedida, 2014). This kind of boundary-less and inclusive approach to stakeholder management might be extremely resource-intensive and costly with the risk of complicated decision-making (Aaltonen et al. 2010, Lehtinen et al., 2019). In contrast, Baraldi (2008) framed the potential differences with regard to goals and resources in a relationship as a matching process. Some level of heterogeneity between member organizations' goals and knowledge bases may provide complementary factors (such as resources) to drive innovation in networks (Corsaro, Cantù, & Tunisini, 2012). The network structure supports the diffusion of environmental business practices (Tate et al., 2013).

Focusing on sustainable goals, Harrison and Easton (2005) adopted the IMP perspective in the analysis of patterns of network actor responses to an environmental change. Eco-sustainability is a value that is created when specific products and facilities cause as little as possible negative impact on natural resources. The ecologically sustainable solutions often require creating closer connections between previously separated networks (Baraldi, Gregori and Perna 2009). Waluszewski, Baraldi and Perna (2016: 54) emphasized how "all the mundane day-to-day interactions concerning the supply and use of products, processes and services create imprints over time on the actors involved, on the resources exchanged and on how they are activated (Håkansson et al., 2009)". According to the Industrial Network approach, firms are embedded in a complex web of interconnected ties through which actors can access the resources to develop business activities. From this perspective, firms' accessibility to new external sources of knowledge and their innovation ability depends on their embedded network (Håkansson et al., 2009). As stated by Sagen and Ingrmansson (2018) "interactive activities are key to understand the development of new relationships resulting from social and environmental concerns" (p. 149).

Concerning the actor devotion to common project goals, Anderson and Weitz (1992: 19) defined commitment as a "desire to develop a stable relationship, a willingness to make short-term sacrifices to maintain the relationship, and a confidence in the stability of the relationship." Applying this conceptualization of commitment to a business relationship leads to stability and many such connections form a network. Håkansson and Snehota (1995) characterized networks in the form of mutual commitments, where firms commit reciprocally to a business relationship. As stated by Ashnai et al. (2016) the commitment concept involves both behavioral and attitudinal aspects. In particular the emphasis on the behavioral aspect is related to the desire to develop the relationship and willingness to make sacrifices, and the underlying emphasis on intentions to maintain and continue the relationship (Anderson & Weitz, 1992; Mohr & Spekman, 1994) rather than looking to replace a relational counterpart with another partner (Anderson & Weitz, 1992; Cook & Emerson, 1978).

3. Sustainability Goals in the Construction Industry

Sustainable construction is a multidimensional concept that requires a holistic perspective taking into account the entire sector rather than considering sustainability for a single project. It can be argued that there is no such thing as a sustainable project but the entire sector must be engaged in the overall objective of developing sustainable solutions (Cruza et al., 2019). Adopting the triple bottom-line approach, the Building Research Establishment (BRE) defines sustainable construction as a compromise between (Cruza et al., 2019) economic sustainability (increasing efficiency and growth, through the more efficient use of resources), environmental sustainability (minimize the negative externalities over the environment) and social sustainability (address the needs of the population and social groups involved in the construction process and sustainable management, over the entire value chain).

The main goals of sustainability in construction can be summarized as minimizing the consumption of resources; maximizing the re-utilization of resources; using renewable and recyclable materials; decreasing the operational consumption; protecting the natural environment; creating a healthy and non-toxic environment; and, improving the quality of the built environment (Hossain, Leminen, & Westerlund, 2019). The holistic approach in sustainable construction has been pursued through interconnected relationships between diverse actors including research (university), industry and users. These practices evolved from participatory design involving research and design approaches characterized by involvement of groups of users (Spinuzzi, 2005), to foster cooperation between users and industries, through direct participation of users in project definition and design specification

(Kensing & Blomberg, 1998). Later, physical homes of the future, were created as testbeds, furnished with the new products and equipped with sensors and monitoring devices, where customers and users would spend several days or weeks (Eriksson, Niitamo, & Kulkki, 2005; Intille, 2002). This concept spread through North America and Europe during the first decade of the 21th century, however was ultimately limited to demo-homes or home labs that did not successfully create real life contexts (Hossain, Leminen, & Westerlund, 2019).

3.1 Sustainability goals in Living Laboratories

The Living Laboratory concept was defined when universities and industries started collaborating in second wave testbeds that provided data on home practices, as well as building performances, and human-products interactions. Diverse industry partners connected with universities to plan research agendas, usually aimed at creating knowledge on users' consumption, behavioral change and sustainable innovations, both in residential and commercial environments (Herrera, 2017; Scott, Bakker, & Quist, 2012). Living Labs are then defined as user-centered spaces, designed by universities and industries that foster co-creation and innovation through sensing, monitoring, validating and refining solutions in real life contexts (Rosado, Hagy, Kalmykova, Morrison, & Ostermeyer, 2015).

As such, long-term cooperation between universities, industry partners and users separates the Living Lab approach from other research methods (Eriksson et al., 2005; Veeckman, Schuurman, Leminen, & Westerlund, 2013). Apart from the three actors needed to define and develop a Living Lab (universities, industries and users), a research theme is fundamental to channel the research (Bowden, Lockton, Gheerawo, & Brass, 2017). Some of the most researched themes are sustainability, energy and building performance, and social studies (Burbridge et al., 2017; Dell'Era & Landoni, 2014; Dvarioniene et al., 2015).

4. Research Methodology

In seeking to investigate the development of a Living Lab project and the parallel management of project (macro) goals and actors' (micro) goals, this research applies a case study design focusing on participant interaction dynamics within two interrelated Living Lab projects. A case study approach is appropriate for our research question as it allows for a richness of data to be considered within complex changing contexts (Yin 2009). Through this approach, we are able to take into account multiple actor perspectives as a way to understand evolving network structures and processes using an ARA (Actors, Resources, Activities) model framework (Håkansson & Johansson, 1992). This aligns with similar research designs which examine the links between actor and network level strategy (Harrison & Prenkert, 2009).

Purposive sampling was used to identify two embedded projects with overlapping participants, so as to partly reduce contextual diversity and enhance our ability to develop a detailed understanding of processes (Harrison & Easton 2004). In addition, Leminen et al

(2016) specifically called for qualitative approaches for the exploration of innovation in Living Labs across countries and time. Data was primarily collected as part of a broader participatory research project involving the design and management of the Living Labs, through a partnership between university researchers and various external stakeholders. Two authors were intimately involved at various stages of the project, taking part in the strategic conceptualization and practical implementation of various activities within both Living Lab cases. Through this involvement, data was collected through direct observation in meetings and interviews with key stakeholders, as well as secondary data from internal documents, publications and media across the study timeframe. This perspective is balanced by two other non-participant authors that commenced involvement during the data analysis stage.

A total of six meetings and regular field work observation were undertaken to collect data on the Sustainable Home Living Lab over the course of four years (2015-2019). More than 20 meetings and weekly field work observation were undertaken to collect data on the Circular Living Lab project over two years (2017-2019), including involvement in project design and planning activities. Notes were recorded based on discussion with key referents including university professors, building managers and industry partner managers. Data was also collected from secondary sources such as internal project documents, publications and on-line material. The case study was developed based on this available data and personal experiences, arranged temporally by key stages as perceived by participant researchers. These projects were then cross-referenced to the experiences of other respondents and interrogated further by two non-participating authors.

4.1 Analysis Approach

The analysis approach involved the preparation of a case description, utilizing the ARA model as a framework for presenting the case (Håkansson & Johansson, 1992) together with the roles of organizations in Living Labs, as identified by Nystrom et al. (2014). Nystrom et al. (2014) identifies 17 key roles in Living Labs: Webber (similar to relationship promoter that acts as the initiator), Instigator (influences actors' decision making processes), gatekeeper (similar to power promoter), advocate (distributes information externally), producer (contributes to the development process), planner (participates in the development process), accessory provider (self-motivated to promote its products), coordinator (coordinates participants), builder (promotes close relationships), messenger (disseminates information), facilitator (offers resources for the use of the net), orchestrator (guides and supports the network's activities and continuation), integrator (integrates heterogeneous knowledge), informant (brings users' knowledge to the Living Lab), tester (tests innovation in real life environments), contributor (collaborates intensively with the other actors to develop new product), co-creator (the user co-design - a service).

This supported the emergence of initial research insights through interpretation of the processes outlined and further comparison with the data collected (Stake 1995). From this point, abductive logic was applied, using a process of systematically combining in order to move between theory and the case data and thereby supporting theory development (Dubois & Gadde 2002). Concepts were drawn from both the business network and Living Lab literature in order to inform the analysis. As stated by Johnsen et al. (2017), IMP also has a distinct focus on understanding the interconnectedness and interdependency of relationships, as companies strive to diffuse sustainability into their wider supply networks the IMP perspective could clearly be used to good effect. As depicted by Von Raesfeld et al. (2012), IMP considers three structural or space mechanisms (resource heterogeneity, actor jointness and activity interdependency) and three processes or time related mechanisms (paths of resources, co-evolution of actors and specialization of activities) that influence the outcomes of interaction between organizations (Hakansson et al., 2009).

The development processes of the Living Labs were organized in accordance with the main stages of their evolution, as they were identified during the analysis, also considering the stages of Innovation Project (Steen and van Bueren, 2017).
The following stages are related to the Sustainable Home Living Lab: Project Conceptualization, Project Design, Project development, the launch of platform and the platform evolution. The last stage relates also to a new project: the Circular Living Lab. In each stage we investigated the actors involved, the resources shared and combined, the activity developed. Furthermore we considered the goals of the project and the goal of the actors.

5. Case background

5.1 Sustainable Home Living Lab. The first project

The Sustainable Home Living Lab is a multi-story, modular building composed of 44 steel frame modules, hosting 29 student apartments based in Sweden. The facility opened in 2015 as a collaborative project between a Swedish university and a National Housing Cooperative, which sought to create a space that would help researchers to explore the home-human relationship: how people use their dwellings, and how the dwellings can improve people's life. It is equipped with more than 2000 sensors that test thermal performance (internal temperature changes relative to external climate), energy and water consumption, and air quality. It features interchangeable façade panels that allow industry and researchers to test new building products and materials in a real-life facility, thereby creating multiple potential formats for future usage of the space.

5.2 The Circular Living Lab. The new project

The Circular Living Lab is a new research facility developed with the intention of fostering the circular economy of building construction both for the building and operational phases. The Living Lab project is situated in a new Australian housing development and fully owned by a local University. Project leaders include academics active in the Swedish Living Lab case seeking to further develop the Living Lab methodology based on their prior experiences. The Living Lab is an example of a reusable, movable and adaptable construction, designed with the application of circular economy principles (reduce, reuse and recycle – the 3R's concept) to diminish the waste created during the construction, utilization and demolition phase of buildings. It is composed of eight steel modules, salvaged from a previous project, and it is entirely disassembled and planned for relocation in 3 years. It is equipped with sensors to test the thermal performance, electricity, water consumption and air quality. The Living Lab is intended to foster innovation networks by hosting start-ups, industry partners and researchers working in the field of the sustainability of buildings, and the new startup designed products can be tested in the Living Lab itself.

5.3 Project Stages

Project Conceptualization: the platform idea

The original idea for the Sustainable Home Living Lab was born from a fortuitous post-conference meeting in 2011 between a University Academic and a manager from an adjacent Science Park, in which they shared their mutual interest in the concept and experiences from other Living Labs around Europe. Following this encounter, the Science Park manager engaged one of their major partners, a national Housing Cooperative (HC) organization, which had expressed interest in developing a modular student housing design. Over the course of several interactions the HC and University began to recognize areas of mutual interest and compatibility between their available expertise and resources that could be put towards a new Living Lab to be located at the Science Park. The general direction of the Living Lab was initially envisioned as homes for tomorrow, which would enhance the sustainability of residential buildings, providing facilities and programs to foster technical and architectural innovation, all supported by research and experimentation.

Given their cooperative organizational model, HC is well poised to create value for members and reinvest revenue back into their business. In line with these objectives, sustainability is listed as a core organizational value and HC endeavored to be at the forefront of developments within the sustainable housing sector. Beyond tangible innovation outcomes, HC was also interested in showcasing their innovation capabilities and it was anticipated that the Living Lab could also support their branding efforts. Central to this aim, was establishing a physical space to interact with other business partners through new approaches such as workshops and demonstrations. It was anticipated the Living Lab could establish a corporate engagement model that could be replicated across the country.

From the University's perspective, the Living Lab aligned with their new industry engagement approach, which was to focus on an increasing degree of applied innovation and bringing companies on to campus to work directly with researchers. For the university's researchers, the Living Lab could be a new flexible format for a research lab, which facilitated direct involvement from users and companies and provided a real world setting to work on various projects. The dynamism of the space could provide for a high level of research activity, which would continuously evolve, with new projects added from incoming grants and new collaborations.

Project Design: the basic platform

Following the preliminary agreement between the University, HC and the Science Park, the main partners began the process of developing the Living Lab project over the next few years. An initial scope was formed for the Living Lab to provide student accommodation, as a basic platform, and monitor building performance and consumption, however the specifics were refined through engagement with other necessary stakeholders. As a starting point, the University provided the expertise on the Living Lab methodology and how to drive research activity within the space, as well as offer access to Swedish and EU research funding. HC provided access to the rest of the value chain needed for developing the project from their existing business relationships, as well as the expertise to manage the facility. The third crucial aspect of the Living Lab methodology – users, were planned be drawn from University students and visitors who could live in the space and participate in research and product testing activities.

Project development: the new idea of platform

Over the next two years, a new HC manager and the University Academic involved in the initial conceptualization, formed a partnership to present the Living Lab proposal to various stakeholders. The platform improved the value provided to stakeholders. This process involved delivering Living Lab workshops to different companies as a way of highlighting the project's value and attracting their involvement. Political interest was also attracted through promotion at national meetings, using existing HC connections. The stakeholder engagement process was used to collect industry contributions in the form of funding, in-kind resources and knowledge to inform Living Lab design and activities. A consortium model was established whereby companies paid an annual fee of approximately €4,000 to become official Living Lab members, which included invitation to partner meetings and promotions, as well as the possibility to initiative applied innovation projects. In total, only one consortium member had an existing relationship with the University, highlighting the project's success in attracting new industry interest.

The intended Living Lab business model was based on providing value to firms/industries interested in the knowledge generated through research and development activities in the building. It was anticipated that companies would utilize the Living Lab as a research asset and initiate and fund research, taking place within the facility. Research income *via* government grants and industry partner investments were critical as the building's advanced features (such as the disassemblable façade and sensors), were more expensive than comparable modular buildings. HC also offset some costs through rental income generated from accommodation provided to users living in the facility, however financial sustainability required a steady stream of competitive research grants and industry funding for product prototyping and testing.

The launch of the platform and the platform evolution

The Living Lab project was successfully launched and has now been in operation for four out of its planned ten year lifespan. From a user perspective, the building has maintained full occupancy and has a waiting list of prospective tenants, suggesting that the Living Lab is recognised as a desirable place to live. Some researchers have noted shifts in the user cohort characteristics over time, with initial students being more interested in sustainability and research than more recent students who place higher value on location and amenities.

Major changes have occurred in relation to Living Lab management with key personnel from both partner organizations leaving for various reasons, to the current point whereby none of the original managers are involved. The partnership between the University and HC has also shifted over time, with the HC now assuming all management responsibilities, at both strategic and daily operational levels. With this shifting dynamic, the Living Lab now operates as a space rental model, gaining revenue in return for providing access to users, researchers and companies. Different projects or events therefore run relatively independently without overarching coordination.

In terms of research activity taking place in the Living Lab, we identified important differences between two phases of the Living Lab. The first phase commenced once the Living Lab was built. During this phase the building was fully rented to students, and this result is partially due to the Living Lab's convenient location and shortage of student rental property in Sweden. Despite this success as a student accommodation, however, the number of research projects taking place in the Living Lab was limited, and this downside lasted for a considerable time, suggesting that the Living Lab was having difficulties in taking off as a university asset. In total, the number of active projects has declined since the Living Lab opened, indicating diminishing University engagement with the Living Lab, as few new projects replaced those that ended. For this reason, the facility is perceived by some as being underutilized for research purposes. One example of this stagnation was the installation and testing of vertical solar panels on disassemblable façade modules, which were never changed or added to different locations around the building despite being designed with that functionality. After this stagnation phase, however, the second phase of the Living Lab registered a large increase in the number of projects carried out in the facility, to the extent that no further projects could start before others were concluded.

This example seems to suggest that, during the first phase, conflicts between HC building managers and University researchers were holding back the potential of the Living Lab in terms of being a research facility. One these conflicts was solved, and the Living Lab moved into its second phase, the number of research projects started to increase. The timespan between first and second phases was between three and four years, and it could have been avoided with a project objective defined from the beginning, partners' goals aligned with the project objective, and by maintaining the management within the University.

At the Living Lab, students and researchers now live and work in order to test innovations and technical solutions for the next generation of housing. The 29 apartments of the living lab, are equipped with monitoring stations and sensors. 33 people live in a changing building where the walls, facades and interiors develop as the research progresses. The involved partners, the sensor systems, and the established processes aim to facilitate and develop sustainable solutions for the future of living. More than 2000 sensors measure energy and material flows and monitor human/technology-interaction and behavior impacts.

The project had a structure where all partners make an annual payment into a joint research fund. The fund will be used for joint research projects agreed between the partners. The Living Lab is now active and its evolution inspired the project of another Living Lab project: the Circular Living Lab.

The project evolution to a more contemporary facility

The idea for the Circular Living Lab stemmed from a team of three University researchers working in the area of circular economy. One academic had originally been involved in conceptualizing and developing the Sustainable Home Living Lab, while another had participated in research projects at that Living Lab.

The orientation to circular economy determined the strategic choices of the founders. The foundation steel frames were rescued from recycling, the ceiling panels are made from recycled plastic bottles, which are also sound absorbent. The carpets were donated from a refurbished building that was newly leased and consequently redecorated. The stairs that connect its two storeys are reclaimed steel from a failed building project, and the stair treads are 100-year-old Jarrah (an Australian native tree) sourced from a disused factory.

Based on their previous experience, the leadership team decided on several new approaches to achieve sustainability innovation outcomes in this new facility. To avoid the initial unsuccessful period of the Sustainable Home Living Lab, a guiding principle of the new Circular Living Lab project is that it would have full University ownership and control, so that the space could maintain a research focus that achieved academic, commercial and social outcomes. In addition, in 2018 the team established a clear Living Lab theme, known as the heart and soul of the facility: the circular economy. This guiding principle was implemented to ensure that the Living Lab becomes a collaborative space to work on practical circular economy projects, and limiting the partners from diverging from the common goals. This reflected collective research interest in the circular economy and the desire to prototype a Living Lab as an outcome of their research.

A first step in getting the project off the ground was for the Living Lab team to articulate the project's value to other stakeholders within the University and gain their approval. The desire to maintain full ownership yet open access required the resolution of internal University tensions, as property managers outside of the project did not initially recognise the research value of the project and were cautious of the potential liabilities it would create. In particular, the intended location outside of the University and the building's transportability was not normal practice for investing in university assets, but were nevertheless considered critical to the circular economy objective of the Living Lab. Support was eventually received along with funding after a series of meetings.

A formal partnership was formed with a State Government organisation that agreed to provide a block of land in a new housing development for a minimum period of two years, as well as AUD $100 000 (about €61 000) funding towards construction (the estimated total value of the building is close to AUD $ 1 million, or € 0,61 million). The Living Lab is intended to be relocated after three years, consistent with the circular economy theme of the facility. Several private companies were also approached to become involved in the project based on their perceived interest in circular construction practices or potential relevance to the project. In some cases, companies were accessed from existing relationships with the University and in other cases they were contacted for the first time. This process led to the formation of multiple sponsorship agreements in which companies contributed either materials, technology or funding in return for later access to the Living Lab and involvement in its activities. Industry motivations for contributing ranged from marketing exposure to interest in the sustainable innovation outcomes stemming from the Living Lab. The novel building practices being applied in the Living Lab construction required substantial time and effort from the design team, which took away from other more commercially valuable projects.

6. Discussion

The analysis of the case outlines how the involvement of multiple actors supports the development of Living Lab projects oriented towards sustainability. As depicted in Table 2, heterogeneous organizations provided resources which facilitated crucial activities for the development of the project. In particular, each actor assumed a specific role (Nystrom et al., 2014) in the different stages of development: project conceptualization, project design, project development, the launch of platform and its evolution, and a more contemporary facility.

Insert Table 1 Here

Focusing on Sustainable Home Living Lab*, the first stage (project conceptualization)* involved the university as focal firm, the Science Park, the HC. Each actor provided resources to ideate the project. For example the University provided technical knowledge and defined the Living Lab approach, while the HC provided its network of business partners. The Science Park provided its technology transfer expertise and facilitated the activation of relationship between the University and the HC. On the basis of the resources provided and the activities developed we can recognize the Webber role to University and HC, and the advocate role to Science Park. In particular the Webber is similar to relationship promoter, while the advocate has a background role and it distributes innovation externally.

In the *project design (second stage)* the main actors involved were the University (Planner and informant), that provided the experience in the Living Lab approach and the HC (gatekeeper and producer) that provided financial resources and its network of business partners. The planner and informant participates in development processes, while the gatekeeper and producer is similar to power promoter as it possesses resources.

In the *third stage (project development)* the main actors involved were the University (knowledge on Living Lab planning, coordinator), the HC (financial resources and project management, facilitator) and industry partner (such as architects, white goods, construction, technical expertise, energy, interior decorating) that provided financial and technical resources (accessory provider). The accessory provider is self-motivated to promote its products, services, and expertise.

In the *fourth stage (the launch of the platform and platform evolution)* the main actors were: University (research capacity, informant and tester), HC (management capability, orchestrator), industry partners (product, technology and financial support - contributors) and users (e.g. students providing personal experience – co-creator). The informant and tester brings users' knowledge, understanding, and opinions to the living lab, while the co-creator concerns the user co-designs a service, product, or process together with the company's R&D team and the other living lab actors.

Considering the *project evolution* to a more *contemporary facility,* we can identify the project conceptualization and design and the future stage (the platform launch and use). In the first stage (project conceptualization and design) the actors involved are University that provided technical knowledge and the first concept (Webber, investigator and planner), state government organization (financial support and other in kind – accessory provider) and Industry partners (who provided many of the circular economy products as knowledge contributors). In the last stage the main actors are: university (management capability, research capacity – integrator, coordinator, informant and tester), state government organization (established network - contributor), industry partners (products – contributors and testers), users (financial support, knowledge and network – co-creation informants). The tester tests innovation in (customers') real-life environments. At present, the Sustainable Home is developing several innovative projects while the Circular Home it's starting its activity.

It follows, as propositions (P), that:
P1 The Living Lab project is not generated in a vacuum but it depends on a network of projects. The development of a complex project depends on the interconnected relationships between the actors belonging to different projects and their experience.

P1.1 The Living Lab can be considered as a particular complex project as the last stage (evolution) should be always active. The realization of the laboratory is not the end of the project as the exploitation of the laboratory platform requires to continuously activate and develop new projects for the involved stakeholders.

The analysis depicted the continuous transformation of the Living Lab project on the basis of the main actors involved in each stage. The interconnected relationships of project development generated the Living Lab as a platform made up by a core solution and additional value solutions to different actors. According to platform thinking (Sawhney, 1998), the objective of platforms is to increase the variety of offerings – products, services or solutions - without increasing the complexity of internal structures

Insert Table 2 Here

Taking into consideration the Sustainable Home Living Lab, the core solutions of the platform provided a facility to conduct research on sustainable living (for the university) while the additional value solution involved a network with industry partners. The Living Lab enhanced the relationships with other universities, and increased the university's prestige.

The core solutions of the platform provided marketing exposure and product testing (to firms such as HC), and additional value solutions (environment to test their business models, network with other firms and universities).

The solution provided to users has been an accommodation to rent. The additional value solution was made up by the contribution to sustainable living, the involvement in research, and the opportunity for students to live and co-create in a high tech facility. Different *functions* have been recognized for the Living Lab platform: research and development projects for the university, the innovation project (launch of a new product) for firms. The users (students) considered the project at the beginning to improve sustainability activity, while then to improve comfort in living home.

The *Circular Living Lab* platform provided as a core solution a facility to conduct research on Circular Economy (to university) as well as the network with industry partners. The Living Lab enhanced the relationships with other universities; increased the university's prestige and the visualization of space to connect across Australia. The solution provided for firms involved marketing exposure and product testing. The network made up the additional value solution for the platform with other firms and the network with the university, meeting and visualization space. The solution provided to users including office space and test ground. The additional value services identified contribution to research and enhancement of the circular economy concept, the involvement in research, the work and use of high tech facility and the involvement in media promotion.

Considering the *functions* recognized for the Circular Living Lab platform, the university developed a series of research projects and strong vision oriented to sustainability (research and development projects), the firms launched a new product (commercial and innovation projects) while the users accessed business services (innovation projects). More and more, as depicted in the case, the core value provided by the platform has been generated by its ability to facilitate networking among the university, the firms and the users. As described in the case study, the Circular Living Lab platform generates value for different organizations but some potentialities could be exploited in a better way through the management of the complexity generated by the different functions recognized to the project that are influenced by the specific actors' goal.

It follows that:

P2 The Living Lab is a multilevel project as each actor involved recognized a different function to the same project: research and development projects, commercial projects, innovation projects. The different functions recognized in the Living Lab project are influenced by the goal of the actor.

The complexity of the interrelated projects has been generated by the difficult alignment between the macro goal of a Living Lab and the specific goal of actors. In the Sustainable Home Living Lab the macro goal of the project was the construction of a living home oriented to sustainability. In each stage the actors were characterized by specific goals (micro goals).

In the first stage (project conceptualization) the University aimed at creating knowledge on sustainability aspects (applied architectural innovation, research lab, grants and new collaboration). The goal of the Science Park was related to technical innovation and to a bond with the university. The HC aimed at promoting the firm image as an innovator. *In the second stage (Project design),* the university aimed at driving research within the space, and at looking for Swedish and European Research Funding. The goal of HC was to create and consolidate network with industries and establish an industry research fund. *In the third stage (project development),* the University aimed at developing the Living Lab around the idea of sustainable living. The aim of HC was to supervise the project. The industry partners aimed at establishing a leader in the housing markets in terms of innovation. *In the fourth stage (launch of the platform and platform evolution)* the goal of the University was to develop a portfolio of research projects. The HC aimed at the continuing development of innovation. Industry partners aimed at testing new products in real-life settings to launch into the market. They desired to develop cooperation platform with the Housing Cooperative. The users wanted live in a sustainable fashion, contribute to knowledge creation on sustainable living.

Considering *the project evolution* to a more contemporary facility (a Circular Living Lab), in project conceptualization and design, the goal of university was to develop a research facility based on the committed goal (heart and soul). The stage government aimed at participating in the creation of the facility to benefit its use, and marketing. The industry partners were interesting in the launch of a new product. In the subsequent stage, the goal of the University is to lead the partners towards the committed goal and research projects. The main aim of the state government organization is to use the facility as an office and showcase. The industry partners aimed at advertising and exposure. The users (the firms) are interesting in the network, and in the use of the platform both as an office and for testing new products. The heterogeneous goals create benefit but also complexity and critical dimensions.

Designs for the Sustainable Home Living Lab were established through extensive cooperation between the University, HC and relevant industry partners. This collaborative process revealed emerging tensions relating to the intended purpose of the Living Lab and the objectives of participating partners. An example of this was one contributing architectural firm that found it difficult to design the building without a clear budget or usage specifications. Eventually further conceptualization of the Living Lab objectives took place in order to align the interests of the two main partners, targeting design outcomes of increasing accommodation capacity within a small building space. The Living Lab design was established to fit the refined Living Lab goals of sustainable high-density housing and combatting student loneliness. Research projects were envisioned to explore sustainable behavior change through building design and use.

As research capacity has been below original expectations, research grant funding has also not been accrued at financially sustainable levels for the Living Lab. Attention has now turned to more applied industry research and development or commercial activities over the pursuit of more innovative sustainability projects. An example of this is company's hiring the space for product demonstrations rather than testing and prototyping. Some researchers have found that industry partnerships have been limited to mostly in-kind contributions of material or products, with limited corporate appetite for riskier radical projects. Industry interest remains high and consortium members are still active, however many use the Living Lab as part of their branding activities or to maintain a strategic relationship with HC.

The gap between the specific goals of actors and the macro goal of the project created conflict between organizations and limitations to the development of the platform. The goals of the actors were strictly related to the function recognized by the actors to the Living Lab. The applied research goal of the university was overcome by the commercial goal of HC and business partners involved. In particular it emerges the attempt of the lead firm to push in a top down perspective the macro function of the Living Lab. At the beginning the university pushed the research orientation, then the HC enforced the commercial orientation of the Living Lab. This top down perspective didn't generate the expected results as organizations that didn't agree with this approach decided to exit the project and this reduced opportunity exploration in the Living Lab.

On the basis of these conflicts the founders of Circular Living Lab decided to enhance business relationships with their business partners from the outset. Given the novel nature of this project, a number of implementation issues arose in the building construction process, leading to new relational tensions that had to be resolved. The building was to be produced by re-engineering salvaged frames to fit with the circular economy theme, a challenging process that had not previously been attempted by the firm. For example, a construction company partner insisted on assembling and testing the structure on site rather than within their factory, in conflict with University researchers who needed to test the structural integrity. This was eventually resolved to allow for such testing to occur. Similarly, other issues arose due to inattention in design execution which required structural adjustments after construction to ensure safety. Common in many of these issues were misalignments between enthusiastic upper management that had agreed to contribute to the Living Lab and designers and architects that were not incentivized to diverge from standard practices.

During operation the model of the Living Lab was designed to maintain balance between industry and societal involvement and research outcomes. A decision was made to run the Living Lab primarily as a research asset, with its main source of income is research funds from government or industry project grants rather than rental income. The Living Lab could also rent out the space to companies for different activities, however motivated by previous experiences, the leadership team did not want this to be relied upon in the financial model. As such, more strategic uses can be pursued, such as providing free space to start-ups which would better align with the innovation aims of the Living Lab. In addition, following the Living Lab's theme, the facility is designed to host regular meetings and events with companies, to encourage the Living Lab to be an active and vibrant space for collaboration.

In particular the founders of the Circular Living Lab supported the combining of the macro goal of the project with the micro goal of the actor, generating the hybrid committed goal (meso goal). This latter is the goal really pursued by the actor that allows reaching the macro goal and the micro goal together. The committed goal is generated in a relational space.

Figure 1 illustrates the Living Lab goal orientation as sitting within the nexus between industry, research and user value perceptions. The committed goal (blue dot) is determined through the interaction processes of the three main stakeholder groups and represents the alignment between individual and common goals. While the goal orientation is first established during Living Lab conceptualization, it changes through Living Lab development and continues to change throughout the life of the project in line with individual stakeholder goals and contributions (resources). The inner triangle (blue dashes) indicates the acceptable range (relational space) within which the goal orientation can move while still delivering value to all stakeholders and maintaining their contributions and commitment.

Insert Figure 1. Here

The second panel (b) in Figure 1 explains how actors can misalign the Living Lab goals by using their influence in the management for their own interests. Specifically, during project development stage of the Sustainable Home Living Lab, there was a shift in the lead firm role. At the beginning the university was considered lead firm but then this role was undertaken by HC. The new lead firm decided to change, through a top down approach, the orientation (function) of the project, considering the own goals and outlining new goals that should be pursue by the organizations involved into the project (meso goals). The goal had been shifted over time towards the interests of industry due to turnover in personnel and changes in the lead actor's value perceptions of the Living Lab.

The top down approach of HC generated critical results. With the altered orientation, researcher and user value was reduced which led to them decreasing their resource contributions and activities within the Living Lab project. Within this new orientation, the innovation outcomes of the Living Lab focused primarily on industry benefit in the form of more routine research and development activities or technology demonstrations for commercial purposes. This is represented by the new (orange) goal orientation being situated on the edge of the inner triangle and partly out of the acceptable range. Research studies and user participation still continued but on a smaller scale, thereby limiting the sustainable innovation outcomes that the Living Lab was initially established to create. If the goal orientation was to move further towards industry, it can be expected that other stakeholders may re-evaluate their involvement in the Living Lab and perhaps withdraw completely. Other phases of the Living Labs can be represented in the same diagram, by studying the position of the goal (the orange dot) in relation to the initial central goal (the blue dot). For instance, in the last stage of the Sustainable Home Living Lab, the increased number of research projects realigned the actual goal with the initial goal of the Living Lab (the meso goal move into the inner triangle).

The interaction processes must continue in order to maintain alignment within mutually acceptable boundaries (Hughes 2014). Collective goals are effective if individual actor goals are nested within them and diverse actor goals requiring common resources do not conflict (Lind 2015).

It follows that

P3 The development of different project stages are founded on the alignment and re-alignment between the specific goals of actors (micro goal), the goal of the project (macro goal) and the committed goal (meso goal pursued by actor).
P3.1 The committed goal should remain within an acceptable nexus (relational space) between researcher, industry and user stakeholder in order to meet the interest of the actors (micro goal) and the evolution of the project (macro goal).

Focusing on coordination, a further insight from the case findings relates to the role of lead actors within Living Lab projects. Prior research has presented typologies of Living Labs based on the characteristics of actors which drive activities in the living lab network (Leminen et al 2012). Lead firms (platform leaders) shape their environments and orchestrate the network to further develop the value platform (Gawer & Cusumano, 2014). In a traditional perspective the lead firm manages in a top down perspective the criticisms and can improve the alignment of goals. In the Sustainable Home Living Lab the lead firm defined the main vocation of the Living Lab, in a top down perspective, but this approach did not allow the exploitation of the innovation potential of the platform.

The Sustainable Home Living Lab case demonstrated the implications of shifting lead actor: at the beginning the lead actor was the University and the orientation was to experiment new technology in building construction oriented to sustainability. Then the lead firm became the HC that began utilizing the space for more commercial operations with reduced support for innovative cross-stakeholder research. The lead actor extensive experience of value creating activities impacted on the overall dynamic within the Living Lab, with reduced interactions between the three stakeholder groups (Kviselius et al., 2009). While the Living Lab remained active, the activities became less aligned with user and researcher values, suggesting insufficient consideration of other perspectives and tensions between participants over time (Leminen et al 2016).

In contrast, the Circular Economy Living Lab highlights how a new actor can seek to align the diverse goals of all stakeholder groups (micro goals) from the preliminary stages of the project. The University acknowledges the need to develop a stable Living Lab theme under which more dynamic goals can continue to evolve between participating actors. Strategic objectives have a direct influence on innovation outcomes and therefore changes in the goals pursued by the actors must be reconciled with the broader goal orientation of the Living Lab.

Adopting the relational perspective, interaction enables adaptation and collective learning among the involved actors because of both confrontational and compromising processes (Håkansson and Waluszewski, 2002; Vildåsen and Ingemansson Havenvid, 2018). In a more specific perspective, our analysis considered the complexity of network development which companies have to try to live with, while influencing others in an incremental manner (Håkansson et al., 2009).

It follows that:

P4 The goals can be re-aligned in a peer-to-peer (P2P) relationship that differs from a top down and bottom up approach, depicting committed meso goals that are generated by the combining of micro and macro goals.

In the top down perspective the lead firm can decide the orientation of the project. In a bottom up perspective the users depict the goal. In P2P relationships actors belonging to the same network are characterized by similarity even if there are different aims and goals.
From a traditional point of view peer relations research is focused on the quality of each individual's peer interactions within a given social unit. In our case the P2P business relationships overcome the top down and bottom up coordination considering the interaction within peer business actors.

On the basis of this coordination, in the Circular Living Lab the university supports the relationships between different organizations and allowed them to depict a committed goal in the inner triangle. In the Circular Living Lab the actors are characterized by different goals but all of them are related to exploitation of circular innovation. This latter goal allows each actor to pursue the specific goal and to pursue the collective goal together. This condition is generated by a strong commitment.

It follows that

P4.1 The coach actor can listen to the requirements of all actors and depict them in the committed goal combining the micro goal of the actors and the macro goal of the project.

The coach is a network facilitator that supports the commitment and the engagement of different actors involved into the project and into the platform activities. The coach serves as a values ambassador promoting circular economy values within the innovation network, and as an intermediary facilitating the relationships between the business partners. The relational power recognized in the coach is generated by the ability to introduce business relationships into the innovative project and by the resources provided into the project.

We therefore propose:

P4.2 The coach sustains P2P relationships, supports the diffusion of a strong vision of sustainability and, improves the commitment and the engagement of the actors involved in the project

In the context of the Sustainable Home Living Lab, it has been recognized that there has been some slow but steady movement and progress in this area with one of the main partners, but for the ecosystem to function properly all involved partners must incorporate these leadership ideas and models into their organizational structures. This is reflected in tenant selection criteria, which was initially based on sustainability values and acceptance of being monitored, but was later relaxed. At present the rental income represents the main revenue stream of the Living Lab and the University also pays to access the space for their activities.

In a different way in the Circular Living Lab, in order to sustain the commitment of business partners and several stakeholders, the University decided to foresee some workshops to present the main potential of a circular economy approach. As stated by one of the entrepreneurs "A lot of people don't actually know that there are others ways to build, as it's never been presented as an option". The project will enable local firms to inexpensively test and de-risk tomorrow's innovations today using the campus facilities. As stated by one of the entrepreneurs "a crucial aspect is that the Circular Living Lab will be open to the public during its testing phase, ensuring people can learn about circular economy and experience first-hand the future possibilities of modular living".

6. Conclusions and Implications

6.1 Theoretical implications

Living labs have been increasingly considered as a practical example of Open Innovation, supporting firms in investigating knowledge beyond their own boundaries (Nieto & Santamaría, 2007). Similar to other forms of open innovation, Living Labs are dynamic, but they are more formally characterized by complexity. As depicted by the case the complexity is generated by the multiple functions recognized in the same Living Lab project by different actors, and by the difficult alignment between the goal of the project and the goal of the actors. Our findings demonstrate that the complex Living Lab project is not generated in a vacuum but it belongs to a network of projects and a network of actors that operate in different projects.

Focusing on a traditional top down perspective, Living Labs are generally viewed as platforms for innovation (Almirall & Wareham, 2008; Anttiroiko, 2016; Dell´Era & Landoni, 2014) where a relevant role is recognized for the lead firm. But as depicted by the case, the outcomes produced with the top down perspective and the key role of the lead firm underutilize the available open innovation opportunities. Some authors have stated that each actor has the potential to dominate operations, and therefore keeping a good balance is paramount to maintaining the Living Lab's innovation agenda (Leminen, Westerlund, & Nyström, 2012).

In the Circular Living Lab the innovation exploitation is founded on a new managerial approach that overcomes the top down and the bottom up perspective. In a traditional perspective the lead firm orchestrates the network in a top down perspective while considering their own power. But in line with the IMP perspective power is dependent on the relationships of a firm. As stated in previous research through a relational process actors strategically align individual and common goals (Corsaro et al 2012). In addition to this, the alignment is not related to a top down approach (lead firm) or a bottom up perspective. The committed goals are generated in peer to peer relationships. The case depicts how project progress depends on the resources provided by business partners and the alignment/re-alignment between the macro goals of the project and the heterogeneous micro goals of the actors that result in the living lab's committed meso goals. The committed goals overcome the orientation depicted by the lead firm, as generated in a win-win relationship. The committed goal should remain within an acceptable nexus (relational space) between researcher, industry and user stakeholder in order to meet the interest of the actors (micro goal) and the evolution of the project (macro goal). This nexus is depicted by the inner triangle.

Moreover, a coach actor that allows actors to be aware of the potential of the macro goal and their micro goal supports achieving the committed goal. This actor, on the basis of its position in the network, can support the sharing of a common vision and the commitment of the involved actors that belong to the project. The coach actor sustains actors in combining the micro goal of the actor and the macro goal of the project in the inner triangle. Mutual commitment is an important element for stabilizing a network and thereby creating and realizing value, and also a necessary means to factor in resource access (Lenney and Easton 2009). In our case the sustainable goal of the Living Lab can be reached through the alignment of the committed goal in the inner triangle. The collective commitment is thus generated by the commitment of each actor in a long term perspective.

6.2 Managerial implications

The development of sustainable construction requires a new strategic approach oriented towards complex projects to realize an innovative Living Lab platform. The complex projects and solutions oriented to sustainability require a relevant attention to the process of management. Actors participating in Living Labs face internal pressures influencing their involvement, which contribute to collective tensions that must be managed through interactions that allow the balance of heterogeneous goals. In particular this complexity can be managed by adopting a project network perspective and identifying the main actors' goals. The development of the project stages is founded on the alignment between the goal of the project and the goals of each actor involved. The alignment, in the relational space (triangle), should be facilitated by a coach. This organization supports the sharing of the vision and the commitment of the actors.

In comparison with other innovation settings, sustainability-focused Living Labs face added pressure in maintaining partner goal alignment over time. Industry stakeholders for instance, will often face internal pressures in contributing to Living Lab activities with no immediately clear commercial benefit while simultaneously pursuing regular profit-orientated business functions. Similarly, researchers are subject to pressures to apply their time, resources and expertise to academically valuable research activities, which must also be of value to the Living Lab user and industry stakeholders. Research without academic value may still be performed, however for different motivations. Lastly, users must be meaningfully engaged in Living Lab research and design, rather than only using the space and facilities for their own benefit. The sustainability approach provided the evolution between the two projects. In the Sustainable Home Living Lab the focus was on sustainable living alone, with less concern for the impact of the building structure/shell. In the Circular Living Lab the team realized the increasing importance of building materials and decided to tackle this impact by adopting the circular economy framework (in addition to sustainable operations).

6.3 **Limitations and future research**

This paper has investigated two interrelated projects. Future research has the potential to go into greater depth in other cases, and investigate the distance between the macro goal of the project, the specific goals of each actor and the committed goal. In particular, the development of these individual goals over time and their interaction with macro project goals is worthy of further investigation, especially considering the influence of individual managers who may not continue through the entire length of the project. Moreover, while the Living Lab model is based on university, industry and users, the cases also note varying levels of involvement from government actors, which may require the incorporation of a quadruple helix perspective to develop a more comprehensive understanding. Future research could also investigate the attitude of the actor to reach a specific goal.

References

Aaltonen K, Kujala J., Lehtonen P. and Ruuska I. (2010). "A stakeholder network perspective on unexpected events and their management in international projects". *International Journal of Managing Projects in Business,* 3 (4), 564-588

Aarikka-Stenroos L., Jaakkola E., Harrison D., Mäkitalo-Keinonen T (2017), "How to manage innovation processes in extensive networks: A longitudinal study", *Industrial Marketing Management*, pp. 67 88–105

Ahola T., Kujala J., Laaksonen T., Aaltonen K. (2013). "Constructing the market position of a project-based firm". *International Journal of Project Management*,

Almirall E., Lee M. and Wareham J. (2012) "Mapping Living Labs in the Landscape of Innovation Methodologies". *Technology Innovation Management Review*

Anderson, E. and Weitz, B. (1992), "The use of pledges to build and sustain commitment in distribution channels", *Journal of Marketing Research*, 29 (1), pp. 18-34.

Anttiroiko, A.–V. 2016. "City-as-a-Platform: The Rise of Participatory Innovation Platforms in Finnish Cities". *Sustainability*, 8(9): 2–31.

Ashnai, B., Henneberg, S.C., Naudé, P. & Francescucci, A., 2016, 'Inter-personal and inter-organizational trust in business relationships: An attitude–behavior–outcome model', Industrial Marketing Management 52, 128–139

Baraldi, E., & Strömsten, T. (2009). "Controlling and combining resources in networks -from Uppsala to Stanford, and back again: The case of a biotech innovation". *Industrial Marketing Management*, 38, 541–552.

Baraldi E. (2008) "Strategy in Industrial Network. Experiences from IKEA". *California Review Management,* 50 (4)

Baraldi, E., Gregori, G.L. and Perna, A. (2011), "Network evolution and the embedding of complex technical solutions: the case of the Leaf House network", *Industrial Marketing Management,* 40 (6), pp. 838-852

Birkinshaw, J., Brannen, M.Y., Tung, R.L. (2011). "From a distance and generalizable to up close and grounded: reclaiming a place for qualitative methods in international business research". J. *Int. Bus. Stud*. 42, 573–581.

Bowden, F., Lockton, D., Gheerawo, R., & Brass, C. (2017). "Participatory Drawing in Ethnographic Research". In *Living Labs* (pp. 179-190): Springer.

Burbridge, M., Morrison, G. M., van Rijn, M., Silvester, S., Keyson, D. V., Virdee, L., Liedtke, C. (2017). "Business models for sustainability in living labs". In Living labs (pp. 391-403): Springer.

Cook, K. S., & Emerson, R. M. (1978). "Power, equity and commitment in exchange networks". *American Sociological Review*, 721–739.

Corsaro, D., Cantù, C., & Tunisini, A. (2012). "Actors' heterogeneity in innovation networks". *Industrial Marketing Management*, 41(5), 780–789.

Cova, B., Mazet, F., & Salle, R. (1994). "From competitive tendering to strategic marketing: An inductive approach for theory-building". *Journal of Strategic Marketing*, 2(1), 29–47.

Crespin-Mazet F., Ingemansson Havenvid M., Linné Å (2016). "Antecedents of project partnering in the construction industry — The impact of relationship history". *Industrial marketing management.*

Cruza C., Gaspar P., De Britoa J. (2019). "On the concept of sustainable sustainability: An application to the Portuguese construction sector" *Journal of Building Engineering* 25

Dell'Era, C., & Landoni, P. (2014). "Living Lab: A methodology between user - centred design and participatory design". *Creativity and Innovation Management*, 23(2), 137-154.

Dubois, A., & Gadde, L. E. (2002). "Systematic combining: an abductive approach to case research". *Journal of Business Research*, 55(7), 553–560

Dvarioniene, J., Gurauskiene, I., Gecevicius, G., Trummer, D. R., Selada, C., Marques, I., & Cosmi, C. (2015). "Stakeholders involvement for energy conscious communities: The Energy Labs experience in 10 European communities". *Renewable Energy*, 75, 512-518.

Eloranta, V., & Turunen, T. (2016). "Platforms in service-driven manufacturing: Leveraging complexity by connecting, sharing, and integrating". *Industrial Marketing Management*, 55, 178–186

ENoLL. 2014. What are Living Labs [Online]. Available: https://enoll.org/about-us/ [Accessed June 2019].

Eriksson, M., Niitamo, V.-P., & Kulkki, S. (2005). "State-of-the-art in utilizing Living Labs approach to user-centric ICT innovation-a European approach. Lulea: Center for Distance-spanning Technology". Lulea University of Technology Sweden: Lulea.

Ford, D., & Håkansson, H. (2002). "How should companies interact in business networks?" *Journal of Business Research*, 55, 133–139.

Ford, D., Gadde, L.-E., Håkansson, H., Snehota, I. and Waluszewski, A. (2008), "Analysing business interaction", *The IMP Journal*, 4 (1), pp. 82-103.

Ford, D., Håkansson, H., & Johanson, J. (1986). "How do companies interact?" *Industrial Marketing and Purchasing*, 1(1), 26–41

Franz, Y. (2015). "Designing social living labs in urban research". Journal of Policy, Regulation and Strategy for Telecommunications, Information and Media, 17, 53-66.

Gawer, A. and Cusumano, M.A. (2014) "Industry Platforms and Ecosystem Innovation". *Journal of Product Innovation Management,* 31, 417-433.

Giard, V. and Midler, C. (Eds.) (1993), "Pilotages de projet et entreprises: diversités et convergences", *Economica,* Paris.

Håkansson H and Johanson J, 1992, "A Model of Industrial Networks", in B Axelsson and G Easton, (eds), *Industrial Networks: A New View of Reality,* London, Routledge, 28-34

Håkansson, H., & Snehota, I. (1995). "Developing relationships in business networks". London Routledge.

Håkansson H., Waluszewski A. (2007), "Knowledge and Innovation in Business and Industry: The importance of using others", Routledge.

Håkansson, H. (Ed.). (1987). "Industrial technological development. A network approach". London Croom Helm.

Halinen, Aino & Törnroos, Jan-Åke, 1998. "The role of embeddedness in the evolution of business networks," *Scandinavian Journal of Management,* 14(3), pages 187-205, March.

Harrison, D., & Easton, G. (2005). “Patterns of actor response to environmental change”. *Journal of Business Research*, 55, 545–552.

Harrison, D., & Prenkert, F. (2009). “Network strategising trajectories within a planned strategy process”. *Industrial Marketing Management*, 38(6), 662–670.

Heikkinen, M. T., Mainela, T., Still, J., & Tähtinen, J. (2007). "Roles for managing in mobile service development nets". *Industrial Marketing Management*, 36(7), 909–925.

Herrera, N. R. (2017). “The emergence of Living Lab methods”. In *Living Labs* (pp. 9-22): Springer.

Hossain, M., Leminen, S., & Westerlund, M. (2019). “A systematic review of living lab literature”. *Journal of Cleaner Production*, 213, 976-988.

Intille, S. S. (2002). “Designing a home of the future”. IEEE pervasive computing, 1(2), 76-82.

Jalkala, A., Cova, B., Salle, R., & Salminen, R. T. (2010). “Changing project business orientations: Towards a new logic of project marketing” *European Management Journal,* 28(2), 124–138

Johnsen, T.E., Miemczyk, J. and Howard, M. (2017), “A systematic literature review of sustainable purchasing and supply research: theoretical perspectives and opportunities for IMP-based research”, *Industrial Marketing Management*, 61, pp. 130-143

Kensing, F., & Blomberg, J. (1998). “Participatory design: Issues and concerns”. *Computer Supported Cooperative Work*, 7(3-4), 167-185.

Kviselius, N.Z., Andersson, P., Ozan, H. and Edenius, M. (2009), “Living labs as tools for open innovation”, *Communications & Strategies*, 74 (2), pp. 75-94.

Laczko P., Hullova D., Needham A., Rossiter A-M., Battisti M. (2019) “The role of a central actor in increasing platform stickiness and stakeholder profitability: Bridging the gap between value creation and value capture in the sharing economy”. *Industrial Marketing Management,* 79, 214-230

Lehtinen J., Aaltonen K., Rajala R. (2019) “Stakeholder management in complex product systems: Practices and rationales for engagement and disengagement”. *Industrial Marketing Management,* 79: 58-70

Leminen, S., DeFillippi, R., & Westerlund, M. (2015). “Paradoxical tensions in living labs. In ISPIM Conference Proceedings (p. 1)”. The International Society for Professional Innovation Management (ISPIM).

Leminen, S., Nyström, A. G., Westerlund, M., & Kortelainen, M. J. (2016). “The effect of network structure on radical innovation in living labs”. *Journal of Business & Industrial Marketing,* 31(6), 743-757.

Leminen, S., Westerlund, M., & Nyström, A.G. (2012). "Living Labs as Open-Innovation Networks". *Technology Innovation Management Review*, 2(9): 6-11.

Lind F. (2015). “Goal diversity and resource development in an interorganisational project”. *Journal of business and industrial marketing* 30(3/4):259-268

Mainela T. and Ulkuniemi P. (2013). “Personal interaction and customer relationship management in project business”. *Journal of Business and Industrial Marketing, 28 (2), 103-110*

Mele, C. (2011), "Conflicts and value co-creation in project networks", *Industrial Marketing Management,* 40 (8), pp. 1377-1385.

Missonier, S., & Loufrani-Fedida, S. (2014). "Stakeholder analysis and engagement in projects: From stakeholder relational perspective to stakeholder relational ontology". *International Journal of Project Management*, 32(7), 1108–1122

Mitrega, M., Forkmann, S., Zaefarian, G., & Henneberg, C. S. (2017). "Networking capability in supplier relationships and its impact on product innovation and firm performance". *International Journal of Operations & Production Management*, 37(5), 577–606.

Mohr, J. J., & Spekman, R. (1994). "Characteristics of partnership success: Partnership attributes, communication behavior, and conflict resolution techniques". *Strategic Management Journal,* 15(2), 135–152.

Möller, K., & Svahn, S. (2009). "How to influence the birth of new business fields—Network perspective". *Industrial Marketing Management*, 38(4), 450–458.

Möller, K., & Rajala, A. (2007). "Rise of strategic nets—New modes of value creation". *Industrial Marketing Management*, 36(7), 895–908

Möller, K., Rajala, A., & Svahn, S. (2005). "Strategic business nets—their type and management". *Journal of Business Research*, 58(9), 1274–1284.

Mulder, I. 2012. "Living Labbing the Rotterdam Way: Co-Creation as an Enabler for Urban Innovation". *Technology Innovation Management* Review

Laczko P., Hullova D., Needham A., Rossiter A-M., Battisti M. (2019) "The role of a central actor in increasing platform stickiness and stakeholder profitability: Bridging the gap between value creation and value capture in the sharing economy". *Industrial Marketing Management,* 79, 214-230

Nieto, M. J., & Santamaría, L. (2007). "The importance of diverse collaborative networks for the novelty of product innovation". *Technovation*, 27(6–7), 367–377.

Nyström, A. G., Leminen, S., Westerlund, M., & Kortelainen, M. (2014). "Actor roles and role patterns influencing innovation in living labs". *Industrial Marketing Management*, 43(3), 483-495.

Perks H., Moxey S. (2011), "Market-facing innovation networks: How lead firms patition tasks, share resources and develop capabilities", *Industrial Marketing Management*, 40(8), pp. 1224–1237.

Perks, H., Kowalkowski, C., Witell, L., & Gustafsson, A. (2017). "Network orchestration for value platform development". *Industrial Marketing Management*, 67, 106–121.

Ramos, C., Henneberg, S. C. and Naudé, P. (2012). "Understanding network picture complexity: An empirical analysis of contextual factors", *Industrial Marketing Management*, 41 (6), pp. 951-972.

Ritter T., GemüNden H.G. (2003), "Network competence: Its impact on innovation success and its antecedents", *Journal of Business Research*, 56(9), pp. 745–755.

Ritvala, T., & Salmi, A. (2010). "Value-based network mobilization: A case study of modern environmental networkers". *Industrial Marketing Management*, 39(6), 898–907.

Rosado, L., Hagy, S., Kalmykova, Y., Morrison, G., & Ostermeyer, Y. (2015). "A living lab co-creation environment exemplifying Factor 10 improvements in a city district". *Journal of Urban Regeneration & Renewal*, 8(2), 171-185.

Rust R (2016) “Outside-in marketing: Why, when and how?”. *Industrial Marketing Management*

Sagen Vildåsen S. and Ingemansson Havenvid M. (2018). “The role of interaction for corporate sustainability”. *IMP Journal*, 12, 148-170

Schuurman, D. (2015). “Bridging the Gap between Open and User Innovation? Exploring the Value of Living Labs as a Means to Structure User Contribution and Manage Distributed Innovation”. Doctoral dissertation. Ghent University and Vrije Universiteit Brussel VUB.

Schuurman D., Protic S (2018). “Living Labs versus Lean Startups: An Empirical Investigation”. *Technology Innovation Management Review*, 8 (12), 7-16

Schuurman, D., DeMoor, K., DeMarez, L., & Evens, T. (2011). “Living Lab research approach for mobile TV”. *Telematics and Informatics*, 28, 271–282

Schuurman, D., De Marez, L., & Ballon, P. (2016). “The Impact of Living Lab Methodology on Open Innovation Contributions and Outcomes”. *Technology Innovation Management Review,* 1(6): 7–16.

Scott, K., Bakker, C., & Quist, J. (2012). “Designing change by living change”. *Design Studies*, 33(3), 279-297

Spinuzzi, C. (2005). “The methodology of participatory design”. *Technical communication*, 52(2), 163-174.

Steen, K. And van Bueren, E. (2017). “Urban Living Labs: A Living Lab Way of Working” *Technological Innovation Management Review*

Ünal, E., Shao, J., (2019). “A taxonomy of circular economy implementation strategies for manufacturing firms: analysis of 391 cradle-to-cradle products”. J. *Clean.Prod*. 212, 754e765

Vaaland, T.I., Håkansson, H. (2003). “Exploring inter-organizational conflict in complex projects: Finland”. *Industrial Marketing Management*, 32(2), pp. 127–138.

Veeckman, C., Schuurman, D., Leminen, S., & Westerlund, M. (2013). “Linking living lab characteristics and their outcomes: Towards a conceptual framework”. *Technology Innovation Management Review,* 3(12).

Venselaar, M., Gruis, V., & Verhoeven, F. (2015). “Implementing supply chain partnering in the construction industry: Work floor experiences within a Dutch housing association”. *Journal of Purchasing and Supply Management*, 21(1), 1-8.

Waluszewski, A., Baraldi, E. and Perna, A. (2017), "The role of policy in innovation", *IMP Journal,* 11 (1), pp. 51-71

Westerlund, M., & Svahn, S. (2008). “A relationship value perspective of social capital in networks of software SMEs”. *Industrial Marketing Management*, 37(5), 492–501.

Table 1 – Changes across Project Stages. (Based on the Living Lab role framework Nystrom et al (2014)[1])

Project Stages	Actors (roles)	Resources	Activities	Actor's Goals	Details about actor's role
Sustainable Home LL – Macro goal: sustainable living					
Project conceptualization	University (webber)	Technical Knowledge	Ideator; defines the LL approach	Create knowledge on sustainability aspects: - Applied Architectural innovation - Research Lab - Grants and new collaborations	Develop the first idea/concept. Initiator, study on LL definitions and established first goal (sustainable living)
	Science Park (advocate)	Technology transfer expertise	Creates network	Technical Innovation, bond with the University	Science Park and National Hosing Cooperative initiate the project with the University, start networking
	National Housing Cooperative (webber)	Network	Collaborates with Science Park in creating networks	Promote the firm image as an innovator	
Project design	University (planner and informant)	Expertise on LL approach	Background research and co-work with external firms (e.g., architects)	Drive research within the space Swedish and European Research Funding	Use the definition of LL and the first goal to design with external firms
	National Housing Cooperative (gatekeeper and producer)	Financial resource and network	Financing and network	Create and consolidate network with industries and establish an industry research fund	Provide financial resources and improve relationships with partners
Project development	University (coordinator)	Knowledge on LL planning	Workshops	Develop the LL around the idea of sustainable living	Coordinate the workshops with internal and external partners
	National Housing Cooperative (facilitator)	Financial resources and project management	Manages partners during the construction stages	Supervise the project First step in an innovation precinct	Provide a platform for the cooperation
	Industry Partners (accessory provider)	Financial and technical resources	First contact, proposal of new products to test; financial contribution	Establish as a leader in the housing market in terms of innovation	Propose of products to test New product development, test in real-life simulation settings

[1] Nyström, A.G., Leminen, S., Westerlund, M. and Kortelainen, M., 2014. Actor roles and role patterns influencing innovation in living labs. *Industrial Marketing Management*, *43*(3), pp.483-495.

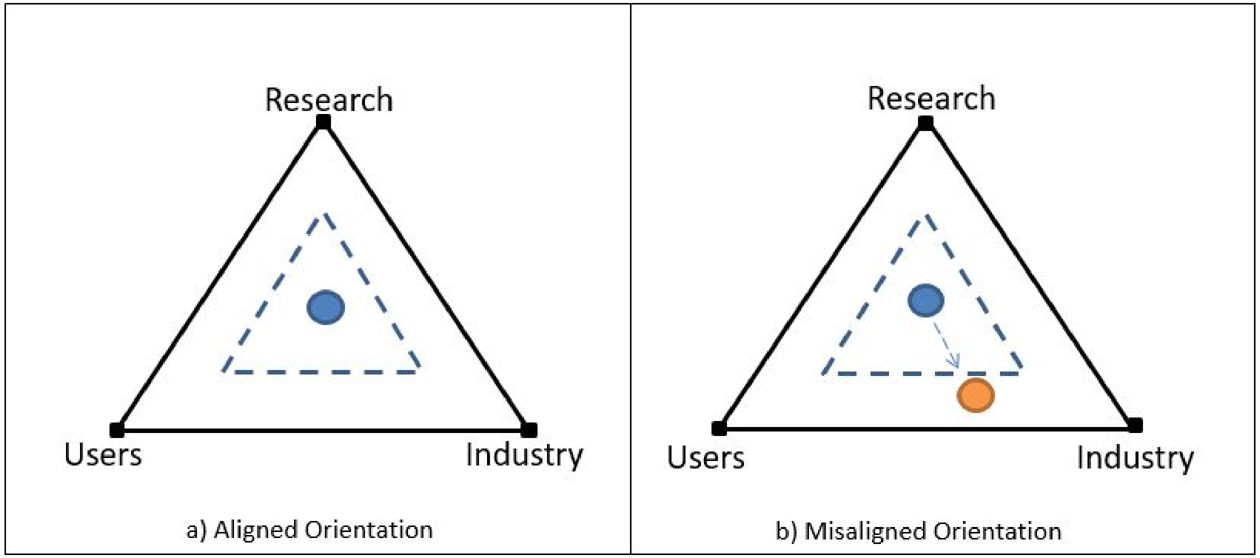
The launch of platform and platform evolution	University (informant, tester)	Research capacity	Monitor and test the new products and users	Research projects	Carrying out research projects involving users and industry partners (co-creation)
	National Housing Cooperative (orchestrator)	Management	Support and promote existing network	Continued development of innovation	Manage the facility (students accommodation) and promotion of the cooperative goals (sustainability)
	Industry partners (contributors)	Products, technology, financial support	Test and promote new products	Test new products in real-life settings to launch into the market. Cooperation platform with the Housing Cooperative	Provide, test and improve products to support research
	Users (co-creator)	Personal experience	Involvement in sustainable lifestyle projects	Live in a sustainable fashion, contribute to knowledge-creation on sustainable living	Rent the apartments and complete surveys
The project evolution to a more contemporary facility					
Project conceptualization and design	University (webber, investigator, planner)	Technical Knowledge, first concept	Ideator; creates the scope of the LL	Develop a research facility based on the committed goal (heart and soul)	Develop the first idea/concept. Establish the relationship with industry partners and donors
	State Government Organization (accessory provider)	Financial support and other in-kind	Financing and network	Participate in the creation of the facility to benefit its use; marketing	Leave decisional freedom to the University
	Industry partners/consortium (contributors)	Products knowledge	Provides products, technologies, and/or cash contribution	Marketing, launch of new products	Offer new products to be tested, or established products to be used in the building
Future stage: platform launch and use	University (integrator, coordinator, informant, tester)	Management, research capacity, leading capacity (coach?)	Carrying out research, establish new partnerships	Lead the partners towards the committed goal Research projects	Maintain the relationships and establish new ones, aimed at increasing the research output
	State Government Organization as a user (contributor)	Established network	Uses the LL for its scopes (as a commercial facility and construction site activation)	Use the facility as an office and showcase	Promotes itself and the LL
	Industry partners/consortium (contributors, testers)	Products	Provide products and test their use	Advertising and exposure	Follows the directions of the University to support their research. Network with the Users
	Users (co-creation,	Financial support,	Rent the hot-desks	Network, use of the platform	Office time and commitment,

	informants) Firms?	knowledge and network	and test their new products	both as an office and for testing new products	research support and network

Table 2- LL Platform: the benefits and solutions to the actors in the two different living labs

Actor	Core solutions	Additional value solutions	Function of the project
Sustainable Home Living Lab			
University	Provide a facility to conduct research on Sustainable Living	Network with industry partners Enhance the relationships with other universities Increase university's prestige	R&D project
Firms	Marketing exposure and product testing	Environment to test their business models Network with other firms Network with university	Launch of a new product
Users	Accommodation to rent	Contribute to sustainable living Involvement in research Live in a high-tech facility	At the beginning: To improve sustainability activities During the project: To improve comfort
	Circular Living Lab		
University	Provide a facility to conduct research on Circular Economy	Network with industry partners Enhance the relationships with other universities Increase university's prestige Visualisation space to connect across Australia	R&D project To develop a strong vision
Firms	Marketing exposure and product testing	Network with other firms Network with university Meeting and visualization space	Launch of a new product
Users	Office space and test ground	Contribute to research and enhancement of the circular economy concept Involvement in research Work and utilize a high-tech facility Involvement in media promotion	To access to business services

Figure 1. Living Lab Goal Orientation



Bibliography

A

Å vajlenka, J., Kozlovská, M., Spišáková, M., 2017. The benefits of modern method of construction based on wood in the context of sustainability. International journal of environmental science and technology. 14, 1591-1602. http://dx.doi.org/10.1007/s13762-017-1282-6.

Aaltonen K, Kujala J., Lehtonen P. and Ruuska I. (2010). “A stakeholder network perspective on unexpected events and their management in international projects”. International Journal of Managing Projects in Business, 3 (4), 564-588

Aarikka-Stenroos L., Jaakkola E., Harrison D., Mäkitalo-Keinonen T (2017), “How to manage innovation processes in extensive networks: A longitudinal study”, Industrial Marketing Management, pp. 67 88–105

Abid, S. R., et al. (2018). "Expansion and strength properties of concrete containing contaminated recycled concrete aggregate." Case Studies in Construction Materials 9: e00201.

Abrão, P.C.R.A., Cardoso, F.A., John, V.M., 2020. Efficiency of Portland-pozzolana cements: Water demand, chemical reactivity and environmental impact. Construction and Building Materials. 247, 118546. https://doi.org/10.1016/j.conbuildmat.2020.118546.

Abuzied, H., Senbel, H., Awad, M., Abbas, A., 2020. A review of advances in design for disassembly with active disassembly applications. Engineering Science and Technology, an International Journal. 23, 618-624. https://doi.org/10.1016/j.jestch.2019.07.003.

Adams, K. T., et al. (2017). "Circular economy in construction: current awareness, challenges and enablers." Proceedings of the Institution of Civil Engineers - Waste and Resource Management 170(1): 15-24.

Adams, K.T., Osmani, M., Thorpe, T., Thornback, J., 2017. Circular economy in construction: current awareness, challenges and enablers, Proceedings of the Institution of Civil Engineers-Waste and Resource Management. Thomas Telford Ltd, pp. 15-24.

Adhikari, S., Ozarska, B., 2018. Minimizing environmental impacts of timber products through the production process “From Sawmill to Final Products”. Environmental Systems Research. 7, 6. 10.1186/s40068-018-0109-x.

Ahmadian FF, A.; Rashidi, T.H.; Akbarnezhad, A.; Waller, S.T. BIM-enabled sustainability assessment of material supply decisions. Eng. Constr. Arch. Manag. 2017, 24, 668–695.

Ahmed, I.M., Tsavdaridis, K.D., 2018. Life cycle assessment (LCA) and cost (LCC) studies of lightweight composite flooring systems. Journal of Building Engineering. 20, 624-633. https://doi.org/10.1016/j.jobe.2018.09.013.

Ahola T., Kujala J., Laaksonen T., Aaltonen K. (2013). "Constructing the market position of a project-based firm". International Journal of Project Management,

Ajayi, S. O., et al. (2015). "Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements." Resources Conservation and Recycling 102: 101-112.

Ajayi, S.O., Oyedele, L.O., Ilori, O.M., 2019. Changing significance of embodied energy: A comparative study of material specifications and building energy sources. Journal of Building Engineering. 23, 324-333. 10.1016/j.jobe.2019.02.008.

Ajayi, S.O., Oyedele, L.O., Jaiyeoba, B., Kadiri, K., David, S.A., 2016. Are sustainable buildings healthy? An investigation of lifecycle relationship between building sustainability and its environmental health impacts. World Journal of Science Technology and Sustainable Development. 13, 190-204. 10.1108/wjstsd-01-2016-0015.

Akadiri, P.O.; Olomolaiye, P.O. Development of sustainable assessment criteria for building materials selection. Eng. Constr. Arch. Manag. 2012, 19, 666–687.

Akanbi, L. A., et al. (2018). "Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator." Resources, Conservation and Recycling 129: 175-186.

Akanbi, L. A., et al. (2019). "Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy." Journal of Cleaner Production 223: 386-396.

Akanbi, L., Oyedele, L., Delgado, J.M.D., Bilal, M., Akinade, O., Ajayi, A., Mohammed-Yakub, N., 2019. Reusability analytics tool for end-of-life assessment of building materials in a circular economy. World Journal of Science Technology and Sustainable Development. 16, 40-55. 10.1108/wjstsd-05-2018-0041.

Akanbi, L.A., Oyedele, L.O., Akinade, O.O., Ajayi, A.O., Davila Delgado, M., Bilal, M., Bello, S.A., 2018. Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. Resources, Conservation and Recycling. 129, 175-186. 10.1016/j.resconrec.2017.10.026.

Akanbi, L.A., Oyedele, L.O., Omoteso, K., Bilal, M., Akinade, O.O., Ajayi, A.O., Davila Delgado, J.M., Owolabi, H.A., 2019. Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. Journal of Cleaner Production. 223, 386-396. https://doi.org/10.1016/j.jclepro.2019.03.172.

Akinade, O. O., et al. (2017). "Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills." Waste Management 60: 3-13.

Alaerts, L., Van Acker, K., Rousseau, S., De Jaeger, S., Moraga, G., Dewulf, J., De Meester, S., Van Passel, S., Compernolle, T., Bachus, K., Vrancken, K., Eyckmans, J., 2019. Towards a more direct policy feedback in circular economy monitoring via a societal needs perspective. Resources, Conservation and Recycling. 149, 363-371. https://doi.org/10.1016/j.resconrec.2019.06.004.

Alembagheri, M., Sharafi, P., Hajirezaei, R., Tao, Z., 2020. Anti-collapse resistance mechanisms in corner-supported modular steel buildings. Journal of Constructional Steel Research. 170, 106083. https://doi.org/10.1016/j.jcsr.2020.106083.

Allwood, J.M., 2014. Chapter 30 - Squaring the Circular Economy: The Role of Recycling within a Hierarchy of Material Management Strategies, in: Worrell, E., Reuter, M.A. (Eds.), Handbook of Recycling. Elsevier, Boston, pp. 445-477.

Allwood, J.M.; Ashby, M.F.; Gutowski, T.G.; Worrell, E. Material efficiency: A white paper. Resour. Conserv. Recycl. 2011, 55, 362–381.

Allwood, J.M.; Cullen, J.M.; Carruth, M.A.; Cooper, D.R.; McBrien, M.; Milford, R.L.; Moynihan, M.C.; Patel, A.C. Sustainable Materials: With Both Eyes Open; UIT Cambridge: Cambridge, UK, 2012.

Almirall E., Lee M. and Wareham J. (2012) "Mapping Living Labs in the Landscape of Innovation Methodologies". Technology Innovation Management Review

Al-Obaidi, K.M.; Wei, S.L.; Ismail, M.A.; Kam, K.J. Sustainable building assessment of colonial shophouses after adaptive reuse in Kuala Lumpur. Buildings 2017, 7, 87.

Ames, D., Droessler, T., Hoit, M., 2011. Structures Congress 2011. American Society of Civil Engineers.

Anderson, E. and Weitz, B. (1992), "The use of pledges to build and sustain commitment in distribution channels", Journal of Marketing Research, 29 (1), pp. 18-34.

Anttiroiko, A.–V. 2016. "City-as-a-Platform: The Rise of Participatory Innovation Platforms in Finnish Cities". Sustainability, 8(9): 2–31.

Arge, K. Adaptable office buildings: Theory and practice. Facilities 2005, 23, 119–127.

Arora, M., Raspall, F., Cheah, L., Silva, A., 2020. Buildings and the circular economy: Estimating urban mining, recovery and reuse potential of building components. Resources, Conservation and Recycling. 154, 104581. https://doi.org/10.1016/j.resconrec.2019.104581.

Asdrubali, F., Baggio, P., Grazieschi, G., Guattari, C., Prada, A., 2019. Dynamic life cycle assessment modelling of a NZEB building. Energy. http://dx.doi.org/10.1016/j.energy.2019.116489.

Ashcraft, H.W. Building information modeling: A framework for collaboration. Constr. Law 2008, 28, 5.

Ashnai, B., Henneberg, S.C., Naudé, P. & Francescucci, A., 2016, 'Inter-personal and inter-organizational trust in business relationships: An attitude–behavior–outcome model', Industrial Marketing Management 52, 128–139

Asif, M., Muneer, T., Kelley, R., 2007. Life cycle assessment: A case study of a dwelling home in Scotland. Building and Environment. 42, 1391-1394. 10.1016/j.buildenv.2005.11.023.

Aste, N., Adhikari, R.S., Buzzetti, M., 2010. Beyond the EPBD: The low energy residential settlement Borgo Solare. Applied Energy. 87, 629-642. 10.1016/j.apenergy.2009.05.029.

Atmaca, A., 2016. Life-cycle assessment and cost analysis of residential buildings in South East of Turkey: part 2—a case study. International Journal of Life Cycle Assessment. 21, 925-942. 10.1007/s11367-016-1051-7.

Atmaca, A., Atmaca, N., 2015. Life cycle energy (LCEA) and carbon dioxide emissions (LCCO2A) assessment of two residential buildings in Gaziantep, Turkey. Energy and Buildings. 102, 417-431. https://doi.org/10.1016/j.enbuild.2015.06.008.

Atmaca, N., 2017. Life-cycle assessment of post-disaster temporary housing. Building Research and Information. 45, 524-538. http://dx.doi.org/10.1080/09613218.2015.1127116.

Aye, L., Ngo, T., Crawford, R.H., Gammampila, R., Mendis, P., 2012. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. Energy and buildings. 47, 159-168. doi.org/10.1016/j.buildenv.2019.106290.

Azzouz, A., Borchers, M., Moreira, J., Mavrogianni, A., 2017. Life cycle assessment of energy conservation measures during early stage office building design: A case study in London, UK. Energy and Buildings. 139, 547-568. https://doi.org/10.1016/j.enbuild.2016.12.089.

B

Babu, S., et al. (2019). "Investigation of an integrated automated blinds and dimmable lighting system for tropical climate in a rotatable testbed facility." Energy and Buildings 183: 356-376.

Bakhshi, A.A., Sharon, M., 2009. A GIS methodology for estimating the carbon footprint in municipal water ana wastewater in Fairfax county, Virginia. Energy Engineering. 106, 7-24. doi.org/10.1080/01998590909594541.

Bakker, C.; Wang, F.; Huisman, J.; Den Hollander, M. Products that go round: Exploring product life extension through design. J. Clean. Prod. 2014, 69, 10–16.

Balasbaneh, A.T., Bin Marsono, A.K., Gohari, A., 2019. Sustainable materials selection based on flood damage assessment for a building using LCA and LCC. Journal of Cleaner Production. 222, 844-855. https://doi.org/10.1016/j.jclepro.2019.03.005.

Baraldi E. (2008) "Strategy in Industrial Network. Experiences from IKEA". California Review Management, 50 (4)

Baraldi, E., & Strömsten, T. (2009). "Controlling and combining resources in networks -from Uppsala to Stanford, and back again: The case of a biotech innovation". Industrial Marketing Management, 38, 541–552.

Baraldi, E., Gregori, G.L. and Perna, A. (2011), "Network evolution and the embedding of complex technical solutions: the case of the Leaf House network", Industrial Marketing Management, 40 (6), pp. 838-852

Basta, A., Serror, M.H., Marzouk, M., 2020. A BIM-based framework for quantitative assessment of steel structure deconstructability. Automation in Construction. 111, 103064. https://doi.org/10.1016/j.autcon.2019.103064.

Baumann, H.a., 2004. The hitch hiker's guide to LCA : an orientation in life cycle assessment methodology and application / Henrikke Baumann & Anne-Marie Tillman. Lund, Sweden : Studentlitteratur.

Baumeister, R.F., Leary, M.R., 1997. Writing Narrative Literature Reviews. Review of General Psychology. 1, 311-320. 10.1037/1089-2680.1.3.311.

Benachio, G.L.F., Freitas, M.d.C.D., Tavares, S.F., 2020. Circular economy in the construction industry: A systematic literature review. Journal of Cleaner Production. 260, 121046. https://doi.org/10.1016/j.jclepro.2020.121046.

Birkinshaw, J., Brannen, M.Y., Tung, R.L. (2011). "From a distance and generalizable to up close and grounded: reclaiming a place for qualitative methods in international business research". J. Int. Bus. Stud. 42, 573–581.

Bischoff, P.H., Perry, S.H., 1991. Compressive behaviour of concrete at high strain rates. Materials and Structures. 24, 425-450. 10.1007/BF02472016.

Biswas, K., Shrestha, S.S., Bhandari, M.S., Desjarlais, A.O., 2016. Insulation materials for commercial buildings in North America: An assessment of lifetime energy and environmental impacts. Energy and Buildings. 112, 256-269. https://doi.org/10.1016/j.enbuild.2015.12.013.

Biswas, W.K., 2014. Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. International Journal of Sustainable Built Environment. 3, 179-186. 10.1016/j.ijsbe.2014.11.004.

Björklund, A.E., 2002. Survey of approaches to improve reliability in LCA. The International Journal of Life Cycle Assessment. 7, 64. htto://dx.doi.org/10.1065/Ica2001.12.071

Blengini, G.A., 2009. Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. Building and Environment. 44, 319-330. 10.1016/j.buildenv.2008.03.007.

Blengini, G.A., Di Carlo, T., 2010. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energy and buildings. 42, 869-880. 10.1016/j.enbuild.2009.12.009.

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering. 33, 308-320. 10.1080/21681015.2016.1172124.

Bocken, N.M.P.; Olivetti, E.A.; Cullen, J.M.; Potting, J.; Lifset, R. Taking the Circularity to the Next Level: A Special Issue on the Circular Economy. J. Ind. Ecol. 2017, 21, 476–482.

Bowden, F., Lockton, D., Gheerawo, R., & Brass, C. (2017). "Participatory Drawing in Ethnographic Research". In Living Labs (pp. 179-190): Springer.

Brambilla, G., Lavagna, M., Vasdravellis, G., Castiglioni, C.A., 2019. Environmental benefits arising from demountable steel-concrete composite floor systems in buildings. Resources, Conservation and Recycling. 141, 133-142. https://doi.org/10.1016/j.resconrec.2018.10.014.

Braungart, M.; McDonough, W.; Bollinger, A. Cradle-to-cradle design: Creating healthy emissions–a strategy for eco-effective product and system design. J. Clean. Prod. 2007, 15, 1337–1348.

Bribian, I.Z., Capilla, A.V., Uson, A.A., 2011. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and Environment. 46, 1133-1140. 10.1016/j.buildenv.2010.12.002.

Bribián, I.Z., Usón, A.A., Scarpellini, S., 2009. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. Building and Environment. 44, 2510-2520. https://doi.org/10.1016/j.buildenv.2009.05.001.

Brogaard, L.K., Damgaard, A., Jensen, M.B., Barlaz, M., Christensen, T.H., 2014. Evaluation of life cycle inventory data for recycling systems. Resources, Conservation and Recycling. 87, 30-45. https://doi.org/10.1016/j.resconrec.2014.03.011.

Brown, M.T., Buranakarn, V., 2003. Emergy indices and ratios for sustainable material cycles and recycle options. Resources, Conservation and Recycling. 38, 1-22. https://doi.org/10.1016/S0921-3449(02)00093-9.

Browning, T.R., Heath, R.D., 2009. Reconceptualizing the effects of lean on production costs with evidence from the F-22 program. Journal of Operations Management. 27, 23-44. https://doi.org/10.1016/j.jom.2008.03.009.

Bruegmann, R.; Zukowsky, J. Chicago Architecture 1872–1922: Birth of a Metropolis; Prestel Verlag: Munich, Germany, 1987.

Burbridge, M., Morrison, G. M., van Rijn, M., Silvester, S., Keyson, D. V., Virdee, L., Liedtke, C. (2017). “Business models for sustainability in living labs”. In Living labs (pp. 391-403): Springer.

Buyle, M., Galle, W., Debacker, W., Audenaert, A., 2019. Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. Journal of Cleaner Production. 218, 141-156. https://doi.org/10.1016/j.jclepro.2019.01.306.

C

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and sustainable energy reviews. 29, 394-416. https://doi.org/10.1016/j.rser.2013.08.037.

Campbell-Johnston, K., Cate, J.T., Elfering-Petrovic, M., Gupta, J., 2019. City level circular transitions: Barriers and limits in Amsterdam, Utrecht and The Hague. Journal of Cleaner Production. 235, 1232-1239. 10.1016/j.jclepro.2019.06.106.

Cantù, C., Corsaro, D., Tunisini, A., Lind, F., 2015. Goal diversity and resource development in an inter-organisational project. Journal of Business & Industrial Marketing.

Cao, X., Li, X., Zhu, Y., Zhang, Z., 2015. A comparative study of environmental performance between prefabricated and traditional residential buildings in China. Journal of Cleaner Production. 109, 131-143. https://doi.org/10.1016/j.jclepro.2015.04.120.

Catalli, V.; Williams, M. Designing for disassembly [An innovative strategy for attaining environmental goals and building adaptability] [Mountain Equipment Co-op Ottawa store case study]. Can. Arch. 2001, 46, 27–29.

Celadyn, M. (2019). "Interior Architectural Design for Adaptive Reuse in Application of Environmental Sustainability Principles." Sustainability 11(14).

Cesprini, E., Resente, G., Causin, V., Urso, T., Cavalli, R., Zanetti, M., 2020. Energy recovery of glued wood waste – A review. Fuel. 262, 116520. https://doi.org/10.1016/j.fuel.2019.116520.

Chan, J., Bachmann, C., Haas, C., 2020. Potential economic and energy impacts of substituting adaptive reuse for new building construction: A case study of Ontario. Journal of Cleaner Production. 259, 120939. https://doi.org/10.1016/j.jclepro.2020.120939.

Chang, C.C., Shi, W., Mehta, P., Dauwels, J., 2019. Life cycle energy assessment of university buildings in tropical climate. Journal of Cleaner Production. 239. 10.1016/j.jclepro.2019.117930.

Chang, Y., Ries, R.J., Lei, S., 2012. The embodied energy and emissions of a high-rise education building: A quantification using process-based hybrid life cycle inventory model. Energy and Buildings. 55, 790-798. https://doi.org/10.1016/j.enbuild.2012.10.019.

Chau, C.K., Hui, W.K., Ng, W.Y., Powell, G., 2012. Assessment of CO 2 emissions reduction in high-rise concrete office buildings using different material use options. Resources, Conservation and Recycling. 61, 22-34. 10.1016/j.resconrec.2012.01.001.

Chau, C.K., Xu, J.M., Leung, T.M., Ng, W.Y., 2017. Evaluation of the impacts of end-of-life management strategies for deconstruction of a high-rise concrete framed office building. Applied Energy. 185, 1595-1603. 10.1016/j.apenergy.2016.01.019.

Chauhan, S.S., Walker, J.C.F., 2006. Variations in acoustic velocity and density with age, and their interrelationships in radiata pine. Forest Ecology and Management. 229, 388-394. https://doi.org/10.1016/j.foreco.2006.04.019.

Chileshe, N., et al. (2018). "Factors driving the implementation of reverse logistics: A quantified model for the construction industry." Waste Management 79: 48-57.

Chomkhamsri, K., Wolf, M.-A., Pant, R., 2011. International reference life cycle data system (ILCD) handbook: review schemes for life cycle assessment, Towards life cycle sustainability management. Springer, pp. 107-117.

Co., L.S., 2015. To Infinity and Beyond: How We're Embracing the Circular Economy. https://www.levistrauss.com/2015/07/21/embracing-the-circular-economy/. (Accessed 28/03/2020.

Cohen, J., 1960. A coefficient of agreement for nominal scales. Educational and psychological measurement. 20, 37-46. doi.org/10.1177/001316446002000104.

Cohen, J., 1968. Weighted kappa: nominal scale agreement provision for scaled disagreement or partial credit. Psychological bulletin. 70, 213. https://doi.org/10.1037/h0026256.

Condit, C.W. The Chicago School of Architecture: A History of Commercial and Public Building in the Chicago Area, 1875–1925; University of Chicago Press: Chicago, IL, USA, 1973.

Cook, K. S., & Emerson, R. M. (1978). "Power, equity and commitment in exchange networks". American Sociological Review, 721–739.

Cornaro, C., Zanella, V., Robazza, P., Belloni, E., Buratti, C., 2020. An innovative straw bale wall package for sustainable buildings: experimental characterization, energy and environmental performance assessment. Energy and Buildings. 208, 1. http://dx.doi.org/10.1016/j.enbuild.2019.109636.

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

Corsaro, D., Cantù, C., & Tunisini, A. (2012). "Actors' heterogeneity in innovation networks". Industrial Marketing Management, 41(5), 780–789.

Costa, C., Marques, J.C., 2018. Feasibility of eco-friendly binary and ternary blended binders made of fly-ash and oil-refinery spent catalyst in ready-mixed concrete production. Sustainability (Switzerland). 10. 10.3390/su10093136.

Cova, B., Mazet, F., & Salle, R. (1994). "From competitive tendering to strategic marketing: An inductive approach for theory-building". Journal of Strategic Marketing, 2(1), 29–47.

Crawford, R.H., 2011. Life cycle assessment in the built environment. Routledge.

Crawford, R.H., 2014. Post-occupancy life cycle energy assessment of a residential building in Australia. Architectural Science Review. 57, 114-124. 10.1080/00038628.2013.819556.

Crespin-Mazet F., Ingemansson Havenvid M., Linné Å (2016). “Antecedents of project partnering in the construction industry — The impact of relationship history”. Industrial marketing management.

Crowther, P. Developing Guidelines for Designing for Deconstruction. In Deconstruction—Closing the Loop; BRE Group: Garston, UK, 18 May 2000.

Cruz Rios, F., Chong, W.K., Grau, D., 2019. Reusing exterior wall framing systems: A cradle-to-cradle comparative life cycle assessment. Waste management. 94, 120-135. http://dx.doi.org/10.1016/j.wasman.2019.05.040.

Cruz Rios, F., Grau, D., Chong, W.K., 2019. Reusing exterior wall framing systems: A cradle-to-cradle comparative life cycle assessment. Waste Management. 94, 120-135. https://doi.org/10.1016/j.wasman.2019.05.040.

Cruza C., Gaspar P., De Britoa J. (2019). “On the concept of sustainable sustainability: An application to the Portuguese construction sector” Journal of Building Engineering 25

Cuellar-Franca, R. M. and A. Azapagic (2012). "Environmental impacts of the UK residential sector: Life cycle assessment of houses." Building and Environment 54: 86-99.

Cullen, J.M. Circular Economy: Theoretical Benchmark or Perpetual Motion Machine? J. Ind. Ecol. 2017, 21, 483–486.

D

da Rocha, C.G., Sattler, M.A., 2009. A discussion on the reuse of building components in Brazil: An analysis of major social, economical and legal factors. Resources, Conservation and Recycling. 54, 104-112. https://doi.org/10.1016/j.resconrec.2009.07.004.

D'Amato, D., Droste, N., Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J., Leskinen, P., Matthies, B.D., Toppinen, A., 2017. Green, circular, bio economy: A comparative analysis of sustainability avenues. Journal of Cleaner Production. 168, 716-734. https://doi.org/10.1016/j.jclepro.2017.09.053.

D'Amico, A., Ciulla, G., Traverso, M., Lo Brano, V., Palumbo, E., 2019. Artificial Neural Networks to assess energy and environmental performance of buildings: An Italian case study. Journal of Cleaner Production. 239. 10.1016/j.jclepro.2019.117993.

Dantata, N., Touran, A., Wang, J., 2005. An analysis of cost and duration for deconstruction and demolition of residential buildings in Massachusetts. Resources, Conservation and Recycling. 44, 1-15. https://doi.org/10.1016/j.resconrec.2004.09.001.

Dara, C., Hachem-Vermette, C., 2019. Evaluation of low-impact modular housing using energy optimization and life cycle analysis. Energy, Ecology and Environment. 4, 286-299. 10.1007/s40974-019-00135-4.

Dara, C., Hachem-Vermette, C., Assefa, G., 2019. Life cycle assessment and life cycle costing of container-based single-family housing in Canada: A case study. Building and Environment. 163, 106332. https://doi.org/10.1016/j.buildenv.2019.106332.

De Ron, A.; Penev, K. Disassembly and recycling of electronic consumer products: An overview. Technovation 1995, 15, 363–374. [Green Version]

Dean, B., Dulac, J., Petrichenko, K., Graham, P., 2016. Towards zero-emission efficient and resilient buildings.: Global Status Report.

Dell'Era, C., & Landoni, P. (2014). "Living Lab: A methodology between user-centred design and participatory design". Creativity and Innovation Management, 23(2), 137-154.

Demir, I.; Orhan, M. Reuse of waste bricks in the production line. Build. Environ. 2003, 38, 1451–1455.

Densley Tingley, D., Cooper, S., Cullen, J., 2017. Understanding and overcoming the barriers to structural steel reuse, a UK perspective. Journal of Cleaner Production. 148, 642-652. https://doi.org/10.1016/j.jclepro.2017.02.006.

Denyer, D. and D. Tranfield (2009). "Producing a systematic review."

Desai, A.; Mital, A. Evaluation of disassemblability to enable design for disassembly in mass production. Int. J. Ind. Ergon. 2003, 32, 265–281.

Desai, A.; Mital, A. Incorporating work factors in design for disassembly in product design. J. Manuf. Technol. Manag. 2005, 16, 712–732.

Di Maria, A.; Eyckmans, J.; Van Acker, K. Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. Waste Manag. 2018, 75, 3–21.

Dixit, M.K., Culp, C.H., Fernández-Solís, J.L., 2013. System boundary for embodied energy in buildings: A conceptual model for definition. Renewable and Sustainable Energy Reviews. 21, 153-164. https://doi.org/10.1016/j.rser.2012.12.037.

Diyamandoglu, V. and L. M. Fortuna (2015). "Deconstruction of wood-framed houses: Material recovery and environmental impact." Resources, Conservation and Recycling 100: 21-30.

Dong, Y., Qin, T., Zhou, S., Huang, L., Bo, R., Guo, H., Yin, X., 2020. Comparative whole building life cycle assessment of energy saving and carbon reduction performance of reinforced concrete and timber stadiums-a case study in China. Sustainability (Switzerland). 12, 1-24. 10.3390/su12041566.

Dubois, A., & Gadde, L. E. (2002). "Systematic combining: an abductive approach to case research". Journal of Business Research, 55(7), 553–560

Dunant, C.F., Drewniok, M.P., Sansom, M., Corbey, S., Allwood, J.M., Cullen, J.M., 2017. Real and perceived barriers to steel reuse across the UK construction value chain. Resources, Conservation and Recycling. 126, 118-131. https://doi.org/10.1016/j.resconrec.2017.07.036.

Dvarioniene, J., Gurauskiene, I., Gecevicius, G., Trummer, D. R., Selada, C., Marques, I., & Cosmi, C. (2015). "Stakeholders involvement for energy conscious communities: The Energy Labs experience in 10 European communities". Renewable Energy, 75, 512-518.

E

Eberhardt, L. C. M., et al. (2019). "Life cycle assessment of a Danish office building designed for disassembly." Building Research and Information 47(6): 666-680.

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. IOP Publishing, p. 012039.

Eberhardt, L.C.M., Birgisdottir, H., Birkved, M., 2019. Life cycle assessment of a Danish office building designed for disassembly. Building Research and Information. 47, 666-680. 10.1080/09613218.2018.1517458.

Eckelman, M.J., Brown, C., Troup, L.N., Wang, L., Webster, M.D., Hajjar, J.F., 2018. Life cycle energy and environmental benefits of novel design-for-deconstruction structural systems in steel buildings. Building and Environment. 143, 421-430. https://doi.org/10.1016/j.buildenv.2018.07.017.

EeBGuide, 2011. EeBGuide Guidance Document - Part A: Products. https://www.eebguide.eu/eebblog/wp-content/uploads/2012/10/EeBGuide-A-FINAL-PR_2012-10-29.pdf. (Accessed April 2020.

Ekanayake, L. L. and G. Ofori (2004). "Building waste assessment score: design-based tool." Building and Environment 39(7): 851-861.

Eleftheriadis, S., Duffour, P., Mumovic, D., 2018. BIM-embedded life cycle carbon assessment of RC buildings using optimised structural design alternatives. Energy and Buildings. 173, 587-600. https://doi.org/10.1016/j.enbuild.2018.05.042.

Elia, V.; Gnoni, M.G.; Tornese, F. Measuring circular economy strategies through index methods: A critical analysis. J. Clean. Prod. 2017, 142, 2741–2751.

Eloranta, V., & Turunen, T. (2016). “Platforms in service-driven manufacturing: Leveraging complexity by connecting, sharing, and integrating”. Industrial Marketing Management, 55, 178–186

Emami, N., Marteinsson, B., Heinonen, J., 2016. Environmental Impact Assessment of a School Building in Iceland Using LCA-Including the Effect of Long Distance Transport of Materials. Buildings. 6. 10.3390/buildings6040046.

ENoLL. 2014. What are Living Labs [Online]. Available: https://enoll.org/about-us/ [Accessed June 2019].

Eriksson, M., Niitamo, V.-P., & Kulkki, S. (2005). “State-of-the-art in utilizing Living Labs approach to user-centric ICT innovation-a European approach. Lulea: Center for Distance-spanning Technology”. Lulea University of Technology Sweden: Lulea.

Esa, M. R., et al. (2017). "Strategies for minimizing construction and demolition wastes in Malaysia." Resources Conservation and Recycling 120: 219-229.

Evangelista, L.; de Brito, J. Mechanical behaviour of concrete made with fine recycled concrete aggregates. Cem. Concr. Compos. 2007, 29, 397–401.

F

Fay, R., Treloar, G., Iyer-Raniga, U., 2000. Life-cycle energy analysis of buildings: a case study. Building Research and Information. 28, 31-41. 10.1080/096132100369073.

Feng, H.B., Liyanage, D.R., Karunathilake, H., Sadiq, R., Hewage, K., 2020. BIM-based life cycle environmental performance assessment of single-family houses: Renovation and reconstruction strategies for aging building stock in British Columbia. Journal of Cleaner Production. 250. 10.1016/j.jclepro.2019.119543.

Fenner, A.E., Kibert, C.J., Woo, J., Morque, S., Razkenari, M., Hakim, H., Lu, X., 2018. The carbon footprint of buildings: A review of methodologies and applications. Renewable and Sustainable Energy Reviews. 94, 1142-1152. https://doi.org/10.1016/j.rser.2018.07.012.

Fercoq, A.; Lamouri, S.; Carbone, V. Lean/Green integration focused on waste reduction techniques. J. Clean. Prod. 2016, 137, 567–578.

Ferdous, W., Bai, Y., Ngo, T.D., Manalo, A., Mendis, P., 2019. New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review. Engineering Structures. 183, 883-893. https://doi.org/10.1016/j.engstruct.2019.01.061.

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., Klüppel, H.-J., 2006. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. The International Journal of Life Cycle Assessment. 11, 80-85. 10.1065/lca2006.02.002.

Ford, D., & Håkansson, H. (2002). "How should companies interact in business networks?" Journal of Business Research, 55, 133–139.

Ford, D., Gadde, L.-E., Håkansson, H., Snehota, I. and Waluszewski, A. (2008), "Analysing business interaction", The IMP Journal, 4 (1), pp. 82-103.

Ford, D., Håkansson, H., & Johanson, J. (1986). "How do companies interact?" Industrial Marketing and Purchasing, 1(1), 26–41

Formoso Carlos, T., Soibelman, L., De Cesare, C., Isatto Eduardo, L., 2002. Material Waste in Building Industry: Main Causes and Prevention. Journal of Construction Engineering and Management. 128, 316-325. 10.1061/(ASCE)0733-9364(2002)128:4(316).

Franz, Y. (2015). "Designing social living labs in urban research". Journal of Policy, Regulation and Strategy for Telecommunications, Information and Media, 17, 53-66.

Fregonara, E.; Giordano, R.; Ferrando, D.G.; Pattono, S. Economic-environmental indicators to support investment decisions: A focus on the buildings' end-of-life stage. Buildings 2017, 7, 65.

Fufa, S.M., Skaar, C., Gradeci, K., Labonnote, N., 2018. Assessment of greenhouse gas emissions of ventilated timber wall constructions based on parametric LCA. Journal of Cleaner Production. 197, 34-46. https://doi.org/10.1016/j.jclepro.2018.06.006.

G

Galan-Marin, C., Martinez-Rocamora, A., Solis-Guzman, J., Rivera-Gomez, C., 2018. Natural Stabilized Earth Panels versus Conventional Facade Systems. Economic and Environmental Impact Assessment. Sustainability. 10. 10.3390/su10041020.

Galle, W.; de Temmerman, N.; Meyer, R.D. Integrating scenarios into life cycle assessment: Understanding the value and financial feasibility of a demountable building. Buildings 2017, 7, 64.

Gálvez-Martos, J.-L., Styles, D., Schoenberger, H., Zeschmar-Lahl, B., 2018. Construction and demolition waste best management practice in Europe. Resources, Conservation and Recycling. 136, 166-178. https://doi.org/10.1016/j.resconrec.2018.04.016.

Gan, V.J.L., Chan, C.M., Tse, K.T., Lo, I.M.C., Cheng, J.C.P., 2017a. A comparative analysis of embodied carbon in high-rise buildings regarding different design parameters. Journal of Cleaner Production. 161, 663-675. 10.1016/j.jclepro.2017.05.156.

Gan, V.J.L., Cheng, J.C.P., Lo, I.M.C., 2019. A comprehensive approach to mitigation of embodied carbon in reinforced concrete buildings. Journal of Cleaner Production. 229, 582-597. 10.1016/j.jclepro.2019.05.035.

Gan, V.J.L., Cheng, J.C.P., Lo, I.M.C., Chan, C.M., 2017b. Developing a CO2-e accounting method for quantification and analysis of embodied carbon in high-rise buildings. Journal of Cleaner Production. 141, 825-836. 10.1016/j.jclepro.2016.09.126.

Gangolells, M., Casals, M., Forcada, N., Macarulla, M., 2014. Analysis of the implementation of effective waste management practices in construction projects and sites. Resources Conservation and Recycling. 93, 99-111. 10.1016/j.resconrec.2014.10.006.

Ganiron Jr, T. U. and M. Almarwae (2014). "Prefabricated technology in a modular house." International Journal of Advanced Science and Technology 73: 51-74.

Gao, W., Ariyama, T., Ojima, T., Meier, A., 2001. Energy impacts of recycling disassembly material in residential buildings. Energy and Buildings. 33, 553-562. https://doi.org/10.1016/S0378-7788(00)00096-7.

Garcez, M.n.R., Abrahão Bernardo, R., Luis Gabriel Graupner de, G., 2018. The role of concrete compressive strength on the service life and life cycle of a RC structure: Case study. Journal of cleaner production. 172, 27-38. http://dx.doi.org/10.1016/j.jclepro.2017.10.153.

Gaustad, G., Krystofik, M., Bustamante, M., Badami, K., 2018. Circular economy strategies for mitigating critical material supply issues. Resources, Conservation and Recycling. 135, 24-33. https://doi.org/10.1016/j.resconrec.2017.08.002.

Gawer, A. and Cusumano, M.A. (2014) “Industry Platforms and Ecosystem Innovation”. Journal of Product Innovation Management, 31, 417-433.

GBCA, 2014. Materials Life cycle Impacts.

Georges, L., Haase, M., Wiberg, A.H., Kristjansdottir, T., Risholt, B., 2015. Life cycle emissions analysis of two nZEB concepts. Building Research and Information. 43, 82-93. 10.1080/09613218.2015.955755.

Ghayeb, H.H., Razak, H.A., Sulong, N.H.R., 2020. Evaluation of the CO2 emissions of an innovative composite precast concrete structure building frame. Journal of Cleaner Production. 242. 10.1016/j.jclepro.2019.118567.

Ghisellini, P., et al. (2018). "Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review." Journal of Cleaner Production 178: 618-643.

Ghisellini, P.; Cialani, C.; Ulgiati, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 2016, 114, 11–32.

Ghose, A., Pizzol, M., McLaren, S.J., 2017. Consequential LCA modelling of building refurbishment in New Zealand- an evaluation of resource and waste management scenarios. Journal of Cleaner Production. 165, 119-133. https://doi.org/10.1016/j.jclepro.2017.07.099.

Giard, V. and Midler, C. (Eds.) (1993), “Pilotages de projet et entreprises: diversités et convergences”, Economica, Paris.

Gibb, A.G. Off-Site Fabrication: Prefabrication, Pre-Assembly and Modularisation; John Wiley & Sons: Hoboken, NJ, USA, 1999.

Go, T.F.; Wahab, D.A.; Rahman, M.N.A.; Ramli, R.; Azhari, C.H. Disassemblability of end-of-life vehicle: A critical review of evaluation methods. J. Clean. Prod. 2011, 19, 1536–1546.

Goh, M., Goh, Y.M., 2019. Lean production theory-based simulation of modular construction processes. Automation in Construction. 101, 227-244. https://doi.org/10.1016/j.autcon.2018.12.017.

Gontia, P., Nägeli, C., Rosado, L., Kalmykova, Y., Österbring, M., 2018. Material-intensity database of residential buildings: A case-study of Sweden in the international context. Resources, Conservation and Recycling. 130, 228-239. https://doi.org/10.1016/j.resconrec.2017.11.022.

Gontia, P., Thuvander, L., Wallbaum, H., 2020. Spatiotemporal characteristics of residential material stocks and flows in urban, commuter, and rural settlements. Journal of Cleaner Production. 251, 119435. https://doi.org/10.1016/j.jclepro.2019.119435.

Gorgolewski, M., 2008. Designing with reused building components: some challenges. Building Research & Information. 36, 175-188. https://doi.org/10.1080/09613210701559499.

Gorgolewski, M., et al. (2008). "Designing buildings using reclaimed steel components." Journal of Green Building 3(3): 97-107.

Govindan, K., Soleimani, H., Kannan, D., 2015. Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. European Journal of Operational Research. 240, 603-626. https://doi.org/10.1016/j.ejor.2014.07.012.

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life Cycle Assessment: Past, Present, and Future. Environmental Science & Technology. 45, 90-96. 10.1021/es101316v.

Guo, H., Huang, H., Liu, Y., Meng, Y., Sun, C., Shao, Y., 2017. A Comparison of the Energy Saving and Carbon Reduction Performance between Reinforced Concrete and Cross-Laminated Timber Structures in Residential Buildings in the Severe Cold Region of China. Sustainability. 9. http://dx.doi.org/10.3390/su9081426.

Guy, B., Shell, S., Esherick, H., 2006. Design for deconstruction and materials reuse. Proceedings of the CIB Task Group. 39, 189-209.

Gwet, K.L., 2008. Computing inter-rater reliability and its variance in the presence of high agreement. British Journal of Mathematical and Statistical Psychology. 61, 29-48. 10.1348/000711006X126600.

H

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. Journal of Industrial Ecology. 19, 765-777. https://doi.org/10.1111/jiec.12244.

Häfliger, I.-F., John, V., Passer, A., Lasvaux, S., Hoxha, E., Saade, M.R.M., Habert, G., 2017. Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials. Journal of Cleaner Production. 156, 805-816. https://doi.org/10.1016/j.jclepro.2017.04.052.

Håkansson H and Johanson J, 1992, "A Model of Industrial Networks", in B Axelsson and G Easton, (eds), Industrial Networks: A New View of Reality, London, Routledge, 28-34

Håkansson H., Waluszewski A. (2007), "Knowledge and Innovation in Business and Industry: The importance of using others", Routledge.

Håkansson, H. (Ed.). (1987). "Industrial technological development. A network approach". London Croom Helm.

Håkansson, H., & Snehota, I. (1995). "Developing relationships in business networks". London Routledge.

Halinen, Aino & Törnroos, Jan-Åke, 1998. "The role of embeddedness in the evolution of business networks," Scandinavian Journal of Management, 14(3), pages 187-205, March.

Hansen, P., Liu, X., Morrison, G.M., 2019. Agent-based modelling and socio-technical energy transitions: A systematic literature review. Energy Research & Social Science. 49, 41-52. https://doi.org/10.1016/j.erss.2018.10.021.

Harrison, D., & Easton, G. (2005). "Patterns of actor response to environmental change". Journal of Business Research, 55, 545–552.

Harrison, D., & Prenkert, F. (2009). "Network strategising trajectories within a planned strategy process". Industrial Marketing Management, 38(6), 662–670.

Hartley, K., van Santen, R., Kirchherr, J., 2020. Policies for transitioning towards a circular economy: Expectations from the European Union (EU). Resources, Conservation and Recycling. 155, 104634. https://doi.org/10.1016/j.resconrec.2019.104634.

Hasibul, I.M., Gustav, B., Malin, T., 2018. Adoption of lean philosophy in car dismantling companies in Sweden-a case study. Procedia Manufacturing. 25, 620-627. https://doi.org/10.1016/j.promfg.2018.06.093.

Hassan, O.A., Öberg, F., Gezelius, E., 2019. Cross-laminated timber flooring and concrete slab flooring: A comparative study of structural design, economic and environmental consequences. Journal of Building Engineering. 100881. https://doi.org/10.1016/j.jobe.2019.100881.

Hay, R., Ostertag, C.P., 2018. Life cycle assessment (LCA) of double-skin façade (DSF) system with fiber-reinforced concrete for sustainable and energy-efficient buildings in the tropics. Building and Environment. 142, 327-341. https://doi.org/10.1016/j.buildenv.2018.06.024.

Heikkinen, M. T., Mainela, T., Still, J., & Tähtinen, J. (2007). "Roles for managing in mobile service development nets". Industrial Marketing Management, 36(7), 909–925.

Heravi, G., Rostami, M., Kebria, M.F., 2020. Energy consumption and carbon emissions assessment of integrated production and erection of buildings' pre-fabricated steel frames using lean techniques. Journal of Cleaner Production. 253, 120045. https://doi.org/10.1016/j.jclepro.2020.120045.

Herrera, N. R. (2017). "The emergence of Living Lab methods". In Living Labs (pp. 9-22): Springer.

Hirschl, B.; Konrad, W.; Scholl, G. New concepts in product use for sustainable consumption. J. Clean. Prod. 2003, 11, 873–881.

Hölzle, I., 2019. Contaminant patterns in soils from landfill mining. Waste Management. 83, 151-160. https://doi.org/10.1016/j.wasman.2018.11.013.

Honic, M., Kovacic, I., Rechberger, H., 2019. Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study. Journal of Cleaner Production. 217, 787-797. https://doi.org/10.1016/j.jclepro.2019.01.212.

Höök, M.; Stehn, L. Applicability of lean principles and practices in industrialized housing production. Constr. Manag. Econ. 2008, 26, 1091–1100.

Hopkinson, P.C., H-M.; Zhou, K.; Wang, Y.; Lam, D., 2018. Recovery and reuse of structural products from end-of-life buildings. Proceedings of the Institution of Civil Engineers. 172, 119-128. http://dx.doi.org/18.00007.

Hossain, M., Leminen, S., & Westerlund, M. (2019). "A systematic review of living lab literature". Journal of Cleaner Production, 213, 976-988.

Hossain, M.U., 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. https://doi.org/10.1016/j.jclepro.2018.09.120.

Hossain, M.U., Poon, C.S., Lo, I.M.C., Cheng, J.C.P., 2016. Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. Resources, Conservation and Recycling. 109, 67-77. https://doi.org/10.1016/j.resconrec.2016.02.009.

Hosseini, M.R., Rameezdeen, R., Chileshe, N., Lehmann, S., 2015. Reverse logistics in the construction industry. Waste Management & Research. 33, 499-514. 10.1177/0734242X15584842.

Hoxha, E., Habert, G., Lasvaux, S., Chevalier, J., Le Roy, R., 2017. Influence of construction material uncertainties on residential building LCA reliability. Journal of Cleaner Production. 144, 33-47. https://doi.org/10.1016/j.jclepro.2016.12.068.

Hu, M., 2019. Building impact assessment—A combined life cycle assessment and multi-criteria decision analysis framework. Resources, Conservation and Recycling. 150, 104410. https://doi.org/10.1016/j.resconrec.2019.104410.

Huang, B. J., et al. (2018). "Construction and demolition waste management in China through the 3R principle." Resources Conservation and Recycling 129: 36-44.

I

Iddon, C.R., Firth, S.K., 2013. Embodied and operational energy for new-build housing: A case study of construction methods in the UK. Energy and Buildings. 67, 479-488. https://doi.org/10.1016/j.enbuild.2013.08.041.

Imbabi, M.S.; Carrigan, C.; McKenna, S. Trends and developments in green cement and concrete technology. Int. J. Sustain. Built Environ. 2012, 1, 194–216. [Green Version]

Intille, S. S. (2002). “Designing a home of the future”. IEEE pervasive computing, 1(2), 76-82.

Invidiata, A., Lavagna, M., Ghisi, E., 2018. Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. Building and Environment. 139, 58-68. https://doi.org/10.1016/j.buildenv.2018.04.041.

IOS, I.O.f.S., 2006. Environmental Management: Life Cycle Assessment; Principles and Framework. ISO.

J

Jackson, M.; Marra, F. Roman Stone Masonry: Volcanic Foundations of the Ancient City. Am. J. Archaeol. 2006, 110, 403–436.

Jain, S., Singhal, S., Pandey, S., 2020. Environmental life cycle assessment of construction and demolition waste recycling: A case of urban India. Resources, Conservation and Recycling. 155, 104642. https://doi.org/10.1016/j.resconrec.2019.104642.

Jalkala, A., Cova, B., Salle, R., & Salminen, R. T. (2010). “Changing project business orientations: Towards a new logic of project marketing” European Management Journal, 28(2), 124–138

Jamieson, E., McLellan, B., van Riessen, A., Nikraz, H., 2015. Comparison of embodied energies of Ordinary Portland Cement with Bayer-derived geopolymer products. Journal of Cleaner Production. 99, 112-118. https://doi.org/10.1016/j.jclepro.2015.03.008.

Jia Wen, T., Chin Siong, H., Noor, Z.Z., 2015. Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia. Energy and Buildings. 93, 295-302. https://doi.org/10.1016/j.enbuild.2014.12.002.

Jiang, Y., et al. (2018). "Characteristics of steel slags and their use in cement and concrete—A review." Resources, Conservation and Recycling 136: 187-197.

Jimenez-Rivero, A. and J. Garcia-Navarro (2017). "Exploring factors influencing post-consumer gypsum recycling and landfilling in the European Union." Resources Conservation and Recycling 116: 116-123.

Jimenez-Rivero, A., Garcia-Navarro, J., 2017a. Best practices for the management of end-of-life gypsum in a circular economy. Journal of Cleaner Production. 167, 1335-1344. 10.1016/j.jclepro.2017.05.068.

Jin, R. Y., et al. (2017). "An empirical study of perceptions towards construction and demolition waste recycling and reuse in China." Resources Conservation and Recycling 126: 86-98.

Johnsen, T.E., Miemczyk, J. and Howard, M. (2017), “A systematic literature review of sustainable purchasing and supply research: theoretical perspectives and opportunities for IMP-based research”, Industrial Marketing Management, 61, pp. 130-143

Junak, J.; Sicakova, A. Effect of surface modifications of recycled concrete aggregate on concrete properties. Buildings 2017, 8, 2.

Junnila, S., Horvath, A., Guggemos, A.A., 2006. Life-cycle assessment of office buildings in Europe and the United States. Journal of Infrastructure systems. 12, 10-17. 10.1061/(ASCE)1076-0342(2006)12:1(10).

K

Kalmykova, Y., Sadagopan, M., Rosado, L., 2018. Circular economy – From review of theories and practices to development of implementation tools. Resources, Conservation and Recycling. 135, 190-201. https://doi.org/10.1016/j.resconrec.2017.10.034.

Kamali, M., Hewage, K., 2016. Life cycle performance of modular buildings: A critical review. Renewable and Sustainable Energy Reviews. 62, 1171-1183. https://doi.org/10.1016/j.rser.2016.05.031.

Karayannis, V.G., 2016. Development of extruded and fired bricks with steel industry byproduct towards circular economy. Journal of Building Engineering. 7, 382-387. 10.1016/j.jobe.2016.08.003.

Kensing, F., & Blomberg, J. (1998). "Participatory design: Issues and concerns". Computer Supported Cooperative Work, 7(3-4), 167-185.

Khan, K.S., Kunz, R., Kleijnen, J., Antes, G., 2003. Five steps to conducting a systematic review. Journal of the royal society of medicine. 96, 118-121.

Khasreen, M.M., Banfill, P.F.G., Menzies, G.F., 2009. Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. Sustainability. 1, 674-701. https://doi.org/10.3390/su1030674.

Kibert, C.J., Chini, A.R., Languell, J., 2000. Deconstruction as an essential component of sustainable construction, Proceedings of the second Southern African conference on sustainable development in the built environment, Pretoria. pp. 1-5.

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

Kirchherr, J., van Santen, R., 2019. Research on the circular economy: A critique of the field. Resources, Conservation and Recycling. 151, 104480. https://doi.org/10.1016/j.resconrec.2019.104480.

Knoeri, C.; Sanyé-Mengual, E.; Althaus, H.-J. Comparative LCA of recycled and conventional concrete for structural applications. Int. J. Life Cycle Assess. 2013, 18, 909–918.

Kofoworola, O.F., Gheewala, S.H., 2009. Life cycle energy assessment of a typical office building in Thailand. Energy and Buildings. 41, 1076-1083. https://doi.org/10.1016/j.enbuild.2009.06.002.

Krikke, H., Blanc, I.l., van de Velde, S., 2004. Product modularity and the design of closed-loop supply chains. California management review. 46, 23-39. 10.2307/41166208.

Kumanayake, R., Luo, H., Paulusz, N., 2018. Assessment of material related embodied carbon of an office building in Sri Lanka. Energy and Buildings. 166, 250-257. https://doi.org/10.1016/j.enbuild.2018.01.065.

Kupwade-Patil, K., De Wolf, C., Chin, S., Ochsendorf, J., Hajiah, A.E., Al-Mumin, A., Büyüköztürk, O., 2018. Impact of Embodied Energy on materials/buildings with partial replacement of ordinary Portland Cement (OPC) by natural Pozzolanic Volcanic Ash. Journal of Cleaner Production. 177, 547-554. https://doi.org/10.1016/j.jclepro.2017.12.234.

Kviselius, N.Z., Andersson, P., Ozan, H. and Edenius, M. (2009), “Living labs as tools for open innovation”, Communications & Strategies, 74 (2), pp. 75-94.

L

Laczko P., Hullova D., Needham A., Rossiter A-M., Battisti M. (2019) “The role of a central actor in increasing platform stickiness and stakeholder profitability: Bridging the gap between value creation and value capture in the sharing economy”. Industrial Marketing Management, 79, 214-230

Laczko P., Hullova D., Needham A., Rossiter A-M., Battisti M. (2019) “The role of a central actor in increasing platform stickiness and stakeholder profitability: Bridging the gap between value creation and value capture in the sharing economy”. Industrial Marketing Management, 79, 214-230

Lan, C.H. The design of multiple production lines under deadline constraint. Int. J. Prod. Econ. 2007, 106, 191–203.

Langerak, E. To shred or to disassemble? Recycling of plastics in mass consumer goods. In Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment, San Francisco, CA, USA, 5–7 May 1997; pp. 63–68.

Lawson, N., Douglas, I., Garvin, S., McGrath, C., Manning, D., Vetterlein, J., 2001. Recycling construction and demolition wastes–a UK perspective. Environmental Management and Health. 12, 146-157. 10.1108/09566160110389898.

Le, H.-B., Bui, Q.-B., 2020. Recycled aggregate concretes – A state-of-the-art from the microstructure to the structural performance. Construction and Building Materials. 257, 119522. https://doi.org/10.1016/j.conbuildmat.2020.119522.

Lederer, J., Trinkel, V., Fellner, J., 2017. Wide-scale utilization of MSWI fly ashes in cement production and its impact on average heavy metal contents in cements: The case of Austria. Waste Management. 60, 247-258. 10.1016/j.wasman.2016.10.022.

Lehtinen J., Aaltonen K., Rajala R. (2019) “Stakeholder management in complex product systems: Practices and rationales for engagement and disengagement”. Industrial Marketing Management, 79: 58-70

Leising, E., Quist, J., Bocken, N., 2018. Circular Economy in the building sector: Three cases and a collaboration tool. Journal of Cleaner Production. 176, 976-989. https://doi.org/10.1016/j.jclepro.2017.12.010.

Leminen, S., DeFillippi, R., & Westerlund, M. (2015). “Paradoxical tensions in living labs. In ISPIM Conference Proceedings (p. 1)”. The International Society for Professional Innovation Management (ISPIM).

Leminen, S., Nyström, A.-G., Westerlund, M., Kortelainen, M.J., 2016. The effect of network structure on radical innovation in living labs. Journal of Business & Industrial Marketing. doi.org/10.1108/JBIM-10-2012-0179.

Leminen, S., Westerlund, M., & Nyström, A.G. (2012). "Living Labs as Open-Innovation Networks". Technology Innovation Management Review, 2(9): 6-11.

Li, H., Deng, Q., Zhang, J., Xia, B., Skitmore, M., 2019. Assessing the life cycle CO2 emissions of reinforced concrete structures: Four cases from China. Journal of Cleaner Production. 210, 1496-1506. https://doi.org/10.1016/j.jclepro.2018.11.102.

Li, S., Altan, H., 2012. Environmental Impact Balance of Building Structures and Substitution Effect of Wood Structure in Taiwan. International Journal of Environmental Protection. 2, 1. 10.5963/IJEP0201001.

Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. Journal of cleaner production. 115, 36-51. https://doi.org/10.1016/j.jclepro.2015.12.042.

Lin, Y.-K., Chang, P.-C., Chen, J.C., 2012. Reliability evaluation for a waste-reduction parallel-line manufacturing system. Journal of Cleaner Production. 35, 93-101. https://doi.org/10.1016/j.jclepro.2012.05.023.

Lind F. (2015). “Goal diversity and resource development in an interorganisational project”. Journal of business and industrial marketing 30(3/4):259-268

Linder, M., Boyer, R.H.W., Dahllöf, L., Vanacore, E., Hunka, A., 2020. Product-level inherent circularity and its relationship to environmental impact. Journal of Cleaner Production. 260, 121096. https://doi.org/10.1016/j.jclepro.2020.121096.

Littell, J.H., Corcoran, J., Pillai, V., 2008. Systematic reviews and meta-analysis. Oxford University Press.

Liu, Y., Guo, H., Sun, C., Chang, W.-S., 2016. Assessing Cross Laminated Timber (CLT) as an Alternative Material for Mid-Rise Residential Buildings in Cold Regions in China—A Life-Cycle Assessment Approach. Sustainability. 8. http://dx.doi.org/10.3390/su8101047.

Lonca, G., Muggéo, R., Imbeault-Tétreault, H., Bernard, S., Margni, M., 2018. Does material circularity rhyme with environmental efficiency? Case studies on used tires. Journal of Cleaner Production. 183, 424-435. https://doi.org/10.1016/j.jclepro.2018.02.108.

London, B., 1932. Ending the depression through planned obsolescence. Retrieved March. 25, 2016.

Lu, K., Jiang, X.Y., Tam, V.W.Y., Li, M.Y., Wang, H.Y., Xia, B., Chen, Q., 2019. Development of a Carbon Emissions Analysis Framework Using Building Information Modeling and Life Cycle Assessment for the Construction of Hospital Projects. Sustainability. 11. 10.3390/su11226274.

Lukacs, I., Björnfot, A., Tomasi, R., 2019. Strength and stiffness of cross-laminated timber (CLT) shear walls: State-of-the-art of analytical approaches. Engineering Structures. 178, 136-147. https://doi.org/10.1016/j.engstruct.2018.05.126.

M

Ma, J., Hipel, K.W., 2016. Exploring social dimensions of municipal solid waste management around the globe–A systematic literature review. Waste management. 56, 3-12. https://doi.org/10.1016/j.wasman.2016.06.041.

MacArthur, E., 2013. Towards the circular economy, economic and business rationale for an accelerated transition. Ellen MacArthur Foundation: Cowes, UK.

Machado, R.C., de Souza, H.A., Verissimo, G.D., 2018. Analysis of Guidelines and Identification of Characteristics Influencing the Deconstruction Potential of Buildings. Sustainability. 10. 10.3390/su10082604.

Mackova, D., Spisakova, M., Kozlovska, M., Svajlenka, J., 2016. Environmental Assessment of Buildings Constructed by Modern Methods of Construction. Applied Mechanics and Materials. 861, 601-608. http://dx.doi.org/10.4028/www.scientific.net/AMM.861.601.

Mainela T. and Ulkuniemi P. (2013). “Personal interaction and customer relationship management in project business”. Journal of Business and Industrial Marketing, 28 (2), 103-110

Mao, C.; Shen, Q.; Shen, L.; Tang, L. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. Energy Build. 2013, 66, 165–176. [Green Version]

Martín-Morales, M., Cuenca-Moyano, G.M., Valverde-Espinosa, I., Valverde-Palacios, I., 2017. Effect of recycled aggregate on physical-mechanical properties and durability of vibro-compacted dry-mixed concrete hollow blocks. Construction and Building Materials. 145, 303-310. https://doi.org/10.1016/j.conbuildmat.2017.04.013.

McDonough, W., Braungart, M., 2010. Cradle to cradle: Remaking the way we make things. North point press.

Mele, C. (2011), “Conflicts and value co-creation in project networks”, Industrial Marketing Management, 40 (8), pp. 1377-1385.

Melià, P., Ruggieri, G., Sabbadini, S., Dotelli, G., 2014. Environmental impacts of natural and conventional building materials: a case study on earth plasters. Journal of Cleaner Production. 80, 179-186. https://doi.org/10.1016/j.jclepro.2014.05.073.

Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. Journal of Cleaner Production. 178, 703-722. https://doi.org/10.1016/j.jclepro.2017.12.112.

Merrild, H.; Jensen, K.G.; Sommer, J. Building a Circular Future; GXN Innovation: Copenhagen, Denmark, 2016.

Mesa, J., González-Quiroga, A., Maury, H., 2020. Developing an indicator for material selection based on durability and environmental footprint: A Circular Economy perspective. Resources, Conservation and Recycling. 160, 104887. https://doi.org/10.1016/j.resconrec.2020.104887.

Meyer, C., 2009. The greening of the concrete industry. Cement and Concrete Composites. 31, 601-605. https://doi.org/10.1016/j.cemconcomp.2008.12.010.

Minunno, R., O’Grady, T., Morrison, G., Gruner, R., Colling, M., 2018. Strategies for applying the circular economy to prefabricated buildings. Buildings. 8, 125. https://doi.org/10.3390/buildings8090125.

Missonier, S., & Loufrani-Fedida, S. (2014). “Stakeholder analysis and engagement in projects: From stakeholder relational perspective to stakeholder relational ontology”. International Journal of Project Management, 32(7), 1108–1122

Mitrega, M., Forkmann, S., Zaefarian, G., & Henneberg, C. S. (2017). “Networking capability in supplier relationships and its impact on product innovation and firm performance”. International Journal of Operations & Production Management, 37(5), 577–606.

Moazzen, N., Karaguler, M.E., Ashrafian, T., 2019. Assessment of the Life Cycle Energy Efficiency of a Primary School Building in Turkey. Applied Mechanics and Materials. 887, 335-343. http://dx.doi.org/10.4028/www.scientific.net/AMM.887.335.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., The, P.G., 2009. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLOS Medicine. 6, e1000097. 10.1371/journal.pmed.1000097.

Mohr, J. J., & Spekman, R. (1994). “Characteristics of partnership success: Partnership attributes, communication behavior, and conflict resolution techniques”. Strategic Management Journal, 15(2), 135–152.

Mok, H.S.; Kim, H.J.; Moon, K.S. Disassemblability of mechanical parts in automobile for recycling. Comput. Ind. Eng. 1997, 33, 621–624.

Möller, K., & Rajala, A. (2007). “Rise of strategic nets—New modes of value creation”. Industrial Marketing Management, 36(7), 895–908

Möller, K., & Svahn, S. (2009). “How to influence the birth of new business fields—Network perspective”. Industrial Marketing Management, 38(4), 450–458.

Möller, K., Rajala, A., & Svahn, S. (2005). “Strategic business nets—their type and management”. Journal of Business Research, 58(9), 1274–1284.

Monahan, J., Powell, J.C., 2011. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. Energy and Buildings. 43, 179-188. https://doi.org/10.1016/j.enbuild.2010.09.005.

Morseletto, P., 2020. Targets for a circular economy. Resources, Conservation and Recycling. 153, 104553. https://doi.org/10.1016/j.resconrec.2019.104553.

Motuzienė, V., Rogoža, A., Lapinskienė, V., Vilutienė, T., 2016. Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: a case study. Journal of Cleaner Production. 112, 532-541. https://doi.org/10.1016/j.jclepro.2015.08.103.

Moyano, M., Camporeale, P.E., Cozar-Cozar, E., 2019. ENVIRONMENTAL IMPACT ASSESMENT APPLYING INDICATORS EMBEDDED INTO A SOCIAL HOUSING BIM MODEL. Revista Habitat Sustentable. 9, 79-93. 10.22320/07190700.2019.09.02.07.

Mulder, E., de Jong, T.P.R., Feenstra, L., 2007. Closed Cycle Construction: An integrated process for the separation and reuse of C&D waste. Waste Management. 27, 1408-1415. https://doi.org/10.1016/j.wasman.2007.03.013.

Mulder, I. 2012. "Living Labbing the Rotterdam Way: Co-Creation as an Enabler for Urban Innovation". Technology Innovation Management Review

Munaro, M.R., Tavares, S.F., 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, 121134. https://doi.org/10.1016/j.jclepro.2020.121134.

Musa, M.F., Yusof, M.R., Mohammad, M.F., Samsudin, N., 2016. Towards the adoption of modular construction and prefabrication in the construction environment: A case study in Malaysia. Journal of Engineering and Applied Sciences. 11, 8122-8131.

Myhre, M.; Mackillop, D.A. Rubber recycling. Rubber Chem. Technol. 2002, 75, 429–474.

N

Nakamura, S., Kondo, Y., 2018. Toward an integrated model of the circular economy: Dynamic waste input-output. Resources Conservation and Recycling. 139, 326-332. 10.1016/j.resconrec.2018.07.016.

Nambisan, S., Sawhney, M., 2011. Orchestration processes in network-centric innovation: Evidence from the field. Academy of management perspectives. 25, 40-57.

Nässén, J., Holmberg, J., Wadeskog, A., Nyman, M., 2007. Direct and indirect energy use and carbon emissions in the production phase of buildings: An input-output analysis. Energy. 32, 1593-1602. 10.1016/j.energy.2007.01.002.

NIAC (2009). "Critical Infrastructure Resilience Final Report and Recommendations by National Infrastructure Advisory Council ".

Nieto, M. J., & Santamaría, L. (2007). “The importance of diverse collaborative networks for the novelty of product innovation”. Technovation, 27(6–7), 367–377.

Nizam, R.S., Zhang, C., Tian, L., 2018. A BIM based tool for assessing embodied energy for buildings. Energy and Buildings. 170, 1-14. https://doi.org/10.1016/j.enbuild.2018.03.067.

Noguchi, T.; Tamura, M. Concrete design towards complete recycling. Struct. Concr. 2001, 2, 155–167.

Nordby, A. S., et al. (2009). "Criteria for salvageability: The reuse of bricks." Building Research and Information 37(1): 55-67.

Nunez-Cacho, P., et al. (2018). "What Gets Measured, Gets Done: Development of a Circular Economy Measurement Scale for Building Industry." Sustainability 10(7).

Nußholz, J.L.K., Nygaard Rasmussen, F., 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. https://doi.org/10.1016/j.resconrec.2018.10.036.

Nwodo, M.N., Anumba, C.J., 2019. A review of life cycle assessment of buildings using a systematic approach. Building and Environment. 162, 106290. https://doi.org/10.1016/j.buildenv.2019.106290.

Nyström, A. G., Leminen, S., Westerlund, M., & Kortelainen, M. (2014). "Actor roles and role patterns influencing innovation in living labs". Industrial Marketing Management, 43(3), 483-495.

O

Oguchi, M.; Tasaki, T.; Moriguchi, Y. Decomposition analysis of waste generation from stocks in a dynamic system: Factors in the generation of waste consumer durables. J. Ind. Ecol. 2010, 14, 627–640.

Oikonomou, N. D. (2005). "Recycled concrete aggregates." Cement and Concrete Composites 27(2): 315-318.

Omran, A.; Tagnit-Hamou, A. Performance of glass-powder concrete in field applications. Constr. Build. Mater. 2016, 109, 84–95.

P

Padilla-Rivera, A., Amor, B., Blanchet, P., 2018. Evaluating the Link between Low Carbon Reductions Strategies and Its Performance in the Context of Climate Change: A Carbon Footprint of a Wood-Frame Residential Building in Quebec, Canada. Sustainability. 10. 10.3390/su10082715.

Papanikolaou, I., Arena, N., Al-Tabbaa, A., 2019. Graphene nanoplatelet reinforced concrete for self-sensing structures – A lifecycle assessment perspective. Journal of Cleaner Production. 240. 10.1016/j.jclepro.2019.118202.

Pargana, N., Pinheiro, M.D., Silvestre, J.D., de Brito, J., 2014. Comparative environmental life cycle assessment of thermal insulation materials of buildings. Energy and Buildings. 82, 466-481. https://doi.org/10.1016/j.enbuild.2014.05.057.

Park, J.Y.; Chertow, M.R. Establishing and testing the "reuse potential" indicator for managing wastes as resources. J. Environ. Manag. 2014, 137, 45–53.

Parron-Rubio, M.E., Perez-Garcia, F., Gonzalez-Herrera, A., Rubio-Cintas, M.D., 2018. Concrete Properties Comparison When Substituting a 25% Cement with Slag from Different Provenances. Materials. 11. 10.3390/ma11061029.

Pauliuk, S., Wang, T., Müller, D.B., 2012. Moving toward the circular economy: The role of stocks in the Chinese steel cycle. Environmental Science and Technology. 46, 148-154. 10.1021/es201904c.

Paulsen, J.S., Sposto, R.M., 2013. A life cycle energy analysis of social housing in Brazil: Case study for the program "MY HOUSE MY LIFE". Energy and Buildings. 57, 95-102. https://doi.org/10.1016/j.enbuild.2012.11.014.

Pearce, D.W.; Turner, R.K. Economics of Natural Resources and the Environment; JHU Press: Baltimore, MD, USA, 1990.

Pei, S., Rammer, D., Popovski, M., Williamson, T., Line, P., van de Lindt, J.W., 2016. An overview of CLT research and implementation in North America. In: WCTE 2016, August 22-25, 2016 Vienna, Austria.

Peng, C., 2016. Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. Journal of cleaner production. 112, 453-465. http://dx.doi.org/10.1016/j.jclepro.2015.08.078.

Penteado, C.S.G.; Viviani De Carvalho, E.; Lintz, R.C.C. Reusing ceramic tile polishing waste in paving block manufacturing. J. Clean. Prod. 2016, 112, 514–520.

Perks H., Moxey S. (2011), "Market-facing innovation networks: How lead firms patition tasks, share resources and develop capabilities", Industrial Marketing Management, 40(8), pp. 1224–1237.

Perks, H., Kowalkowski, C., Witell, L., & Gustafsson, A. (2017). "Network orchestration for value platform development". Industrial Marketing Management, 67, 106–121.

Petrovic, B., Myhren, J.A., Zhang, X., Wallhagen, M., Eriksson, O., 2019. Life cycle assessment of a wooden single-family house in Sweden. Applied Energy. 251. 10.1016/j.apenergy.2019.05.056.

Pierobon, F., Huang, M., Simonen, K., Ganguly, I., 2019. Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest. Journal of Building Engineering. 26, 100862. https://doi.org/10.1016/j.jobe.2019.100862.

Pittau, F., Lumia, G., Heeren, N., Iannaccone, G., Habert, G., 2019. Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. Journal of Cleaner Production. 214, 365-376. https://doi.org/10.1016/j.jclepro.2018.12.304.

Pollard, S.J.T.; Fowler, G.D.; Sollars, C.J.; Perry, R. Low-cost adsorbents for waste and wastewater treatment: A review. Sci. Total. Environ. 1992, 116, 31–52.

Pomponi, F., Moncaster, A., 2017. Circular economy for the built environment: A research framework. Journal of Cleaner Production. 143, 710-718. https://doi.org/10.1016/j.jclepro.2016.12.055.

Power, D.; Gruner, R.L. Variable use of standards-based IOS enabling technologies in Australian SMEs: An examination of deliberate and emergent decision making processes. Eur. J. Inf. Syst. 2017, 26, 164–184.

Q

Qiangfeng, L., Weiqiong, Z., Gaoshang, W., Jinhua, C., Tao, D., Bojie, W., Liang, L., Qindong, Y., 2018. Material and value flows of iron in Chinese international trade from 2010 to 2016. Resources Policy. 59, 139-147. doi.org/10.1016/j.resourpol.2018.06.011.

R

Rahman, M.E., Muntohar, A.S., Pakrashi, V., Nagaratnam, B., Sujan, D., 2014. Self compacting concrete from uncontrolled burning of rice husk and blended fine aggregate. Materials & Design. 55, 410-415. https://doi.org/10.1016/j.matdes.2013.10.007.

Ramage, M.H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D.U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., Allwood, J., Dupree, P., Linden, P.F., Scherman, O., 2017. The wood from the trees: The use of timber in construction. Renewable and Sustainable Energy Reviews. 68, 333-359. https://doi.org/10.1016/j.rser.2016.09.107.

Ramos, C., Henneberg, S. C. and Naudé, P. (2012). “Understanding network picture complexity: An empirical analysis of contextual factors”, Industrial Marketing Management, 41 (6), pp. 951-972.

Rashid, A.F.A., Yusoff, S., 2015. A review of life cycle assessment method for building industry. Renewable & Sustainable Energy Reviews. 45, 244-248. http://dx.doi.org/10.1016/j.rser.2015.01.043.

Reap, J., Roman, F., Duncan, S., Bras, B., 2008. A survey of unresolved problems in life cycle assessment. The International Journal of Life Cycle Assessment. 13, 374. https://doi.org/10.1007/s11367-008-0009-9.

Rios, F.C., Chong, W.K., Grau, D., 2015. Design for Disassembly and Deconstruction - Challenges and Opportunities. Procedia Engineering. 118, 1296-1304. https://doi.org/10.1016/j.proeng.2015.08.485.

Ritter T., GemüNden H.G. (2003), "Network competence: Its impact on innovation success and its antecedents", Journal of Business Research, 56(9), pp. 745–755.

Ritvala, T., & Salmi, A. (2010). "Value-based network mobilization: A case study of modern environmental networkers". Industrial Marketing Management, 39(6), 898–907.

Robati, M., Daly, D., Kokogiannakis, G., 2019. A method of uncertainty analysis for whole-life embodied carbon emissions (CO2-e) of building materials of a net-zero energy building in Australia. Journal of cleaner production. 225, 541-553. http://dx.doi.org/10.1016/j.jclepro.2019.03.339.

Robertson, A.B., Lam, F.C.F., Cole, R.J., 2012. A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete. Buildings. 2, 245-270. 10.3390/buildings2030245.

Rodrigues, C. and F. Freire (2017). "Adaptive reuse of buildings: Eco-efficiency assessment of retrofit strategies for alternative uses of an historic building." Journal of Cleaner Production 157: 94-105.

Roh, S., Tae, S., Kim, R., 2018. Analysis of Embodied Environmental Impacts of Korean Apartment Buildings Considering Major Building Materials. Sustainability. 10. 10.3390/su10061693.

Rosado, L., Hagy, S., Kalmykova, Y., Morrison, G., Ostermeyer, Y., 2015. A living lab co-creation environment exemplifying Factor 10 improvements in a city district. Journal of Urban Regeneration & Renewal. 8, 171-185.

Rose, C.M., Bergsagel, D., Dufresne, T., Unubreme, E., Lyu, T.Y., Duffour, P., Stegemann, J.A., 2018. Cross-Laminated Secondary Timber: Experimental Testing and Modelling the Effect of Defects and Reduced Feedstock Properties. Sustainability. 10. 10.3390/su10114118.

Rossi, B., Marique, A.F., Glaumann, M., Reiter, S., 2012. Life-cycle assessment of residential buildings in three different European locations, basic tool. Building and Environment. 51, 395-401. 10.1016/j.buildenv.2011.11.017.

Rust, R.T., 2019. Outside-in marketing: Why, when and how? Industrial Marketing Management.

S

Saade, M.R.M., Guest, G., Amor, B., 2020. Comparative whole building LCAs: How far are our expectations from the documented evidence? Building and Environment. 167, 106449. https://doi.org/10.1016/j.buildenv.2019.106449.

Sacks, R., Radosavljevic, M., Barak, R., 2010. Requirements for building information modeling based lean production management systems for construction. Automation in construction. 19, 641-655. doi.org/10.1016/j.autcon.2010.02.010.

Sagen Vildåsen S. and Ingemansson Havenvid M. (2018). "The role of interaction for corporate sustainability". IMP Journal, 12, 148-170

Saghafi, M.D., Teshnizi, Z.A.H., 2011. Building Deconstruction and Material Recovery in Iran: An Analysis of Major Determinants. Procedia Engineering. 21, 853-863. https://doi.org/10.1016/j.proeng.2011.11.2087.

Salama, T., Salah, A., Moselhi, O., Al-Hussein, M., 2017. Near optimum selection of module conFiguration for efficient modular construction. Automation in Construction. 83, 316-329. https://doi.org/10.1016/j.autcon.2017.03.008.

Salama, W., 2017. Design of concrete buildings for disassembly: An explorative review. International Journal of Sustainable Built Environment. 6, 617-635. https://doi.org/10.1016/j.ijsbe.2017.03.005.

Salazar, J., Meil, J., 2009. Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. Journal of Cleaner Production. 17, 1563-1571. 10.1016/j.jclepro.2009.06.006.

Sanchez, B., Haas, C., 2018. A novel selective disassembly sequence planning method for adaptive reuse of buildings. Journal of Cleaner Production. 183, 998-1010. https://doi.org/10.1016/j.jclepro.2018.02.201.

Sanchez, B., Rausch, C., Haas, C., Saari, R., 2020. A selective disassembly multi-objective optimization approach for adaptive reuse of building components. Resources, Conservation and Recycling. 154, 104605. https://doi.org/10.1016/j.resconrec.2019.104605.

Sanchez, B.; Haas, C. Capital project planning for a circular economy. Constr. Manag. Econ. 2018, 36, 303–312.

Sarc, R., Curtis, A., Kandlbauer, L., Khodier, K., Lorber, K.E., Pomberger, R., 2019. Digitalisation and intelligent robotics in value chain of circular economy oriented waste management – A review. Waste Management. 95, 476-492. https://doi.org/10.1016/j.wasman.2019.06.035.

Sartori, T., Calmon, J.L., 2019. Analysis of the impacts of retrofit actions on the life cycle energy consumption of typical neighbourhood dwellings. Journal of Building Engineering. 21, 158-172. 10.1016/j.jobe.2018.10.009.

Scherrer-Rathje, M.; Boyle, T.A.; Deflorin, P. Lean, take two! Reflections from the second attempt at lean implementation. Bus. Horiz. 2009, 52, 79–88.

Scheuer, C., Keoleian, G.A., Reppe, P., 2003. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy and Buildings. 35, 1049-1064. https://doi.org/10.1016/S0378-7788(03)00066-5.

Schultmann, F., Sunke, N., 2007. Organisation of reverse logistics tasks in the construction industry. Portugal SB07: Sustainable Construction, Materials and Practices. 577-584.

Schulze, P. and N. A. Engineering (1996). Engineering Within Ecological Constraints, National Academies Press.

Schuurman D., Protic S (2018). "Living Labs versus Lean Startups: An Empirical Investigation". Technology Innovation Management Review, 8 (12), 7-16

Schuurman, D. (2015). "Bridging the Gap between Open and User Innovation? Exploring the Value of Living Labs as a Means to Structure User Contribution and Manage Distributed Innovation". Doctoral dissertation. Ghent University and Vrije Universiteit Brussel VUB.

Schuurman, D., De Marez, L., & Ballon, P. (2016). "The Impact of Living Lab Methodology on Open Innovation Contributions and Outcomes". Technology Innovation Management Review, 1(6): 7–16.

Schuurman, D., DeMoor, K., DeMarez, L., & Evens, T. (2011). "Living Lab research approach for mobile TV". Telematics and Informatics, 28, 271–282

Schuurman, D., Protic, S.M., 2018. Living Labs versus Lean Startups: An Empirical Investigation. Technology Innovation Management Review. 8.

Scott, K., Bakker, C., & Quist, J. (2012). "Designing change by living change". Design Studies, 33(3), 279-297

Sedláková, A., Vilčeková, S., Burák, D., Tomková, Ž., Moňoková, A., Doroudiani, S., 2020. Environmental impacts assessment for conversion of an old mill building into a modern apartment building through reconstruction. Building and Environment. 172, 106734. https://doi.org/10.1016/j.buildenv.2020.106734.

Senaratne, S., Lambrousis, G., Mirza, O., Tam, V.W.Y., Kang, W.-H., 2017. Recycled Concrete in Structural Applications for Sustainable Construction Practices in Australia. Procedia Engineering. 180, 751-758. https://doi.org/10.1016/j.proeng.2017.04.235.

Serrano, A.A.R., Alvarez, S.P., 2016. Life Cycle Assessment in Building: A Case Study on the Energy and Emissions Impact Related to the Choice of Housing Typologies and Construction Process in Spain. Sustainability. 8. 10.3390/su8030287.

Sharma, A., Saxena, A., Sethi, M., Shree, V., Varun, 2011b. Life cycle assessment of buildings: A review. Renewable and Sustainable Energy Reviews. 15, 871-875. https://doi.org/10.1016/j.rser.2010.09.008.

Shetty, M., 2005. Concrete technology. S. chand & company LTD. 420-453.

Shih, P.H.; Chang, J.E.; Lu, H.C.; Chiang, L.C. Reuse of heavy metal-containing sludges in cement production. Cem. Concr. Res. 2005, 35, 2110–2115.

Sicignano, E., Di Ruocco, G., Melella, R., 2019. Mitigation Strategies for Reduction of Embodied Energy and Carbon, in the Construction Systems of Contemporary Quality Architecture. Sustainability. 11. 10.3390/su11143806.

Siddaway, A.P., Taylor, P.J., Wood, A.M., Schulz, J., 2015. A meta-analysis of perceptions of defeat and entrapment in depression, anxiety problems, posttraumatic stress disorder, and suicidality. Journal of affective disorders. 184, 149-159. https://doi.org/10.1016/j.jad.2015.05.046.

Siddaway, A.P., Wood, A.M., Hedges, L.V., 2019. How to Do a Systematic Review: A Best Practice Guide for Conducting and Reporting Narrative Reviews, Meta-Analyses, and Meta-Syntheses. Annual Review of Psychology. 70, 747-770. 10.1146/annurev-psych-010418-102803.

Siddique, R.; Naik, T.R. Properties of concrete containing scrap-tire rubber—An overview. Waste Manag. 2004, 24, 563–569.

Sieffert, Y., et al. (2014). "Sustainable construction with repurposed materials in the context of a civil engineering-architecture collaboration." Journal of Cleaner Production 67: 125-138.

Sim, J., Sim, J., Park, C., 2016. The air emission assessment of a South Korean apartment building's life cycle, along with environmental impact. Building and Environment. 95, 104-115. 10.1016/j.buildenv.2015.09.008.

Singh, A., Berghorn, G., Joshi, S., Syal, M., 2010. Review of life-cycle assessment applications in building construction. Journal of Architectural Engineering. 17, 15-23. 10.1061/(ASCE)AE.1943-5568.0000026.

Singh, J., Ordoñez, I., 2016. Resource recovery from post-consumer waste: important lessons for the upcoming circular economy. Journal of Cleaner Production. 134, 342-353. https://doi.org/10.1016/j.jclepro.2015.12.020.

Snyder, H., 2019. Literature review as a research methodology: An overview and guidelines. Journal of Business Research. 104, 333-339. https://doi.org/10.1016/j.jbusres.2019.07.039.

Sodagar, B., Rai, D., Jones, B., Wihan, J., Fieldson, R., 2011. The carbon-reduction potential of straw-bale housing. Building Research and Information. 39, 51-65. 10.1080/09613218.2010.528187.

Solís-Guzmán, J., et al. (2009). "A Spanish model for quantification and management of construction waste." Waste Management 29(9): 2542-2548.

Sormunen, P., Kärki, T., 2019. Recycled construction and demolition waste as a possible source of materials for composite manufacturing. Journal of Building Engineering. 24, 100742. https://doi.org/10.1016/j.jobe.2019.100742.

Sovacool, B.K., Axsen, J., Sorrell, S., 2018. Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. Energy Research & Social Science. 45, 12-42. https://doi.org/10.1016/j.erss.2018.07.007.

Sparksman, G.; Groak, S.; Gibb, A.; Neale, R. Standardisation and pre-assembly: Adding value to construction projects. CIRIA Rep. 1999, 176.

Spinuzzi, C. (2005). “The methodology of participatory design”. Technical communication, 52(2), 163-174.

Sri Ravindrarajah, R.; Tam, C.T. Recycling concrete as fine aggregate in concrete. Int. J. Cem. Compos. Lightweight Concr. 1987, 9, 235–241.

Srisangeerthanan, S., Hashemi, M.J., Rajeev, P., Gad, E., Fernando, S., 2020. Review of performance requirements for inter-module connections in multi-story modular buildings. Journal of Building Engineering. 28, 101087. https://doi.org/10.1016/j.jobe.2019.101087.

Stahel, W.R., 1997. Some Thoughts on Sustainability, Insurability and Insurance. The Geneva Papers on Risk and Insurance - Issues and Practice. 22, 477-495. 10.1057/gpp.1997.33.

Stahel, W.R., 2016. The circular economy. Nature. 531, 435-438. 10.1038/531435a.

Steen, K. And van Bueren, E. (2017). "Urban Living Labs: A Living Lab Way of Working" Technological Innovation Management Review

Steinhilper, R.; Hieber, M. Remanufacturing-the key solution for transforming "downcycling" into "upcycling" of electronics. In Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment, Denver, CO, USA, 9 May 2001; pp. 161–166.

Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., 2013. Climate change 2013: The physical science basis. Cambridge University Press Cambridge.

Su, S., Li, X.D., Wang, T., Zhu, Y.M., 2016. A comparative study of environmental performance between CFST and RC columns under combinations of compression and bending. Journal of Cleaner Production. 137, 10-20. 10.1016/j.jclepro.2016.07.043.

Su, X., Zhang, X., 2016. A detailed analysis of the embodied energy and carbon emissions of steel-construction residential buildings in China. Energy and Buildings. 119, 323-330. https://doi.org/10.1016/j.enbuild.2016.03.070.

Suwaed, A.S.H., Karavasilis, T.L., 2020. Demountable steel-concrete composite beam with full-interaction and low degree of shear connection. Journal of Constructional Steel Research. 171, 106152. https://doi.org/10.1016/j.jcsr.2020.106152.

Svajlenka, J., Kozlovska, M., 2017. Modern method of construction based on wood in the context of sustainability. Civil Engineering and Environmental Systems. 34, 127-143. 10.1080/10286608.2017.1340458.

T

Tabsh, S.W.; Abdelfatah, A.S. Influence of recycled concrete aggregates on strength properties of concrete. Constr. Build. Mater. 2009, 23, 1163–1167.

Takano, A., Hughes, M., Winter, S., 2014. A multidisciplinary approach to sustainable building material selection: A case study in a Finnish context. Building and Environment. 82, 526-535. 10.1016/j.buildenv.2014.09.026.

Takano, A., Pal, S.K., Kuittinen, M., Alanne, K., Hughes, M., Winter, S., 2015. The effect of material selection on life cycle energy balance: A case study on a hypothetical building model in Finland. Building and Environment. 89, 192-202. https://doi.org/10.1016/j.buildenv.2015.03.001.

Tam, V.W.Y. Economic comparison of concrete recycling: A case study approach. Resour. Conserv. Recycl. 2008, 52, 821–828.

Tam, V.W.Y., Tam, C.M., 2006. A review on the viable technology for construction waste recycling. Resources, Conservation and Recycling. 47, 209-221. https://doi.org/10.1016/j.resconrec.2005.12.002.

Tatiya, A., et al. (2018). "Cost prediction model for building deconstruction in urban areas." Journal of Cleaner Production 195: 1572-1580.

Tavares, V., Lacerda, N., Freire, F., 2019. Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The "Moby" case study. Journal of Cleaner Production. 212, 1044-1053. 10.1016/j.jclepro.2018.12.028.

Teh, S.H., Wiedmann, T., Castel, A., de Burgh, J., 2017. Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. Journal of Cleaner Production. 152, 312-320. 10.1016/j.jclepro.2017.03.122.

Teixeira, E.R.; Mateus, R.; Camõesa, A.F.; Bragança, L.; Branco, F.G. Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material. J. Clean. Prod. 2016, 112, 2221–2230.

Thormark, C., 2002. A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. Building and Environment. 37, 429-435. https://doi.org/10.1016/S0360-1323(01)00033-6.

Thormark, C., 2006. The effect of material choice on the total energy need and recycling potential of a building. Building and Environment. 41, 1019-1026. https://doi.org/10.1016/j.buildenv.2005.04.026.

Tingley, D.D., Cooper, S., Cullen, J., 2017. Understanding and overcoming the barriers to structural steel reuse, a UK perspective. Journal of Cleaner Production. 148, 642-652. doi.org/10.1016/j.jclepro.2017.02.006.

Tingley, D.D., Davison, B., 2011. Design for deconstruction and material reuse. Proceedings of the institution of civil engineers-energy. 164, 195-204. doi.org/10.1680/ener.2011.164.4.195.

Tollefson, J., 2017. The wooden skyscrapers that could help to cool the planet. Nature News. 545, 280. doi:10.1038/545280a.

Toniolo, S., Mazzi, A., Pieretto, C., Scipioni, A., 2017. Allocation strategies in comparative life cycle assessment for recycling: Considerations from case studies. Resources, Conservation and Recycling. 117, 249-261. https://doi.org/10.1016/j.resconrec.2016.10.011.

Topalovic, M.N., Stankovic, M., Cirovic, G., Pamucar, D., 2018. Comparison of the Applied Measures on the Simulated Scenarios for the Sustainable Building Construction through Carbon Footprint EmissionsCase Study of Building Construction in Serbia. Sustainability. 10. 10.3390/su10124688.

Tranfield, D., Denyer, D., Smart, P., 2003. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. British journal of management. 14, 207-222. https://doi.org/10.1111/1467-8551.00375.

Truttmann, N.; Rechberger, H. Contribution to resource conservation by reuse of electrical and electronic household appliances. Resour. Conserv. Recycl. 2006, 48, 249–262.

Tsoumis, G., 1991. Science and technology of wood: structure, properties, utilization. Van Nostrand Reinhold New York.

Tulevech, S.M., Hage, D.J., Jorgensen, S.K., Guensler, C.L., Himmler, R., Gheewala, S.H., 2018. Life cycle assessment: a multi-scenario case study of a low-energy industrial building in Thailand. Energy and Buildings. 168, 191-200. https://doi.org/10.1016/j.enbuild.2018.03.011.

Tumminia, G., Guarino, F., Longo, S., Ferraro, M., Cellura, M., Antonucci, V., 2018. Life cycle energy performances and environmental impacts of a prefabricated building module. Renewable and Sustainable Energy Reviews. 92, 272-283. https://doi.org/10.1016/j.rser.2018.04.059.

U

Ünal, E., Shao, J., (2019). “A taxonomy of circular economy implementation strategies for manufacturing firms: analysis of 391 cradle-to-cradle products”. J. Clean.Prod. 212, 754e765

Urbinati, A., Chiaroni, D., Chiesa, V., 2017. Towards a new taxonomy of circular economy business models. Journal of Cleaner Production. 168, 487-498. https://doi.org/10.1016/j.jclepro.2017.09.047.

V

Vaaland, T.I., Håkansson, H., 2003. Exploring interorganizational conflict in complex projects. Industrial Marketing Management. 32, 127-138.

van den Berg, M., Voordijk, H., Adriaanse, A., 2020. Recovering building elements for reuse (or not) – Ethnographic insights into selective demolition practices. Journal of Cleaner Production. 256, 120332. https://doi.org/10.1016/j.jclepro.2020.120332.

Van den Berghe, K., Vos, M., 2019. Circular area design or circular area functioning? A discourse-institutional analysis of circular area developments in Amsterdam and Utrecht, The Netherlands. Sustainability (Switzerland). 11. 10.3390/su11184875.

Van Der Wiel, A.; Bossink, B.; Masurel, E. Reverse logistics for waste reduction in cradle-to-cradle-oriented firms: Waste management strategies in the Dutch metal industry. Int. J. Technol. Manag. 2012, 60, 96–113.

Van Erp, G.; Rogers, D. A highly sustainable fibre composite building panel. In Proceedings of the International Workshop on Fibre Composites in Civil Infrastructure–Past, Present and Future, Toowoomba, Queensland, Australia, 1–2 December 2008.

Varun, Sharma, A., Shree, V., Nautiyal, H., 2012. Life cycle environmental assessment of an educational building in Northern India: A case study. Sustainable Cities and Society. 4, 22-28. https://doi.org/10.1016/j.scs.2012.03.002.

Vecchio, F.J., Collins, M.P., 1986. The modified compression-field theory for reinforced concrete elements subjected to shear. ACI J. 83, 219-231.

Veeckman, C., Schuurman, D., Leminen, S., & Westerlund, M. (2013). “Linking living lab characteristics and their outcomes: Towards a conceptual framework”. Technology Innovation Management Review, 3(12).

Vefago, L. H. M. and J. Avellaneda (2013). "Recycling concepts and the index of recyclability for building materials." Resources, Conservation and Recycling 72: 127-135.

Venselaar, M., Gruis, V., & Verhoeven, F. (2015). “Implementing supply chain partnering in the construction industry: Work floor experiences within a Dutch housing association”. Journal of Purchasing and Supply Management, 21(1), 1-8.

Verbinnen, B., Billen, P., Van Caneghem, J., Vandecasteele, C., 2017. Recycling of MSWI Bottom Ash: A Review of Chemical Barriers, Engineering Applications and Treatment Technologies. Waste and Biomass Valorization. 8, 1453-1466. 10.1007/s12649-016-9704-0.

Verian, K. P., et al. (2018). "Properties of recycled concrete aggregate and their influence in new concrete production." Resources, Conservation and Recycling 133: 30-49.

Vieira, D.R., Calmon, J.L., Coelho, F.Z., 2016. Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review. Construction and Building Materials. 124, 656-666. https://doi.org/10.1016/j.conbuildmat.2016.07.125.

Visintin, P., Xie, T., Bennett, B., 2020. A large-scale life-cycle assessment of recycled aggregate concrete: The influence of functional unit, emissions allocation and carbon dioxide uptake. Journal of Cleaner Production. 248, 119243. https://doi.org/10.1016/j.jclepro.2019.119243.

W

Waluszewski, A., Baraldi, E. and Perna, A. (2017), "The role of policy in innovation", IMP Journal, 11 (1), pp. 51-71

Wang, E., Shen, Z., 2013. A hybrid Data Quality Indicator and statistical method for improving uncertainty analysis in LCA of complex system – application to the whole-building embodied energy analysis. Journal of Cleaner Production. 43, 166-173. https://doi.org/10.1016/j.jclepro.2012.12.010.

Wang, J., Yu, C., Pan, W., 2018. Life cycle energy of high-rise office buildings in Hong Kong. Energy and Buildings. 167, 152-164. https://doi.org/10.1016/j.enbuild.2018.02.038.

Wei, W., Larrey-Lassalle, P., Faure, T., Dumoulin, N., Roux, P., Mathias, J.-D., 2015. How to Conduct a Proper Sensitivity Analysis in Life Cycle Assessment: Taking into Account Correlations within LCI Data and Interactions within the LCA Calculation Model. Environmental Science & Technology. 49, 377-385. 10.1021/es502128k.

Westerlund, M., & Svahn, S. (2008). “A relationship value perspective of social capital in networks of software SMEs”. Industrial Marketing Management, 37(5), 492–501.

Westin, A.L., Kalmykova, Y., Rosado, L., Oliveira, F., Laurenti, R., Rydberg, T., 2019. Combining material flow analysis with life cycle assessment to identify environmental hotspots of urban consumption. Journal of Cleaner Production. 226, 526-539. https://doi.org/10.1016/j.jclepro.2019.04.036.

Wheaton, W.G. Designing for Disassembly in the Built Environment. Master’s Thesis, Univesrity of Washington, Seattle, WA, USA, 2017.

Winans, K., et al. (2017). "The history and current applications of the circular economy concept." Renewable and Sustainable Energy Reviews 68: 825-833.

Woods, L.; Bakshi, B.R. Reusable vs. disposable cups revisited: Guidance in life cycle comparisons addressing scenario, model, and parameter uncertainties for the US consumer. Int. J. Life Cycle Assess. 2014, 19, 931–940.

Wu, H.J.J., Yuan, Z.W.W., Zhang, L., Bi, J., 2012. Life cycle energy consumption and CO2 emission of an office building in China. International Journal of Life Cycle Assessment. 17, 105-118. 10.1007/s11367-011-0342-2.

Wu, S.-H. Use BIM and Prefabrication to Reduce Construction Waste. Master's Thesis, Univesrity of Washington, Seattle, WA, USA, March 2017.

X

Xiao, J., Wang, C., Ding, T., Akbarnezhad, A., 2018. A recycled aggregate concrete high-rise building: Structural performance and embodied carbon footprint. Journal of Cleaner Production. 199, 868-881. https://doi.org/10.1016/j.jclepro.2018.07.210.

Xiao, J., Wang, C., Ding, T., Akbarnezhad, A., 2018. A recycled aggregate concrete high-rise building: Structural performance and embodied carbon footprint. Journal of Cleaner Production. 199, 868-881. https://doi.org/10.1016/j.jclepro.2018.07.210.

Y

Yan, H., Shen, Q., Fan, L.C.H., Wang, Y., Zhang, L., 2010. Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. Building and Environment. 45, 949-955. https://doi.org/10.1016/j.buildenv.2009.09.014.

Yang, X.N., Hu, M.M., Wu, J.B., Zhao, B., 2018. Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China. Journal of Cleaner Production. 183, 729-743. 10.1016/j.jclepro.2018.02.070.

Yazdanbakhsh, A., Lagouin, M., 2019. The effect of geographic boundaries on the results of a regional life cycle assessment of using recycled aggregate in concrete. Resources, Conservation and Recycling. 143, 201-209. https://doi.org/10.1016/j.resconrec.2019.01.002.

Yellishetty, M., Mudd, G.M., 2014. Substance flow analysis of steel and long term sustainability of iron ore resources in Australia, Brazil, China and India. Journal of Cleaner Production. 84, 400-410. https://doi.org/10.1016/j.jclepro.2014.02.046.

Yellishetty, M., Mudd, G.M., Ranjith, P.G., 2011. The steel industry, abiotic resource depletion and life cycle assessment: a real or perceived issue? Journal of Cleaner Production. 19, 78-90. https://doi.org/10.1016/j.jclepro.2010.08.020.

Yellishetty, M.; Mudd, G.M.; Ranjith, P.G.; Tharumarajah, A. Environmental life-cycle comparisons of steel production and recycling: Sustainability issues, problems and prospects. Environ. Sci. Policy 2011, 14, 650–663.

Yin, R.K., 2011. Applications of case study research. sage.

Yu, D., Tan, H., Ruan, Y., 2011. A future bamboo-structure residential building prototype in China: Life cycle assessment of energy use and carbon emission. Energy and Buildings. 43, 2638-2646. https://doi.org/10.1016/j.enbuild.2011.06.013.

Yu, H.; Tweed, T.; Al-Hussein, M.; Nasseri, R. Development of lean model for house construction using value stream mapping. J. Constr. Eng. Manag. 2009, 135, 782–790.

Yuan, Z., Sun, C., Wang, Y., 2018. Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. Automation in Construction. 88, 13-22. https://doi.org/10.1016/j.autcon.2017.12.021.

Z

Zabalza Bribián, I., Valero Capilla, A., Aranda Usón, A., 2011. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and Environment. 46, 1133-1140. https://doi.org/10.1016/j.buildenv.2010.12.002.

Zaman, A.U., 2014. Identification of key assessment indicators of the zero waste management systems. Ecological Indicators. 36, 682-693. https://doi.org/10.1016/j.ecolind.2013.09.024.

Zaman, A.U., Arnott, J., McLntyre, K., Hannon, J., 2018. Resource Harvesting through a Systematic Deconstruction of the Residential House: A Case Study of the 'Whole House Reuse' Project in Christchurch, New Zealand. Sustainability. 10. 10.3390/su10103430.

Zhang, Y., Zheng, X., Zhang, H., Chen, G., Wang, X., 2016. Carbon emission analysis of a residential building in China through life cycle assessment. Frontiers of Environmental Science and Engineering. 10, 150-158. 10.1007/s11783-014-0684-7.

Zhao, Z., Courard, L., Groslambert, S., Jehin, T., LÉOnard, A., Xiao, J., 2020. Use of recycled concrete aggregates from precast block for the production of new building blocks: An industrial scale study.

Resources, Conservation and Recycling. 157, 104786. https://doi.org/10.1016/j.resconrec.2020.104786.

Zhijun, F., Nailing, Y., 2007. Putting a circular economy into practice in China. Sustainability Science. 2, 95-101. 10.1007/s11625-006-0018-1.

Zink, T., Geyer, R., 2017. Circular economy rebound. Journal of Industrial Ecology. 21, 593-602. https://doi.org/10.1111/jiec.12545.

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