Beyond Recycling:

Design for Disassembly, Reuse, and Circular Economy in the Built Environment

by

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ABSTRACT

Today, we use resources faster than they can be replaced. Construction consumes more resources than any other industry and has one of the largest waste streams. Resource consumption and waste generation are expected to grow as the global population increases. The circular economy (CE) is based on the concept of a closed-loop cycle (CLC) and proposes a solution that, in theory, can eliminate the environmental impacts caused by construction and demolition (C&D) waste and increase the efficiency of resources' use. In a CLC, building materials are reused, remanufactured, recycled, and reintegrated into other buildings (or into other sectors) without creating any waste.

Designing out waste is the core principle of the CE. Design for disassembly or design for deconstruction (DfD) is the practice of planning the future deconstruction of a building and the reuse of its materials. Concepts like DfD, CE, and product-service systems (PSS) can work together to promote CLC in the built environment. PSS are business models based on stewardship instead of ownership. CE combines DfD, PSS, materials' durability, and materials' reuse in multiple life cycles to promote a low-carbon, regenerative economy. CE prioritizes reuse over recycling. Dealing with resource scarcity demands us to think beyond the incremental changes from recycling waste; it demands an urgent, systemic, and radical change in the way we design, build, and procure construction materials.

This dissertation aims to answer three research questions: 1) How can researchers estimate the environmental benefits of reusing building components, 2) What variables are susceptible to affect the environmental impact assessment of reuse, and 3) What are the barriers and opportunities for DfD and materials' reuse in the current design practice in the United States.

The first part of this study investigated how different life cycle assessment (LCA) methods (i.e., hybrid LCA and process-based LCA), assumptions (e.g., reuse rates, transportation distances, number of reuses), and LCA timelines can affect the results of a closed-loop LCA. The second part of this study built on interviews with architects in the United States to understand why DfD is not part of the current design practice in the country.

I dedicate this dissertation to all women in architecture, engineering, and construction.

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1. MOTIVATION

The shift to a circular economy (CE) will be evolutionary (European Environment Agenct [EEA], 2016). Major global trends are proving that the linear economy model is not sustainable. These trends include resource scarcity, information technology, climate change, environmentally conscious consumers, and the increase of renting and sharing business models (Ellen MacArthur Foundation [EMF], 2013; McGlyn, 2015). There is overwhelming scientific evidence that the impacts of climate change are happening faster and stronger than expected (Steyer, 2017). On the other hand, the CE was defined as the ultimate low-carbon economy (Stahel, 2016). The ultimate goal of the CE is to generate more value and economic opportunity while designing out waste and using fewer resources that can be reused for a long time (EMF, 2013). By increasing the share of renewable resources, enhancing energy efficiency, and promoting products' durability and reuse, the CE can reduce greenhouse gas emissions by 70% (Wijkman & Skånberg, 2015).

Resource scarcity is a serious threat to all industries, but especially for the construction sector. Construction consumes 40% of the global resources (Pacheco-Torgal, 2014). According to McGlyn (2015), today we use resources 50% faster than they can be replaced, and the supply for certain metals (e.g., copper) will not be enough to meet the increasing demand. The author added that by 2030, half the world could face water scarcity. By 2020, global resource extraction will have grown by 26% over the 2010 levels. The population growth will lead to even more drastic increases in resource consumption. By 2050, the global population is projected to grow from the current 7.6 billion to 9 billion. At the same time, three billion people are expected to join the middle class, which will cause the largest and fastest demand for resources ever experienced in the world (EMF, 2013). Resource scarcity will lead to high and volatile material and energy prices, which can be mitigated by CE strategies such as product's reuse (EMF, 2013). Steel is another example of a resource that is expected to have larger demand than supply in the next years. By 2025, global steel demand is predicted to rise by more than 50% over the current levels (EMF, 2013). The demand for other natural resources, such as iron ore, is expected to increase by at least a third in the next decade (EMF, 2013). Steel scarcity and the volatility of its price pose a serious threat to the construction industry. As the population grows, the construction activities are expected to keep growing, and materials' demand is expected to double by 2050 (Pacheco-Torgal, 2014). China alone is growing at such a rate that the area taken by the country's residential and commercial buildings will increase the equivalent to one New York City every two years until 2030 (Pacheco-torgal & Labrincha, 2013). Consequently, we will need to find a way to increase resources' use efficiency from 4- to 10-fold in the next 30 years (Pacheco-Torgal, 2014).

Extending products' lifespan and allowing for their reuse is a powerful response to resource scarcity. Recycling products is not enough to prevent resource scarcity and should be done only when reuse or remanufacturing are not possible (Stahel, 2016). The CE is designed to promote products' reuse with the support of renting and sharing business models (Stahel, 2016), information technology, reverse logistics, and design for disassembly (EMF, 2013).

Besides being a response to resource scarcity, the CE also aims to "design out waste" (EMF, 2013). The construction industry has one of the largest waste streams on the planet (Zhao, Leeftink, & Rotter, 2010). The United States generates 160 million tons of construction and demolition (C&D) waste every year (Kibert, 2013). In 2000, 90% of the total C&D waste was generated by demolition activities (Chini, 2005).

The CE builds on the concept of closed-loop cycles (CLC), or cradle-to-cradle (C2C), which proposes a solution that, in theory, can eliminate the environmental impacts caused by C&D waste and increase the efficiency of resources' use (McDonough & Braungart 2002; Braungart et al., 2007). In a CLC, building materials are reused and recycled and reintegrated into other buildings (or into other sectors) without creating any waste (Sassi, 2008). For every unit of building material integrated into a CLC, another 16 units of building material have likely been conserved (Guy, 2013). Designing products to make them easy to dismantle in the future is the core of the CE (EMF, 2013). This design practice is known as design for disassembly (DfD). In the built environment, DfD is also called design for deconstruction and allows for the future disassembly (or deconstruction) of buildings and the reuse of building components.

Concepts like the DfD, CE, and product-service systems (PSS) can work together to promote CLC in the built environment. PSS are business models to support CE; they focus on leasing or sharing materials (instead of buying) to maximize resource efficiency. In the built environment, PSS can provide building owners and users with access to highly efficient, sustainable alternatives without the burden of ownership. In PSS models, the manufacturers are responsible for the maintenance of the products, which allows for reverse logistics (or take-back), repair, remanufacturing, and reuse. These business models, combined with CE and DfD, aim at extending the durability and reusability of products while being competitive and fulfilling user's needs (Goedkoop, Van Halen, Te Riele, & Rommens, 1999). PSS, CE, and DfD are proactive strategies to promote resource efficiency. Dealing with the problem of resource scarcity demands us to think beyond the incremental changes from recycling waste; it demands an urgent, systemic, and radical change in the way we design, build, and procure construction materials.

This change is already happening (EMF, 2013), but despite the strong case for a CE, the United States is falling behind. Europe currently leads research and practice in the field with the support of the European Union (Michelini, Moraes, Cunha, Costa, & Ometto, 2017). Also, there is a huge research gap in the construction industry, and not only in the United States. A study investigated the content of academic papers in Civil Engineering and construction that were published by Elsevier and ASCE journals from 2009 to 2013. Their conclusions were alarming: in 2,500 papers, only 10% were related to environmental concerns to some degree, despite the progressive environmental regulations in the European Union (Pacheco-torgal & Labrincha, 2013). According to the authors, the overwhelming evidence of resource scarcity means that the research in the construction sector must investigate resource efficiency solutions.

This dissertation aims to contribute to the emerging field of CE in the building environment and is focused on the context of the United States. This contribution was intended in two major areas: 1) assessing the environmental impact of reusing construction materials and 2) identifying empirically-based challenges and opportunities for DfD of buildings in the U.S.

The next chapter of this dissertation is a literature review of the core concepts mentioned above, followed by a review of the two methods used in this dissertation: life cycle assessment and grounded theory.

2. LITERATURE REVIEW

In this chapter, the fundamental concepts that guided this dissertation are presented, followed by a review of the two methods used for data analysis. The concepts are DfD, CE, and PSS, while the methods are life cycle assessment (LCA) and grounded theory.

Design for Disassembly and materials' reuse

Kibert (2013) argued that the concepts of deconstruction and DfD were mandatory to shift toward closed-loop materials. Deconstruction is the disassembly of a building with the objective of increasing the reuse and recycling rate of its materials. DfD, in turn, is the practice of easing deconstruction processes through planning and design. Conversely, poor design decisions can result in up to one-third of the C&D waste (Osmani et al., 2008). Figure 1 shows the concept of DfD in relation to the waste management hierarchy.

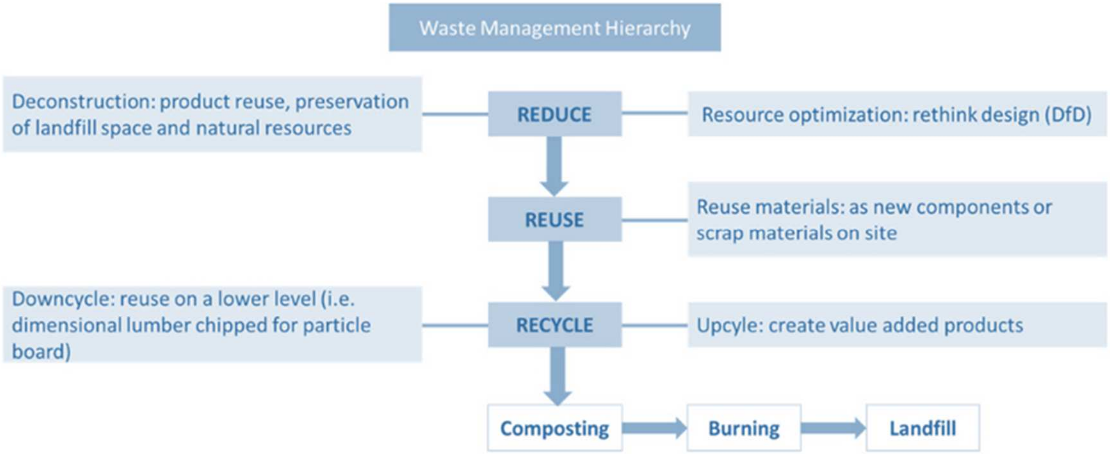

Figure 1. DfD and the waste management hierarchy. Adapted from: Kibert & Chini (2000)

As a form of C2C design, DfD can reduce the extraction of raw materials, the embodied energy, and carbon emissions of the construction industry (Chong & Hermreck, 2010;

Diyamandoglu & Fortuna, 2015; Environmental Protection Agency [EPA], 2008). A closed loop, similar to the C2C model, is an analogy to the biological metabolism present in nature, where "waste" is turned into "feed" (McDonough & Braungart, 2002). Also known as technical metabolism, this endless cycle turns the reused and recycled waste into "nutrients" (i.e., new materials or uses) for new buildings. Figure 2 shows how the materials flow into a cycle when reusing and recycling activities are implemented.

Besides reducing embodied energy and carbon in the construction sector, other environmental benefits of closed loops include reducing the extraction of raw materials and decreasing the cost of materials (if the supply chain is mature).

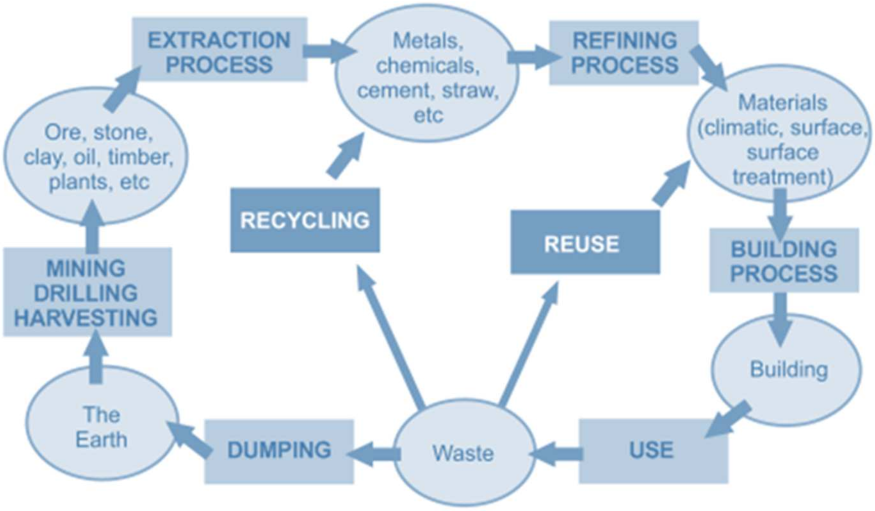

Figure 2. Closing the loop in the material life cycle. Adapted from: EPA (2008)

Key principles of DfD include: 1) proper documentation of materials and methods for deconstruction; 2) design of accessible connections to ease dismantling (e.g., minimizing chemical and welding connections; using bolted, screwed, and nailed connections; using prefabricated and/or modular structure); 3) separation of non-recyclable, non-reusable, and non-disposal items, such as mechanical, electrical, and plumbing (MEP) systems; 4) design of simple structure and forms that allow the standardization of components and dimensions; and 5) design that reflects labor practices, productivity, and safety (Guy & Ciarimboli, 2007).

Challenges in reusing building materials

Some of the challenges related to reusing building materials were addressed in past studies. For example, the uncertainty of the quantity and quality of used materials is quite a disincentive for buyers, due to varying quality and quantity from unreliable sources (Dolan, Lampo, & Dearborn, 1999; EPA, 2008; Kibert, Chini, & Languell, 2001). As DfD facilitates deconstruction and creates new market opportunities, the development of large storage yards can be a solution to ensure a more stable supply chain (EPA, 2008). There is also a lack of rules and standards to regulate the construction with salvaged materials (Kibert & Chini, 2000; Kibert et al., 2001), but the growth of DfD can directly impact the potential improvement of standards and regulations in this area. Through governments and public involvement, building codes and regulations would begin to address issues related to the reuse of building materials (National Association of Home Builders [NAHB], 2001).

One of the greatest challenges of reuse in the built environment is the low demand for salvaged materials (Nakajima, 2014). As designers start designing for disassembly and specifying the use of salvaged materials, the demand will naturally increase. Besides, a successful project inspires others and increases the overall demand for reuse (EPA 2008. Another issue is that the damage of materials on-site during deconstruction can make some components unusable (Nakajima, 2014). These damages can be caused by a lack of appropriate training in deconstruction techniques and/or by structures built without considering the deconstruction process. A detailed deconstruction plan can ease this process if combined with easily dismantlable joints (Webster, Gumpertz, Costello, & Co, 2005).

Finally, there is a challenge related to the consumer's taste—a common negative perception of salvaged materials. They are often perceived as being inferior in quality compared to virgin materials, both aesthetically and for safety reasons (EPA, 2008). The key to improving the overall perception of reused materials in the market is a growing number of successful case studies.

Why are we not there yet?

Although DfD sounds great in theory, very few architects have incorporated such strategies to their projects, and there are perhaps a few more than two dozen buildings that have actually been designed for disassembly. A sum of factors may be the cause of this implementation gap. Architects have little knowledge about DfD, owners have no liability for the buildings' end-of-life (EOL), most green building rating systems do not mention DfD, and planning for deconstruction may stretch the project's initial schedule and budget. On top of this, DfD guides and manuals list a set of design principles to be followed, and although some of them are feasible in today's practices (e.g., the use of modular and prefabricated building components), others involve major changes in the way construction stakeholders are used to doing things (e.g., providing standard and permanent identification of materials chemistry). Chapter 7 of this thesis aimed at interviewing architects in the United States to understand the reasons for the lack of DfD strategies in the current practice.

Another problem is a lack of emphasis on deconstruction practices in the academic field. Most research about environmental impacts caused by buildings focuses on the operational phase, that is, the building's use. That is because most of the environmental impacts related to the built environment were caused by the energy used for lighting and heating, ventilating, and air conditioning (HVAC) systems. In response to that, the construction sector developed highly energy-efficient building technologies, and today energy use during the operational phase is much lower than before. In fact, high-performance buildings have evolved so much over time that some studies have found that outside temperatures no longer have a significant impact on their energy consumption (Cruz Rios, Naganathan, Chong, Lee, & Alves, 2017; Mohareb, Kennedy, Harvey, & Pressnail, 2011). Lower energy consumption means that the pre-use and post-use phases of the building's lifecycle have a much larger relative importance than before (Junnila & Horvath, 2003; Kofoworola & Gheewala, 2009; Hoxha et al., 2017; Thormark, 2002); thus, the next opportunities for reducing environmental impacts are in the pre-use and post-use (EOL) phases. The pre-use and EOL are the phases of a building's life cycle that can benefit the most from DfD (as shown in Figure 3). A way to quantify the DfD benefits is to analyze the impacts of materials' reuse in the building's lifecycle. Chapters 5 and 6 of this dissertation are aimed at understanding how one can account for the potential benefits of reuse through life cycle assessment.

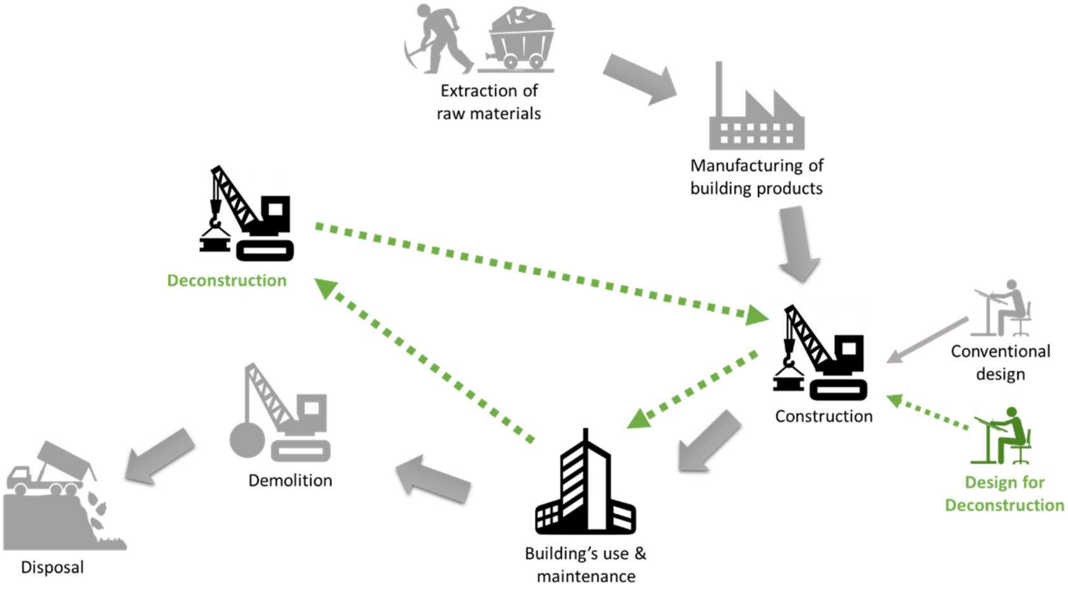

Figure 3. Design for disassembly in a building's lifecycle.

Life Cycle Assessment (LCA) is a methodology used to quantify the environmental impacts of a product or process throughout the product or process' life cycle. A building's or a building component's life cycle is everything that happens from the extraction of raw materials (e.g., logging, mining) to the waste management after demolition or deconstruction (Figure 3). Many of the building-related LCA studies were done to inform decision-making in the design process, and LCA is expected to become common practice in the Architecture, Construction, and Engineering (AEC) industry (Parrish & Chester, 2014). The methodology section of this dissertation (Chapter 4) discusses the current practice of LCA in the built environment and explains how the analyses in Chapters 5 and 6 were designed to contribute to this field.

The circular economy in the built environment

"The transition to a CE will be evolutionary" (EEA, 2016). The evolution has already started. The industry is facing increasing resource prices, strong competition from low-wage countries, and increasingly progressive environmental legislation (especially in Europe). As a response, companies are starting to explore circular business models and rethinking the way they design products (Bakker, Wang, Huisman, & den Hollander, 2014). The concept of the CE has many definitions in literature, but most of them are vague or ambiguous (Geissdoerfer, Savaget, Bocken, & Hultink, 2017; Kirchherr, Reike, & Hekkert, 2017; Korhonen, Honkasalo, & Seppälä, 2018). Geissdoerfer et al. (2017) attempted to conceptualize CE as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling." (Geissdoerfer et al., 2017). After analyzing 114 definitions of CE, Kirchherr et al. (2017) added that CE aims to accomplish sustainable development and is enabled by innovative business models and responsible consumers.

Several concepts from sustainability research have inspired the definition of CE. These include industrial ecology, cleaner production, product-service systems, cradle-to-cradle design, biomimicry, the resilience of socio-ecological systems, the performance economy, natural capitalism, and the concept of zero emissions—perhaps cradle-to-cradle and industrial ecology most of all (Korhonen et al., 2018). According to Korhonen et al. (2018), the main contributions of CE to existing literature were highlighting the importance of materials' durability and linking shared economy and sustainable production in a shift toward a more sustainable production-consumption culture.

The European Environment Agency (EEA, 2016) listed the following as key factors in enabling a CE: design for durability, remanufacture, reuse, extended producer responsibility (EPR), product-service systems, and education. The EMF (2013) claimed that one of the powers of a CE is the "power of circling longer," that is, maximizing products' durability so they can be reused in multiple consecutive cycles. Despite that, there is a research gap in addressing the effect of increasing the materials' durability as a CE strategy (Elia, Gnoni, & Tornese, 2017).

Figure 4 is an attempt to represent the various factors that, combined, would create the ideal conditions to promote a CE in the built environment. Besides the factors mentioned above, other top-down and bottom-up efforts are needed. Examples of top-down initiatives are offering market incentives for salvaged materials (as explored in Chapter 7), increasing landfill fees as a way to increase the financial benefits of waste diversion, implementing tax incentives to reduce carbon emissions from buildings, and promoting educational programs about the CE in the built environment through federal agencies. Examples of bottom-up initiatives are DfD, PSS (as explored in the next section), prefabrication and modularization (Chapter 7), advanced design technologies like Building Information Modeling (BIM) that allow for higher collaboration among stakeholders and the supply chain, and materials' tracking technologies (e.g., Ness et al., 2015).

In an article in *Nature*, the architect Walter R. Stahel defended that the CE would change economic logic by replacing production with sufficiency. "Reuse what you can, recycle what cannot be reused, repair what is broken, remanufacture what cannot be repaired (Stahel, 2016)," he wrote. According to Stahel, the CE is the ultimate low-carbon economy (Stahel, 2016). Indeed, a European study found that shifting to a CE could decrease greenhouse gas emissions by up to 70% and increase the workforce by about 4% (Wijkman & Skånberg, 2015). The authors combined three different key steps for achieving a CE: enhancing energy efficiency, increasing the percentage of renewable energy in the energy mix, and organizing manufacturing along the lines of a CE. The latter strategy involved a 25% overall increase in material efficiency, a substitution of 50% of virgin materials by reused materials, and a doubling of the lifespan of durable products (Wijkman & Skånberg, 2015). The results were compared to a linear economy of the same size of the potential CE for European countries.

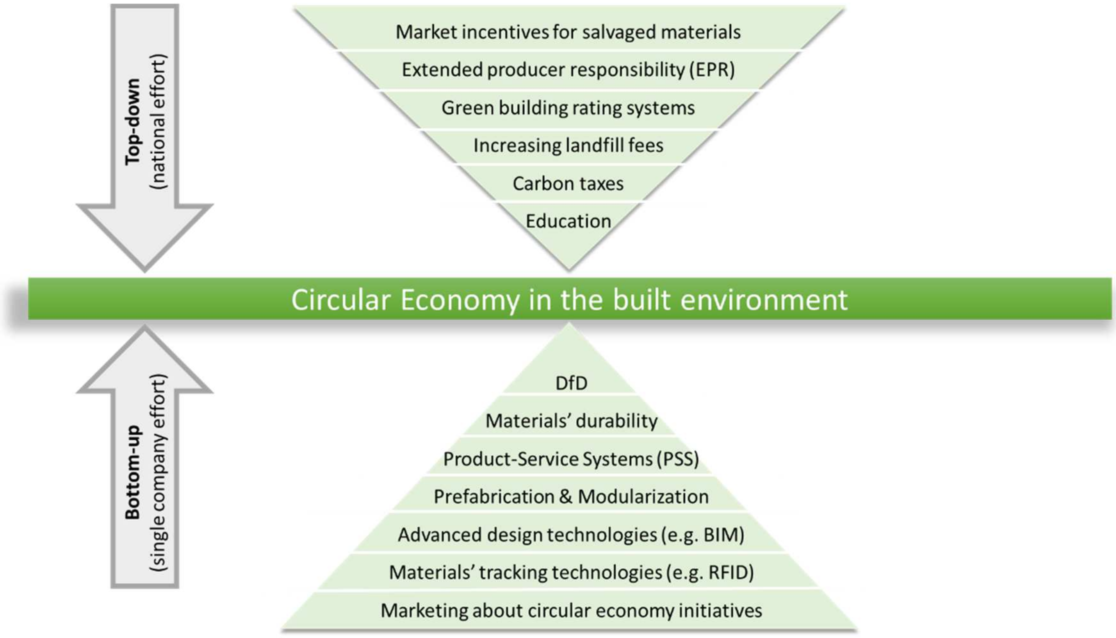

Figure 4. Factors involved in the implementation of CE in the built environment. Adapted from: Lieder & Rashid (2016).

Despite its importance, "CE is only rarely and fragmentary applied in practice" (Ritzén & Sandström, 2017). Ritzén and Sandström (2017) clarified that most of the literature in CE to date is conceptual and theoretical, and the barriers identified in past studies were rarely empirically based. Urbinati et al. (2017) reviewed existing CE efforts in 86 companies from various sectors and locations. Only five out of the 86 companies fell into the built environment sector. The authors found that the adoption of circular business models depended on the owners' commitment and not on external factors such as the size of the company, location, and market sectors (Urbinati et al., 2017).

In their famous publication titled "Towards Circular Economy," the EMF referred to the construction and demolition (C&D) waste as a noteworthy opportunity for CE. According to the Foundation, only 20 to 30% of all C&D waste is recycled or reused, often because buildings are not designed for disassembly and reuse, which results in a "significant loss of valuable materials for the system" (EMF, 2013). EMF highlighted the central role of design in the shift toward CE:

> At its core, a circular economy aims to 'design out' waste. Waste does not exist—products are designed and optimized for a cycle of disassembly and reuse. These tight component and product cycles define the circular economy and set it apart from disposal and even recycling where large amounts of embedded energy and labor are lost. (EMF, 2013)

According to Stahel (2016), designing products for reuse must become the norm, and modularization and prefabrication of components can help with that. Besides the lack of DfD acting as a barrier for CE, Stahel claimed that the lack of education about CE and the fear of the unknown have also been kept CE from moving forward. "As a holistic concept, [the CE] collides with the silo structures of academia, companies, and administrations (Stahel 2016)."

Another reason why CE has not gained traction yet is the vague definitions of CE and waste hierarchy. Kirchherr et al. (2017) found it concerning that only a third of the definitions of CE explained the waste hierarchy. For example, some authors "entirely equate CE with recycling." The authors explained that such definitions of CE are subverted because companies can conveniently adopt these definitions to claim that they have CE business models just by increasing recycling rates, for example. But a true CE demands a systemic change that is inherently disruptive of the status quo.

CE does not equal recycling. If anything, it argues that recycling should only be an alternative for what cannot be reused or remanufactured. Recycling is a reactive strategy to resource scarcity (Goldsworthy, 2013). The proactive strategy is to choose high quality, durable materials that can be reused for a long time in multiple life cycles and that can only be achieved if we intentionally design for reuse. But design is not enough; producer-centered take-back systems must substitute conventional waste management as the material collection system in place (J. Singh & Ordoñez, 2016). Also, rent, lease, and share business models (e.g., product-service systems) must substitute our linear economy models based on ownership and the right to destroy (EMF, 2013; Stahel, 2016). In a CE, the consumer becomes the user and a future supplier (EMF, 2013). Thus, the consumer is also considered an enabler of CE (Kirchherr et al., 2017).

Product-service systems: A business model for Circular Economy

In an economic context, the need for improving resource productivity led to the idea of "dematerialization," that is, the reduction of the material flows in production and consumption (Mont, 2002). A dematerialized economy is a service-oriented economy, where the consumer values the utilization of the product rather than the product per se. "Functional economy" is another term for a service-based economy, where the manufacturers focus on the provision and performance of services (Mont, 2002). For example, the consumer would buy mobility instead of cars; thus, the manufacturer would provide mobility services that might or might not be related to directly selling cars (e.g., carpooling or car sharing services). The objective of a functional economy is to "create the highest possible use value for the longest possible time while consuming as few material resources and energy as possible" (Mont, 2002).

A product-service system (PSS) was defined as “a marketable set of products and services capable of jointly fulfilling a user’s need” (Goedkoop et al., 1999). This idea became popular among researchers from the mid-1990s (Tukker, 2015) and is part of the concept of functional economy. Some authors have argued that PSS has the potential to enable a CE (e.g., Mont 2002; Tukker, 2015; Annarelli et al., 2016). In theory, a PSS is designed to be competitive, satisfy customers’ needs, and create less environmental impacts than a product-based business model. PSSs are expected to close material cycles, reduce consumption, and increase resource productivity (Mont, 2002). Also, in theory, it would bring benefits to manufacturers, such as adding value to the products and increasing their competitiveness in a global market, improving relationships with customers and customers’ loyalty (because the manufacturer and customer would be connected throughout the product’s and/or service’s life cycle), and giving manufacturers an early advantage by anticipating future take-back legislations (Mont, 2002). In a successful PSS, the extended involvement of the manufacturer throughout the product’s and/or service’s life cycle would allow not only for take-back and reuse practices but also refurbishment, remanufacturing, and products’ durability because of timely maintenance and repairs. The engineering field (especially from Europe and Asia) leads the crescent number of PSS publications in the last decade, followed by computer sciences, business, environmental science, and decision sciences (Tukker, 2015).

A PSS is divided into product-, use-, or result-oriented services (Tukker, 2004). A product-oriented service focuses on selling products with some services added, like maintenance, insurance, a take-back agreement, or consultancy for more efficient product use. This type of PSS is not expected to radically boost resource efficiency (Tukker, 2015). In a use-oriented service, the ownership remains with the provider. Examples are product leasing, renting, sharing, or pooling—where the resource use is less intensive and more efficient. Finally, in a result-oriented service, the client and the provider agree on a result that does not involve any predefined products (e.g., activity management, outsourcing, pay-per-service units).

Michelini et al. (2017) did a literature review on CE and PSS to find out if researchers agreed that PSS was a business model to increase resource-efficiency and support a CE. The authors found very few papers that linked PSS to CE and explained that this was a very recent topic in the literature. From the ten papers selected (50% of which were from engineering fields), the authors concluded that PSSs have real contributions to CE only when the customer pays for the provision of a service instead of the product's ownership. That way, when the service is over, the producer takes back the product and either leases it to another customer or uses its components to manufacture a different product that would offer another kind of service (Michelini et al., 2017).

At the time the PSS concept was created, there were three main uncertainties associated with the concept: 1) the readiness of companies to adopt PSS, 2) the readiness of customers to accept PSS, and 3) the environmental implications related to PSS (Mont, 2002). Although nowadays PSS is still difficult to design, implement, and bring to mainstream (Vezzoli et al. 2015), we do have new technology advances that can provide the structure required for PSSs to happen, such as the creation of new networks (e.g., research networks, information-sharing networks, and industrial symbiosis networks). Recent technologies such as Radio Frequency Identification (RFID), Internet of Things (IoT), Building Information Modeling (BIM), and big data analytics may have an important role in boosting PSS business models (and consequently CE). For example, Ness et al. (2015) proposed using RFID coupled with BIM to enable tracking and reuse of steel structural elements in buildings. The authors argued that this approach could create "a platform for the company to provide a 'steel service,' retaining ownership of the steel over its lifetime, licensing its use by customers in appropriate locations and circumstances, and providing it as part of a PSS, with some similarities to leasing and renting" (Ness et al., 2015). Thus, the authors described a potential for a use-oriented PSS.

However, one of the main challenges for PSS implementation remains the acceptance by the final user. The product's ownership is still an intangible value for many consumers, and so are things like sense of control, brand value, and ease of access. That is why PSSs are most accepted in communal societies, such as Scandinavia, the Netherlands, and Switzerland (Vezzoli et al., 2015), and/or in business-to-business (B2B) instead of business-to-client (B2C) models. When a PSS overcomes this acceptance barrier, however, it has the potential to create not only environmental and economical but also socio-ethical benefits. For instance, leasing high-quality, technically advanced products can ease the access of such options by low-income populations by cutting down initial costs (Vezzoli et al., 2015). For example, low-income customers can have access to renewable energy by leasing solar panels instead of buying them. They do not have the burden of the initial investment and can start having the benefits of the product right away. Because of such possibilities, authors started referring to PSSs as potentially (yet not inherently) sustainable models.

The relationship between PSS and environmental sustainability was discussed by Tukker (2004), but the term Sustainable Product Systems (S.PSS) was proposed by Vezzoli et al. (2015), as:

> an offer model providing an integrated mix of products and services that are together able to fulfil a particular customer demand (to deliver a 'unit of satisfaction'), based on innovative interactions between the stakeholders of the value production system (satisfaction system), where the economic and competitive interest of the providers continuously seeks environmentally and socio-ethically beneficial new solutions (Vezzoli et al., 2015).

The United Nations Environmental Programme (UNEP) added a chapter for PSS in its report *Design for Sustainability: A Step by Step Approach*, published in 2009 (Crul, M.R.M. et al., 2009).

Since 2006, some PSS case studies have been published. An example that addresses the built environment is the EU-funded project called Sustainable Product Development Network (SusProNet). SusProNet tested many PSS implementations, including some related to construction materials (the project was documented in Tukker & Tischner, 2006), like the service of recovering and reselling materials from demolition or energy conservation systems for existing homes. In the last one, the service provider paid the monthly energy bills of homeowners and supplied energy-saving building materials. The authors suggested other construction-related PSS ideas such as a result-oriented system in which the supplier would provide a “dry environment” to a house instead of selling a roof. The roof would be designed by the supplier, who would likely be responsible for maintenance and take-back services. The authors classified the implementation issues as related to internal, value-chain, partnership, technical, and institutional problems (e.g., legislation).

Major problems to PSS implementation, such as customer behavior and satisfaction, stakeholders’ cooperation and networks, and policy support, need yet to be deeper studied (Gelbmann & Hammerl, 2015; Vezzoli et al., 2015). Examples of policy actions that could boost PSS are indirect actions (e.g., carbon taxes, extender producer responsibility [EPR], eco-labeling) and direct actions (e.g., green public procurement focused on S.PSS, direct incentives to S.PSS models, support of S.PSS pilot projects) (Vezzoli et al., 2015). These actions can be local, regional, national, or international, and some of them are already being implemented in European countries. Plepys et al. (2015) reviewed ongoing policies in Europe, such as research and development (R&D) support, energy efficiency obligation schemes, waste, and transportation policies. The authors recommended further research that aims to understand the market conditions that allow for servicizing solutions, better policy designs, and policy packages to enable servicizing solutions to decouple economic growth and resources use.

Finally, since PSSs or S.PSSs are not inherently sustainable (Tukker, 2015; Vezzoli et al., 2015), it is important to study and quantify the environmental, social, and economic benefits of different case studies. One of the benefits is the reuse of components in a leasing system. For example, high-quality prefabricated building components can be leased to building owners (such as a university, commercial building, or multi-family apartment complex) over time. The fabricators would be responsible for the maintenance and repair of the building components. At the building's end of the life, during a renovation, or even during a change of the building's ownership, the fabricators would disassemble the building components and take them back for remanufacturing or reuse in other buildings. That way, PSS, reuse, and DfD can work together to promote a CE in the built environment.

Life Cycle Assessment in the building industry

To understand the full potential of reusing building materials, we must quantify the environmental benefits of reuse and, consequently, the environmental benefits of designing for disassembly and reuse. These benefits can be estimated through life cycle assessment (LCA). LCA estimates the environmental impacts of a product or process throughout its life cycle. A building's or a building component's life cycle is everything that happens from the extraction of raw materials (e.g., logging, mining) to the waste management after demolition or deconstruction. The LCA framework is described by the international standards for environmental management in ISO14040:2006 (International Organization for Standardization, 2006). The iterative framework is divided into four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

Life cycle assessment (LCA) methods have been used to assess the environmental impacts of products through their life in many industries, but its application in construction is recent (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014). Many of the building-related LCA studies had the goal to inform decision-making in the design process, and LCA is expected to become common practice in the construction industry (Parrish & Chester 2014).

There are two major groups of LCA in the built environment: whole building LCAs and LCAs that focus on comparing building materials or components. Whole building LCAs are the most recent application to the construction industry and aim to analyze the effect of the building structure and envelope in the energy performance of the building over time. Usually, whole building LCAs compare the designed building to a baseline construction or a reference building from the same market sector. They can also compare the effect of different choices of materials in the energy performance of the building over its lifespan. Whole building LCAs are done in the later stages of design and are mostly used for “documenting the consequences of already established choices” and in a lesser extent to compare different choices of materials (Ronning & Brekke, 2014) . The results of a whole building LCA are subject to the specific characteristics of the building under evaluation and the climate zone where it is located. Because of that, and because of inconsistencies in the methodology used for this type of LCA (e.g., system boundaries and timeline of the analysis), it is very hard to compare two different whole building LCAs (Ronning & Brekke, 2014).

Most research about buildings’ environmental impacts focuses on the operational phase, that is, the building’s use. That is because lighting systems and HVAC cause most of the environmental impacts. In response to that, the industry has developed highly energy efficient building technologies, and today the buildings’ energy use during the operational phase is much lower than it was. As a result, the pre-use (i.e., extraction and processing of raw materials) and post-use phases (i.e., waste management) of the building’s lifecycle have a much larger relative importance than before in the LCA (Junnila & Horvath, 2003; Kofoworola & Gheewala, 2009; Hoxha et al., 2017; Thormark, 2002). Thus, the next opportunities for reducing environmental impacts are in the pre-use and EOL phases.

Building's embodied energy in LCA

In the literature, there are different interpretations of what "embodied energy" means (Cabeza et al., 2013), that is, whether it includes the EOL phase, for example. In this dissertation, I refer to "embodied energy," "embodied carbon," or "embodied water" as the amount of energy/carbon dioxide emissions/water used by building materials during the extraction of raw materials, manufacturing, transportation, and waste management at the EOL.

LCAs to compare the embodied energy of building materials or components can be done to aid decision-making in earlier design stages. However, many studies that compare different building materials include the operational phase in the analysis. To do so, the LCA practitioners must use an existing building and/or specific geographical location (usually a city) as a reference. The downside of this approach is that the environmental impacts in the use phase depend on that specific building design and location. For example, Saiz et al. (2006) compared standard flat roofs and green roofs and used a specific residential building in Madrid as a functional unit. Regardless of which roof solution they concluded to be "greener," this information would not be very useful for a designer who wants to build a commercial building in Phoenix, Arizona. An alternative would be to divide the building-related LCAs into two phases. First, one would assess the embodied energy of construction materials and components (i.e., exclude the use phase from the LCA) and use this information to aid decision-making during early design. Second, during the latter design stages, the designers would perform a whole building LCA to assess the consequences of their decisions, combined with the local climate, in the building's performance over its life cycle.

For example, Souza et al. (2015) compared the embodied energy of different roof-covering materials (clay and concrete tile). The authors assumed that the energy use during the operational phase was the same for both materials and, thus, did not use a building as scope for their analysis. Because this type of study is related to the materials regardless of a building and a climate zone, it can be used to aid decision-making in early design stages. However, comparing building envelope materials is only possible if the materials under study have matching functionalities, like if the compared roof-covering materials are suitable for similar climate zones, roof slopes, and roof frames.

There is, though, very little research on embodied energy of construction materials, and the different studies and their data are not comparable among themselves (Cabeza et al., 2013). That happens because of differences in methodology (e.g., what life cycle phases to include), assumptions (e.g., transportation distances), and database (e.g., when and in what country the data was collected, what technology was used for processing materials, etc.). Consequently, the results of the embodied energy and carbon among materials vary greatly from study to study, and it is not possible to compare different studies yet. It is expected that as research in embodied energy and life cycle assessment advances, some of these inconsistencies can be eliminated and the studies become more comparable.

The embodied energy of the building's envelope

The building's envelope has the largest single contribution to the total embodied energy of a building (Cole & Kernan, 1996). Because of that, it is also the building's component that can benefit the most from deconstruction and reuse. Many authors compared the environmental impacts caused by different external walls' systems and materials (e.g., Bolin & Smith, 2011; Börjesson & Gustavsson, 2000; Cole & Kernan, 1996; Diyamandoglu & Fortuna, 2015; John et al., 2008; Johnson, 2006; Jonsson et al., 1998; Kahhat et al., 2009; Lenzen & Treloar, 2002;

Nässén et al., 2012; Sandin et al., 2014; Upton et al., 2008). Yet only a couple of these studies have considered the effects of reuse in the results (Börjesson & Gustavsson, 2000; Diyamandoglu & Fortuna, 2015). Jonsson et al. (1998) assumed reuse as a waste management scenario but did not factor the avoidance of raw materials that may result from reusing building components. Finally, only one of the latter studies was published in the United States (Diyamandoglu & Fortuna, 2015).

Building's end-of-life in LCA

Although some authors found the EOL phase to be negligible in building-related LCAs (e.g., Kahhat et al. 2009; Ochoa et al., 2002), others proved EOL to be significant (Sandin et al., 2014; Gustavsson et al., 2006; Börjesson & Gustavsson, 2000). An example of a study that integrates LCA, EOL, and closed-loop cycle (CLC) concepts in a building's context was performed by Coelho and De Brito (2012). The authors used LCA to analyze EOL alternative scenarios for a building's waste, including CLC options like reuse and recycling. They used data from real buildings and demolition contractors. Their results showed that the transportation energy used during the recycling process undermined the benefits of a partial, selective demolition followed by reuse and recycling. However, when the buildings were fully deconstructed for reuse and recycling, the impacts on climate change, acidification, and summer smog reduced significantly when compared to demolition and disposal of the materials in landfills.

Accounting for EOL scenarios in building-related LCAs is essential to understanding the potential environmental benefits of a closed-loop system with DfD and reuse. Reusing building materials is one of the most effective ways to reduce the embodied impacts in the built environment. Yet, most building-related LCAs fail to consider reuse among the waste management strategies and limit EOL scenarios to landfill and recycling. Chapters 5 and 6 of this dissertation describe attempts to perform cradle-to-cradle LCAs by integrating reusable building materials in multiple life cycles. The building components analyzed were part of the building's envelope: external wall framing (Chapter 5) and roof-covering materials (Chapter 5).

It is important to mention that despite its benefits, the LCA methodology has many inherent uncertainties; it depends on data quality and reliability, time and location of the study, assumptions, type of product under study (e.g., building type and materials use), processes to be included and excluded from the analyses, and methods (e.g., economic input-output, process-based, and hybrid methods) and tools used.

Despite its limitations, LCA seemed to be the most complete methodology to support CE assessments to date (Elia et al., 2017). Yet most of the studies that attempted to measure CE strategies created their own index to assess results, and only 19% used a well-known method such as LCA. Also, all studies failed in addressing the effect of increasing the materials' durability as a CE strategy (Elia et al., 2017).

Grounded Theory

The grounded theory method is appropriate when there is little prior knowledge on the area under investigation and when there is a need for new theoretical explanations built on empirical knowledge to explain what is happening in the field (Grbich, 2013). Both reasons are true in this study. There is little prior knowledge and a remarkable lack of practice of DfD in the AEC industry, and my goal was to understand *why*.

In this section, I explain the concepts of ontology and epistemology and their influences on the choice of methodology. Then, I discuss the differences between constructivist and positivist ontologies and justify my choice for a constructivist methodology. Finally, I clarify the differences between the objectivist grounded theory method and the constructivist grounded theory method. The data collection and analysis processes through grounded theory method are presented in Chapter 7.

A paradigm is a set of beliefs that define the researcher's worldview and guide her or his actions (Denzin & Lincoln, 1998). Every paradigm has its ontology, epistemology, and methodology. The ontology is how the researcher defines reality. What is the nature of such reality? Is there a "real" reality that we strive to apprehend? Or is reality relative, and therefore there are several realities constructed by our individual experiences? These are ontological questions. Epistemology is how we understand the relationship between the researcher and "what can be known." For example, if the researcher believes in a "real" reality, s/he must adopt an objectivist posture that is detached of her or his personal values or biases. Conversely, if the researcher believes that reality is constructed and situational, s/he must take into consideration her or his own values in order to understand how they help to shape a constructed reality. Finally, the methodology deals with how we can gain knowledge about the world. The choice of methodology depends on what the researcher's ontological and epistemological standpoints are. "The researcher cannot afford to be a stranger to the paradigms discussed. He or she must understand the basic ontological, epistemological, and methodological assumptions of each, and be able to engage them in dialogue (Guba, 1990)."

Historically, the positivist paradigm has dominated science. The emphasis on quantification as a condition for achieving scientific maturity has been central in the so-called "hard" sciences (Denzin & Lincoln, 1998). Positivists believe in a "real" reality and try to explain such reality by verifying a priori hypotheses that often can be converted into mathematical equations. Positivist research must have "rigor," objectivity, and allow for generalization. Positivist researchers deny the influence of their values in the analysis and present their work as a "disinterested scientist" willing to inform decision-makers (Guba & Lincoln, 1998). The positivist version of "theory" aims to explain and predict the relationship between variables (Charmaz, 2014). In recent years, critiques of the positivist paradigm have emerged in many fields (Guba & Lincoln, 1998). One of these critiques involved the "context stripping" inherent to positivism, that is, the exclusion of all the variables that are not included in the specific subset under analysis and the consequent exclusion of their effects on the results. Another critique was related to the fact that generalizations cannot be applied to individual cases. Guba and Lincoln (1998) exemplified the generalization problem: “The fact, say, that 80% of individuals presenting given symptoms have lung cancer is at best incomplete evidence that a particular patient presenting with such symptoms has lung cancer.” Qualitative data can help both the context stripping and the generalization problem (Guba & Lincoln, 1998). Other critiques, however, could not be overcome by merely applying qualitative analysis to positivist research. Instead, they questioned the fundamental assumptions behind the positivist paradigm and proposed alternative paradigms (such as constructivism). For example, the approach to hypothesis verification assumes that the hypothesis under analysis is independent, when it is now established that theories and facts are interdependent. Another example is the critique of the inquirer’s objectivity. In a positivist view, the researcher has no influence on the phenomena under study and vice versa. However, such assumption was debunked in the hard sciences by Heisenberg’s uncertainty principle and Bohr’s complementarity principle (Guba & Lincoln, 1998). These principles generated evidence that contradict the “realist ontology of positivism” and motivated scientists to rethink epistemology and methodology in research (Tuzeman, 2016).

Constructivism emerged as a response to the critiques of the positivist paradigm. Constructivist researchers believe that reality is relative; there are several and possibly contradicting social realities that are constructed by individuals and change over time according to their experiences. Therefore, the constructivist epistemology assumes that knowledge is created from the interaction among investigator and respondents (Guba & Lincoln, 1998). The aim of the constructivist research is to understand the several realities under study, rather than to explain or predict a “real,” universal reality. The researcher does not exclude her or his personal values and beliefs from the analysis but acknowledges their influence in the results. Constructivist research is not presented by a “disinterested” or impartial scientist; instead, it is presented with a passion (Guba & Lincoln, 1998). Maybe one of the most important differences between the positivist and constructivist approaches is the assessment of the study’s “goodness” or “quality.” Positivist research is judged by its generalizability, robustness, and objectivity. It should be obvious by now that such “measures of quality” are linked to a positivist ontology and epistemology. Thus, constructivist research cannot have its quality evaluated by the same standards. The issue of quality in constructivist research is still a topic of discussion in academia, and it can vary according to the method.

Overview of the method: objectivist and constructivist grounded theory

In the mid-1990s, positivist researchers questioned the reliability of qualitative methods. Qualitative research was seen as anecdotal and biased by many quantitative scientists and was used merely to refine quantitative methods such as surveys (Charmaz, 2014). In 1967, Barney Glaser and Anselm Strauss changed the course of qualitative research methods with the publication of *The Discovery of Grounded Theory*. Through their book, Glaser and Strauss proposed a systematic approach to qualitative inquiry. More importantly, they contradicted the positivist belief that qualitative research could not generate theory (Charmaz, 2014). The authors developed guidelines for qualitative analysis that fit the dominant positivist view, which helped grounded theory to gain recognition across scientific fields. However, grounded theory does not propose gathering data to verify a hypothesis. Instead, the theory emerges from the data, which makes the method particularly useful when there is “little or no prior knowledge of an area” (Grbich, 2013).

Glaser and Strauss’ grounded theory involved: simultaneous data collection and analysis; construction of analytic codes and categories from data; constant comparison between categories;

theory development in every stage of analysis; and memo-writing to create and define categories and the relationships between them (Charmaz, 2014).

The main critiques about Glaser and Strauss' grounded theory (or objectivist grounded theory) were driven by critiques to positivism's ontological and epistemological assumptions. That is, critics argued that grounded theory "fragmented the respondent's story, relied on the authoritative voice of the researcher, blurred difference, and uncritically accepted Enlightenment grand metanarratives about science, truth, universality, human nature, and worldviews" (Charmaz, 2014). In the same way that constructivist ontology and epistemology emerged as a response to such critiques, so did constructivist methodology, including the constructive grounded theory developed by Kathy Charmaz.

Objectivist grounded theorists believe in an objective approach to data analysis, see the researcher as neutral and passive, and aim to "achieve context-free generalizations" (Charmaz, 2014). Conversely, constructivist grounded theorists acknowledge subjectivities in the data analysis process, see the researcher—and her or his values and priorities—as active pieces in the data analysis puzzle. Constructivist grounded theory views generalization as partial and situational, that is, dependent on time, space, beliefs, and interactions among researcher and participants. It does not dismiss the social context from which the data comes, as does objectivist grounded theory. When it comes to establishing quality criteria, objectivist grounded theory aims to create "theory that fits, works, has relevance, and is modifiable." On the other hand, the constructivist approach for quality in grounded theory aims for "credibility, originality, resonance, and usefulness" (Charmaz, 2014).

Credibility is related to the ability to provide enough evidence for the researcher's claims so the reader can agree with such claims. According to Charmaz (2014), a credible grounded theory study makes systematic comparisons between categories and observations and builds a logical argument grounded in the data interpretation. Originality refers to how "fresh" the categories are, that is, whether they offer new insights into the field. An original grounded theory study challenges, extends, or refines current ideas and practices (Charmaz, 2014). Resonance, in turn, refers to whether the grounded theory makes sense to the participants and other people in the same situation (in the case of this research, architects in the United States). A study that has resonance offers the participants deeper insights about their situations. Finally, usefulness is linked to the contribution of the research in relation to the overall knowledge about the topic under study. A grounded theory study is useful when it provides "interpretations that people can use in their everyday worlds" (Charmaz, 2014) and when it motivates further research in related areas.

According to Charmaz (2014), the following are enough evidence for a grounded theory study:

1) simultaneous and iterative data collection and analysis;
2) analysis of actions rather than themes;
3) the use of comparative methods between categories and observations;
4) development of conceptual categories that draw on narratives and descriptions; and
5) development of "inductive abstract analytic categories through systematic data analysis."

There are many ways to engage in grounded theory through the steps listed above. Grounded theory researchers may use different versions of the method according to their fundamental assumptions, but Charmaz believes that they share much in common:

> *"We may have different standpoints and conceptual agendas yet we all begin with inductive logic, subject our data to rigorous comparative analysis, aim to develop theoretical analysis, and value grounded theory studies for informing policy and practice."* (Charmaz, 2014, p. 14)

3. OBJECTIVES AND SCOPE

This session introduces the research questions, objectives, and the scope of the analyses described in Chapters 5, 6, and 7.

Research questions and objectives

After an initial literature review about CE and DfD —presented in the Literature Review section of this dissertation—two problems became clear: 1) there is a lack of quantitative studies that aim to estimate the environmental benefits of reuse in the construction industry, and 2) DfD strategies are not part of the current design practice in the United States. These problems generated the three research questions this dissertation aims to answer:

1) How can researchers estimate the environmental impact of reusing building components?
2) What variables are likely to affect the environmental impact assessment of reuse?
3) Why do architects not design for disassembly in the United States?

Research questions 1 and 2 generated the following research objectives:

a. To investigate whether the use of different LCA methods can significantly alter the results of a cradle-to-cradle LCA (Chapter 5);
b. To explore how much variables such as transportation distances and reuse rates can affect the potential environmental benefits of reuse (Chapter 5);
c. To estimate the environmental benefits of specifying highly durable materials and integrating these materials in multiple life cycles (Chapter 6);
d. To understand how to frame the LCA methodology to inform early design as a complementary strategy to performing whole building LCAs (Chapter 6).

The third research question generated the following research objectives:

e. To identify challenges that have been keeping DfD from being implemented in the United States (Chapter 7);
f. To identify potential solutions for the barriers to DfD (Chapter 7).

Scope

The envelope has the largest share of a building's embodied impacts. Because of that, building envelope materials were used as the scope for the two LCAs in this research. External wall frame systems were investigated in Chapter 5, and roof-covering materials were studied in Chapter 6. In Chapter 5, a single-use wood frame was compared to a reusable steel frame. Because of steel and wood's different thermal properties, the insulation materials had to be included in the analysis. For example, steel needs continuous insulation because of its thermal bridge. Conversely, wood frames can be designed with cavity insulation. In Chapter 6, only the roof-covering materials were analyzed and compared (i.e., copper, zinc, asphalt shingles, aluminum, and steel cladding). Insulation materials were not included in the analysis since it was assumed that all roof-covering materials could be applied on the top of the same roofing system (e.g., one with layers of continuous insulation).

Chapter 7 describes the qualitative analysis that aimed to explain why architects do not adopt DfD strategies as part of their current practice in the U.S. As a scope, 13 architects from large design firms across the country were interviewed. The sample's demographic data is presented in Chapter 7. The interview script used in data collection can be found in Appendix D.

The methodology used to answer the research questions is described in the next section.

4. METHODOLOGY

This section presents the iterative research process from literature review to interpretation of results (Figure 5). An overview of the methods used in this research (i.e., life cycle assessment and grounded theory) were presented in Chapter 2.

Chapters 5 and 6 of this dissertation were designed to achieve the objectives *a* to *d* (see Chapter 4), while Chapter 7 aimed at objectives *e* and *f*. Chapters 5 and 6 describe quantitative analysis through cradle-to-cradle life cycle assessments (that is, considering a closed-loop through reuse in multiple life cycles), and Chapter 7 presents a qualitative analysis through grounded theory.

The literature in life cycle assessment in the built environment (Chapter 2) has shown a few research gaps in this developing field. First, most building-related LCAs used a building as the scope of the analysis and, therefore, were used to inform latter design stages. As a result, there is a lack of LCA studies that focus on the embodied energy of construction materials—separate from a building—that can be used to inform early design. Second, when we include the operational energy in the analysis, it becomes hard to compare two LCAs because of their different scope (e.g., different building types, different climate zones). Finally, there are various LCA studies that compared different building envelope materials, but—besides the differences in scope mentioned above—most of them fail to include reuse as a waste management scenario at the EOL.

The LCAs described in Chapters 5 and 6 aim at comparing the embodied impact of different building envelope materials. The analyses did not include the operational phase, and both chapters use LCA to assess potential environmental benefits of reuse. Chapter 5 investigates methodological choices when doing a cradle-to-cradle LCA, such as different LCA methods (e.g., hybrid LCA versus process-based LCA) and different variables (e.g., reuse rates, number of reuse, transportation distances). The differences between the methods and how they altered the LCA results are explained in Chapter 5.

Chapter 6 investigates how accounting for the durability and reusability of building materials can influence the LCA results. Highly durable materials were compared to less durable alternatives in three scenarios: 1) with no lifespan considered, 2) based on an average building's lifespan, and 3) based on the most durable materials' lifespan. Also, in Chapter 6, the materials are analyzed as products, that is, not attached to a building as the scope of the analysis. Thus, the results can inform early decision-making when the building's design is preliminary.

Chapter 7 uses constructivist grounded theory to explain why DfD is not part of the current design practices in the United States. Grounded theory is a useful method when there is little prior research about a subject (which is true for DfD). It is also useful when there is a need for new theoretical explanations built on empirical knowledge to explain changes in the field (Grbich, 2013). The literature review on DfD showed that, despite the challenges for the practice being theoretically explored in the past, there is a lack of empirically-based research to understand the state-of-the-art of DfD in the current design practice.

In Chapter 7, interviews with 13 architects from large design firms across the country were transcribed and coded following the constructivist grounded theory practices described in Chapter 2. The iterative process involved three stages of coding, simultaneous data collection and analysis, constant comparison, diagramming, and memo-writing through the data analysis. As a result, core categories were created to explore the lack of DfD in the current design. The core categories were listed and explained through writing and diagrams in Chapter 7. The relationship between the categories was discussed, and a detailed diagram of the grounded theory process was presented in Chapter 7.

Constructivist methodology in a positivist field

As explained in Chapter 2, paradigms are human constructions. They are built on a set of beliefs that are well-argued but impossible to prove as absolute truth and, therefore, “must be accepted simply on faith” (Guba & Lincoln, 1998). That said, advocates of either positivism or constructivism must rely on persuasiveness and utility rather than proof. The same is true of any constructivist analysis, including the one to be presented in this dissertation. The results from this analysis are inherently linked to the researcher’s worldview (that is, mine), and thus, I cannot force the reader to accept my interpretation as the absolute truth. What I can do is to be persuasive and “demonstrate the utility of my position”—as said by Guba & Lincoln (1998) —for the architects and the construction stakeholders in general.

As a field heavily grounded in the “hard” sciences, engineering research is overwhelmingly positivist. It does not help that scientists often treat positivist as “the scientific method,” when “positivism represents one rather than all ways of accomplishing scientific work” (Charmaz, 2014). Because positivism is taken for granted in this field, many construction engineering researchers go through their academic lives without ever understanding the fundamental assumptions behind the methodology they choose. I admit that it was not until my last year of doctorate studies that I understood why I felt uneasy when reading most of the positivist research. After learning about constructivism, it became clear to me that I must take a constructivist stance, even though I may anticipate criticism from the positivist engineering community. In Chapters 5 and 6 of this dissertation, I presented quantitative data analyses that were best fit to answer questions about the environmental impacts of disassembly and reuse of building materials. In Chapter 7 of this dissertation, I presented the results of a qualitative analysis that aimed to explore the reasons for the lack of DfD among architects. In both quantitative and qualitative analyses, I have committed to carefully documenting my process and assumptions and to be transparent about the study's limitations and alternative scenarios. With such effort, I hope to demonstrate my alignment to a constructivist way of thinking, analyzing, and interpreting data.

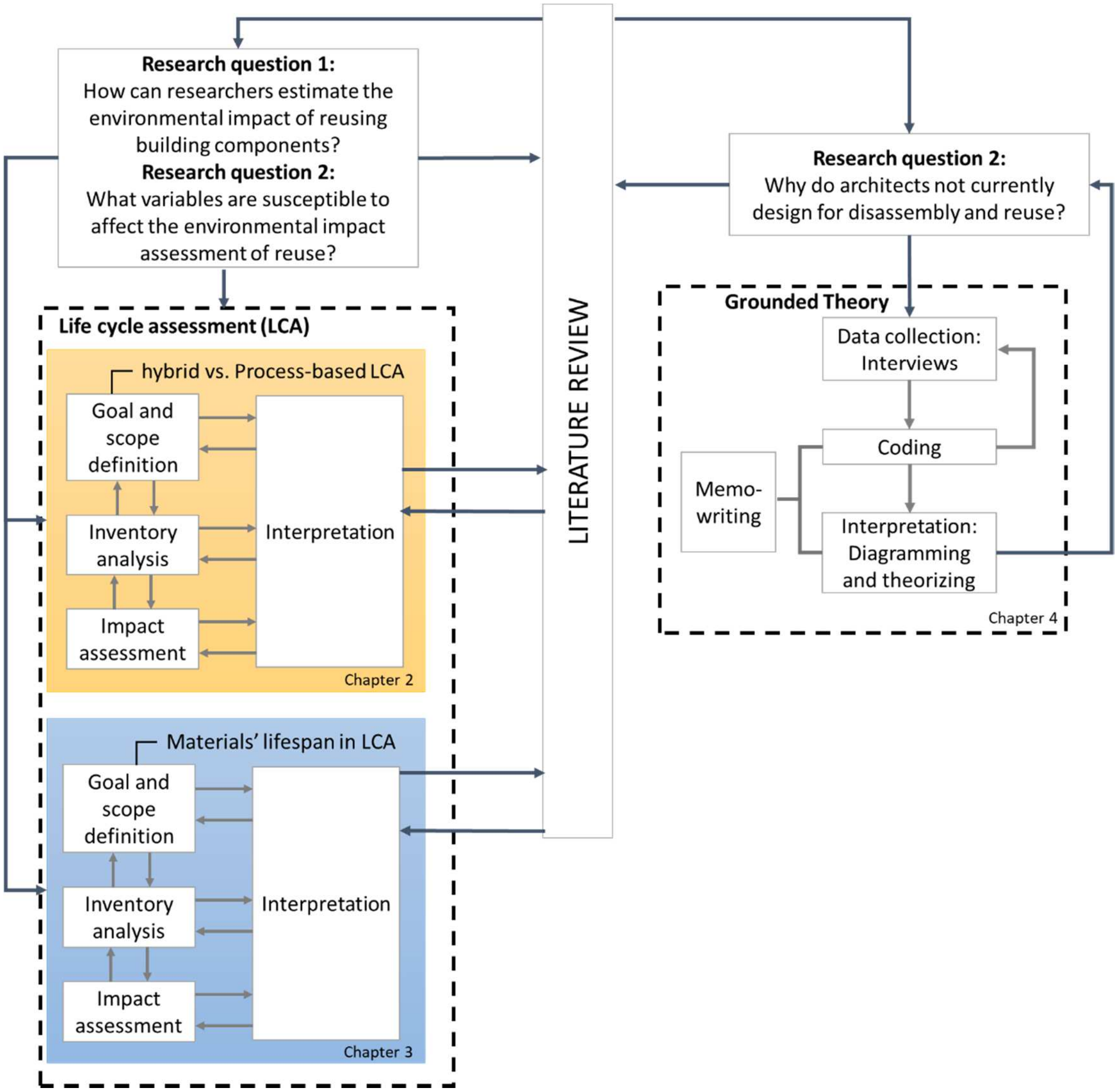

Figure 5. Research Methodology

5. HYBRID VERSUS PROCESS-BASED: HOW DIFFERENT METHODS AFFECT THE RESULTS OF A CRADLE-TO-CRADLE LCA

Goals and scope

This chapter aims to compare the results of a cradle-to-cradle LCA using two different methods: hybrid LCA and process-based LCA. Another objective of the analysis is to understand how the reuse rates and transportation distances from deconstruction to reuse site can affect the LCA results. As scope for this chapter, the embodied energy, embodied carbon, and embodied water of external wall frames for a tiny house in the U.S. were analyzed. A single-use wood-framed wall and a reusable steel-framed wall[1] were compared. The results of this comparison depended on assumptions (e.g., reuse rates, transportation distances) that were tested for uncertainty through different scenarios.

Figure 6 illustrates the baseline scenario used as the scope for the LCA. For each life cycle, a wood frame structure was manufactured and disposed of (incinerated with energy recovery) with no reuse, while a steel frame was reused (reuse rate = 90%) from one life cycle to another. Each time a steel frame was reused, a wood frame was demolished and rebuilt, and we avoid producing a new steel frame. Therefore, the total primary energy use, water use, and global warming potential correspond to three wood-framed houses and one steel-framed house. The steel

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[1] Although wood framing is more common than steel framing for residences in the U.S., both external wall framing types are largely used in the country. Wood-framed are more difficult to reuse (i.e., they need to be de-nailed and often re-graded) and, thus, are often treated as a single-use structure. On the other hand, I explored the reuse potential of steel framing studs because they have bolted connections that ease the deconstruction process. Although the baseline scenario assumes the wood-framed wall as a single-use component, I investigated an alternative scenario where the wood frame is reused.

frame house was reused from one life cycle to another at a reuse rate of 90%. In this scenario, the insulation materials were disposed in landfills at the end of each life cycle.

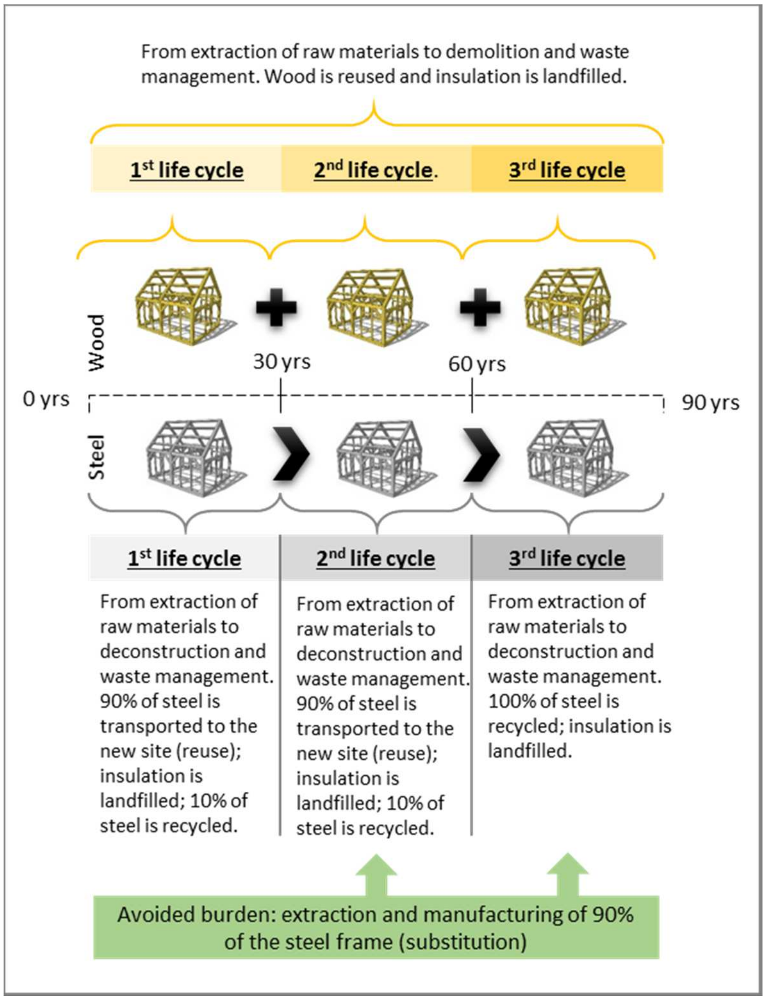

Figure 6. The scope of this analysis

This study was performed following the guidelines for LCA-recommended practices from the International Reference Life Cycle Data System (ILCD) Handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). The

ILCD guidelines incorporate the international standards for LCA (i.e., ISO:140040:2006) and add other best practices to be followed by LCA practitioners aiming for high-quality LCA studies.

Tiny houses

In this chapter, I used mostly U.S.-based data for studying the results of reusing a tiny house's external wall framing system. Tiny houses are residential units that range from 100–400sf (Vail, 2016). The concept of tiny houses was discussed in the late '80s (Walker, 1987) but became popular after the creation of tiny house owners' blogs and communities on social media and TV shows such as "Tiny House Nation" (2014). However, it is difficult to track how many tiny houses are built in the U.S. every year since many of them are built on trailers, mostly to avoid legal restrictions for small living spaces. Nonetheless, demand for tiny houses keeps on increasing at a significant rate by those who want a simple and low-cost lifestyle.

Tiny houses are the object of this study due to their significance for disassembly and reuse. The first reason is the lack of the owners' resistance to reuse; most of the tiny houses' owners are committed to sustainable living (Vail, 2016; Schenk, 2015) and are assumed to be more open to waste reduction strategies. Second, tiny houses are growing in popularity in the U.S. but they last less time than permanent houses. Therefore, their EOL demands more urgent strategies. Also, because their EOL is likely to happen sooner than the average house, there are fewer uncertainties about the future reuse of its materials. Third, tiny houses use much less electricity than the average house, so their embodied environmental impacts are much more relevant to their life cycle. Finally, a tiny house's structure is simple enough to make it an excellent candidate for deconstruction and reuse. In fact, it is a manual process that can be done by the owner and does not depend on deconstruction contractors or specific equipment (EPA, 2008).

Functional unit

The LCA functional unit is defined as follows: the area of external walls needed to enclose a single-family tiny house over its lifetime and with a thermal resistance equal to R-15. This functional unit is based on the main functions of an external wall structure: to encapsulate a certain house type (because the wall materials may vary according to the building type) and provide insulation (thermal comfort) over a period of time (durability).

The reference flow was 878 square feet (81.57m2)[2] of external wall framing system with thermal resistance R-15 over approximately 90 years. The exact time does not affect the results but serves as a reference for the reuse assumptions.

Impact categories

This study analyzed the global warming potential (GWP), primary energy use (nonrenewable energy, NRE + renewable energy, RE), and water use for the steel and wood framings. Alternatively, these can be called embodied carbon, embodied energy, and embodied water, respectively. These are common categories associated with building LCAs (e.g., Proietti et al., 2013; Zabalza et al., 2013) and, hence, are easily understandable by construction stakeholders (Anand & Amor, 2017).

Wood framing and steel framing specifications

The wood framing was designed with 2x4'' untreated wood studs (spaced 16 inches from each other's center) and fiberglass batt insulation. The steel framing was designed with 33mil cold-

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[2] Assuming a 24.5 ft (7.47m) long, 8 ft (2.44m) wide, and 13.5 ft (4.12m) tall tiny house, common dimensions for tiny houses built on trailers.

formed steel studs spaced 24 inches from each other's center. Wood-framed houses are commonly insulated with fiberglass as a cavity insulation (between wood studs), while steel framed houses normally use a continuous insulation (applied to the external face of the studs), such as polyisocyanurate rigid foam. Both insulation materials can grant an R-value of 15 with 3.5 inches of fiberglass batt insulation[3] for the wood frame and 2 inches of polyiso insulation[4] for the steel frame.

LCA methods

This chapter describes an attributional LCA. In this context, I compared two LCA methods: a process-based LCA and a hybrid approach. In the hybrid approach, I used the Economic Input-Output Life Cycle Assessment (EIO-LCA) developed by the Carnegie Mellon University (2002) as a data source for the pre-use phase of steel frame and wood frame. The EIO-LCA method, in theory, should result in larger environmental impacts than the process-based LCA. The reason is that the EIO method takes into consideration all the economic sectors involved in the manufacturing of a product or material and includes direct and indirect environmental burdens (Hendrickson et al., 1997).

Most authors used the process-based LCA for other studies related to building materials (Börjesson & Gustavsson, 2000; Cole & Kernan, 1996; John et al., 2008; Jonsson et al., 1998; Nässén et al., 2012; Bolin & Smith, 2011; Johnson, 2006; Kahhat et al., 2009; Upton et al., 2008; Diyamandoglu & Fortuna, 2015). However, some authors recommended applying the hybrid approach to building-related LCAs, since the process-based method may underestimate the environmental impacts of the pre-use phases (Ochoa et al., 2002; Guggemos & Horvath, 2005;

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[3] See https://energy.gov/energysaver/types-insulation.

[4] Manufacturer's data. See: https://www.jm.com.

Nassen et al., 2007; Guan et al., 2016; Norman et al., 2006; Treloar et al., 2001). A limitation of the hybrid approach for this study was the lack of quality data for the insulation materials in the EIO-LCA database. Thus, I opted for using process-based data sources for the manufacturing of insulation components.

It is important to mention that both the process-based LCA and the EIO or the hybrid LCA methods have their benefits and limitations. There is no consensus about which one has the most accurate results. However, as mentioned above, the data based on the EIO-LCA method are expected to generate much larger impacts related to the pre-use phase. The main benefits of reuse are related to the pre-use phase (e.g., avoiding the burden of extraction and manufacturing of raw materials), so the hybrid approach is expected to be more "optimistic" about the reuse benefits. Therefore, contrasting both methods is the most valid way of presenting the results.

System Boundaries

The processes and activities that I included and excluded from the system boundaries are shown in Table 1. Figures 24 and 25 (Appendix A) illustrate the system boundaries of this study. System boundaries diagrams were created according to the ILCD template (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) and are presented in Appendix A.

Construction (steel and wood frame installation), deconstruction, use, and maintenance phases were excluded from the analyses. Construction and deconstruction of the external walls of a tiny house are manual processes that can be done by the house owner and do not necessarily demand contractors, skilled workers, or equipment. Previous studies also chose to exclude the construction phase from the system boundaries (e.g., Kellenberger & Althaus, 2009; Nässén et al., 2012; Sandin et al., 2014; Johnson, 2006). The use phase was excluded since the thermal resistance is the same for both external walls designs. Maintenance of external wall framing is negligible since they are not exposed to weather conditions and require very low maintenance. Other studies also chose not to include maintenance because the authors assumed the different wall systems to have the same maintenance requirements (John et al., 2008; Sandin et al., 2014; Upton et al., 2008). Finally, I included ancillary materials (i.e., bolts and nails), as recommended by Kellenberger and Althaus (2009).

Table 1. System boundaries (illustrated in Figures 24 and 25 in Appendix A)

Included	**Excluded**
Extraction of raw materials	Steel and wood frame installation and removal
Production and manufacturing of raw materials	Construction of capital equipment
Manufacturing of end products (steel studs, wood studs, nails, screws, fiberglass batts, polyiso rigid panels)	Maintenance and operation of support equipment
Recycling of steel (studs, screws, and nails)	Human labor
Disposal of insulation in a landfill	Administrative services
Incineration of wood	Construction of infrastructure (i.e. facilities)
Disposal of slags and residues of wood incineration in a landfill	Use phase
Reuse of steel (studs and screws)	Maintenance of steel and wood frame`
Transportation between all life cycle stages	Long-term emissions from landfill (exception: slags and residues of wood incineration, as it is included in the data)

Life Cycle Inventory: Data sources and quality

The data collected in this study were third-party secondary data from established life cycle inventory (LCI) databases and peer-reviewed reports. I prioritized data reflecting national averages because of their precision and accuracy. Thus, the data quality requirements for this study were to find average data collected in the U.S. in the last ten years. I performed a data quality requirement (DQR) calculation for each unit process, according to the ILCD Handbook guidelines. The ILCD divides the DQR in “data estimate,” “basic quality,” and “high quality,” according to the results of the calculations they provide (see European Commission, 2010). The data for all processes in this study fell under the “basic quality” category, except for the data related to the polyiso insulation’s life cycle, which fell under the “high quality” category, and the EIO-LCA that were considered “data estimate.” The data quality indicators and the results for the data quality calculation for each process are presented in Appendix B. Appendix C lists the assumptions used in this study (e.g., transportation distances, material densities).

Results

This section presents the results for embodied carbon, energy, and water for the three life cycles (two reuses) illustrated by Figure 6. The results were explained by impact and then by the method: hybrid LCA (Figure 7) and process-based LCA (Figure 8).

The results were tested for the following uncertainty scenarios:

1) Varying transportation distances (from 50km to 20,000km);
2) Varying reuse rates (from 0 to 100%);
3) One reuse of steel (an alternative to two reuses assumed in the baseline scenario presented as the scope of this analysis).
4) Worst and best-case scenarios (the description of each scenario and their results are presented at the end of this section);

The results of the uncertainty analyses from 1 to 3 are explained in the following sections. The description of the worst-case and best-case scenario are presented separately at the end.

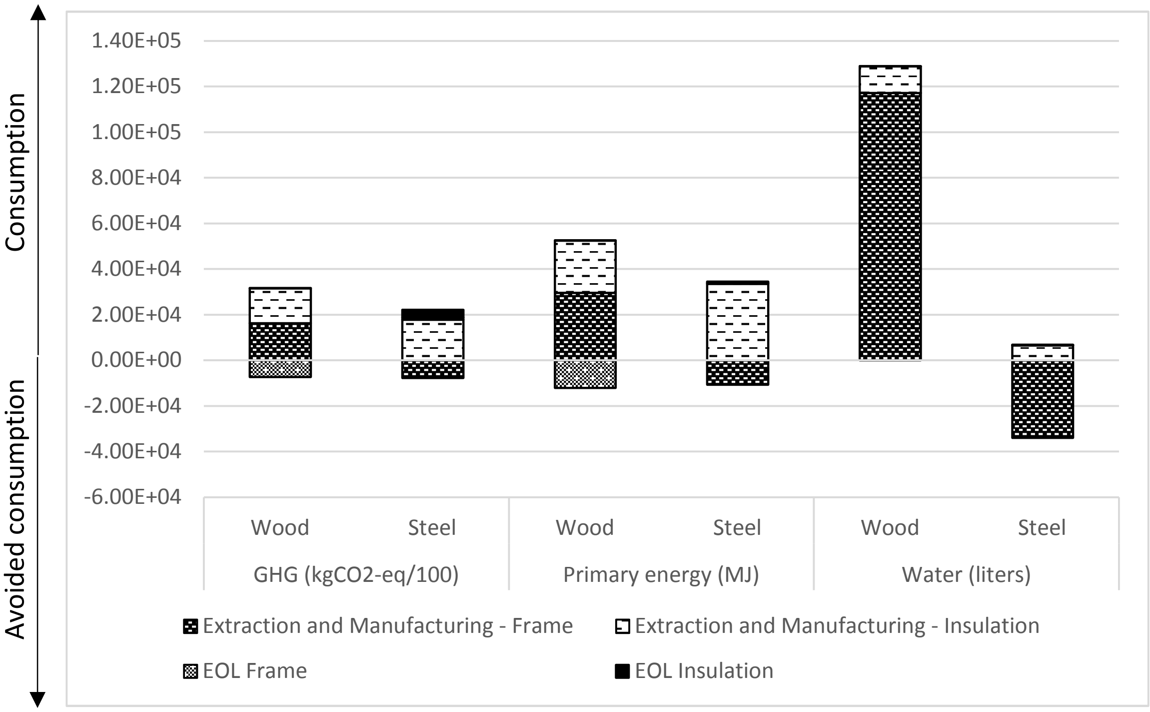

Figure 7. Hybrid LCA results

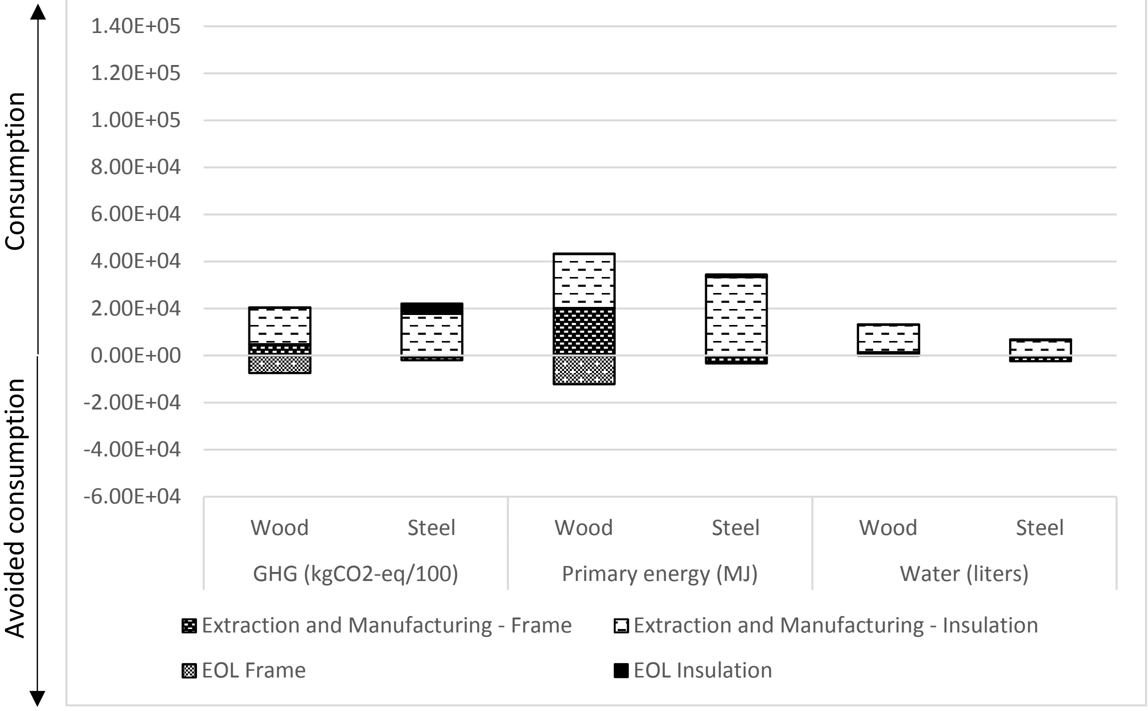

Figure 8. Process-based LCA results

Global warming potential (GWP) or embodied carbon

Hybrid LCA

Steel[5] had 60% of the CO_2-eq emissions created by wood when the reuse rate (RR) is 90%. The polyiso panels had the largest shares of the steel's global warming potential (GWP). Because of the reuse of the steel frame with avoidance of two new frames, the extraction and manufacturing of steel had negative impacts (Figure 7). The savings caused by the avoided manufacturing of steel were four times larger than those found in the process-based LCA. This was expected since the EIO data are based on all involved economy sectors (as opposed to specific processes), and thus the pre-use impacts tend to be much larger. The wood frame had the largest GWP share of the wood-framed houses, followed closely by the insulation.

Uncertainty: Steel did better than wood when the RR was larger than 70%. For RR=90% and distances between construction sites of 3,000km or larger, wood had less GWP than steel. If the steel frame was only reused once, the GWP of steel and wood would have been similar (Figure 9).

Process-based LCA

Wood did better in terms of GWP; it had 65% of the CO_2-eq emissions created by the steel-framed wall after two reuses of the steel frame. The reason for such difference was the GWP savings caused by the incineration of wood (see process 2.5 in Table 9, Appendix B). Polyiso and

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[5] In this section, for the sake of simplicity, "wood" means wood-framed walls, and "steel" means steel-framed walls. Both include the effect of the respective insulation.

fiberglass insulations had the largest share of GWP for the steel- and wood-framed house, respectively (Figure 8).

Uncertainty: Had the steel frame been reused with RR=100% and had the reuse happened on-site (no transportation distances), wood would still have had lower GWP than steel.

Primary energy use or embodied energy

Hybrid LCA

Steel used only 60% of the wood frame's primary energy use (Figure 7). When RR<70%, wood used less energy. Most of steel's renewable energy (RE) use came from the polyiso insulation, and most of steel's nonrenewable energy (NRE) use came from the steel frame. The wood frame had the largest RE share in the wood-framed houses, while the fiberglass insulation had the largest share of NRE. The EIO data for primary energy use of wood manufacturing was larger than the process-based data by a factor of 1.46. Similarly, the EIO data for energy savings from steel reuse was larger than the process-based data by a factor of 3.27.

Uncertainty: Steel and wood had similar energy use if the steel frame was only reused once (Figure 9). Steel did better than wood when RR>70%. Given RR=90% (baseline), steel used less energy than wood unless the transportation distances from site to site were larger than 20,000km (which is very unlikely).

Process-based LCA

Steel and wood had similar results for primary energy use. The reason steel does not use less energy than wood after two reuses is due to the very large share of energy used by the polyiso insulation (97% before savings by the avoided frames, mostly used to extract raw materials). On the other hand, the wood frame had a similar energy use share compared to the fiberglass insulation (Figure 8).

Uncertainty: The steel frame would have similar results compared to the wood frame, even if it was only reused once (Figure 10). When RR<50%, steel had higher embodied energy than wood. Given RR=90%, wood had lower energy use when the transportation distances from site to site were larger than 10,000km (that is, equal to a road trip from San Diego to Quebec to get the second-hand steel frame, which is unlikely).

Embodied water

Hybrid LCA

Steel had a negative water use. Wood consumed 156,000 liters more than steel, which equals two tiny houses completely full of water. There was an unreasonable difference between the EIO data and the process-based data for water consumption (EIO water use was 14 times larger for steel and 78 times larger for wood! See Figure 7). I could not identify the cause of such difference because the process-based database does not specify how the water calculations are made. As for the EIO data, 48% and 64% of the water use was caused by the power generation and supply (for wood and steel, respectively). Farming sectors were responsible for another 35% of the wood frame’s water usage.

Uncertainty: After only one reuse, steel used only 19% of the water consumed by the wood frame (Figure 9). When RR<20%, wood used less water than steel. The transportation distances from site to site had a negligible effect on the results.

Process-based LCA

Steel used 35% of the water used by wood. The extraction and manufacturing of insulation had the largest water use share for both wood and steel.

Uncertainty: Had the steel frame been reused only once, it would use 61% of the wood frame's water consumption (Figure 10). When RR<40%, wood used less water than steel.

Uncertainty analysis

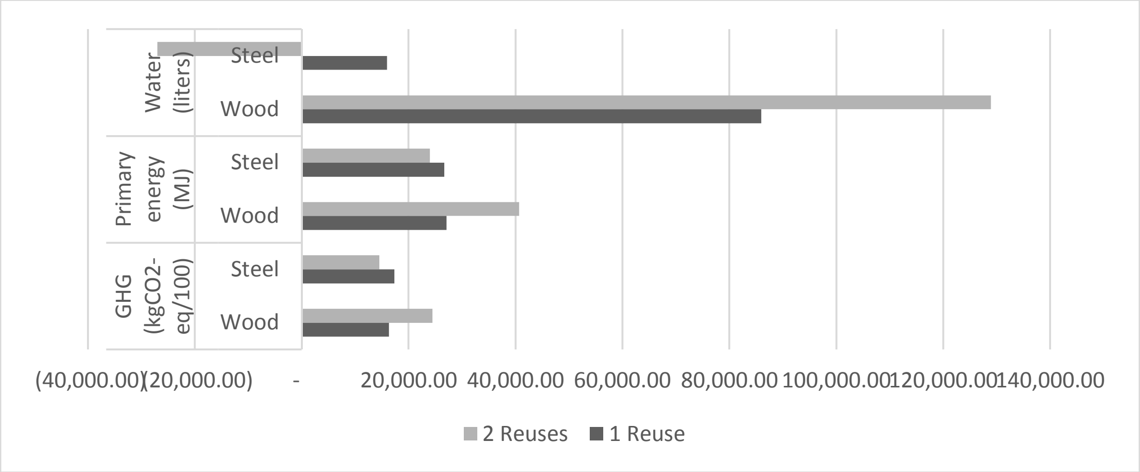

Figure 9. One vs. two reuses of steel frame (hybrid LCA)

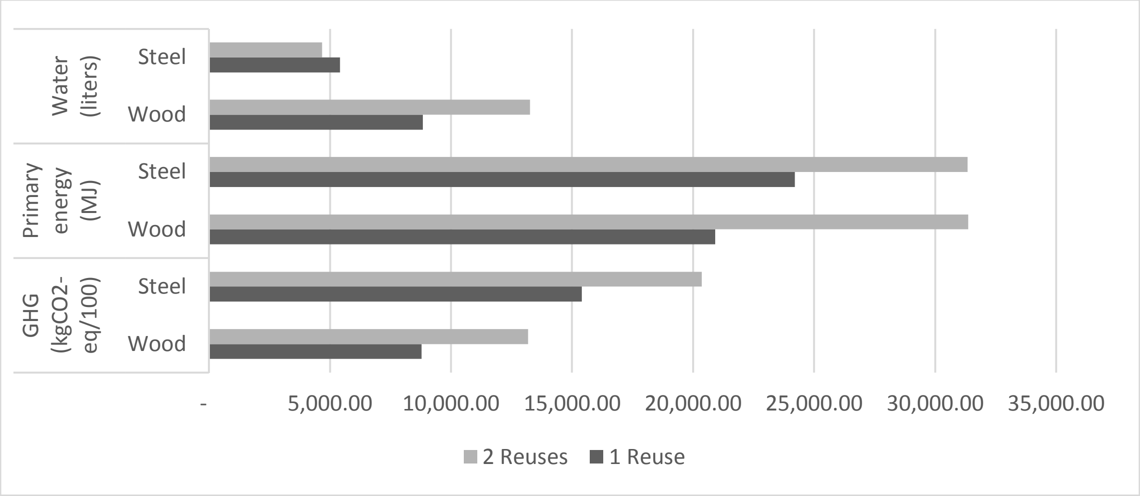

Figure 10. One vs. two reuses of steel frame (process-based LCA)

The results were tested for uncertainty considering two other scenarios, as described below.

Worst case scenario

Scenario description: There is no reuse of the steel frame. All of the steel frame is recycled and re-manufactured at the beginning of each life cycle. The wood is disposed of in landfills with no incineration. All the insulation materials are disposed of in landfills.

Results: Steel had twice as much embodied carbon than wood. Steel and wood's embodied energy had no significant difference. Steel used 28% more water than wood.

Implications: The recyclability of steel frames are not enough to compensate for their high embodied carbon, energy, and water use. That said, specifying that a steel frame be used for the external walls must come with the responsibility of easing the future reuse of the steel studs. For example, one should choose to bolt instead of welding.

Best case scenario

Scenario description: The reuse rate of steel is 100%. No steel is recycled before the final use (i.e., the third life cycle). The wood frame is assumed to be de-nailed and reused (reuse rate = 80%), and the wood that is damaged and not suitable for reuse is incinerated with energy recovery. The nails resulting from the de-nailing process are recycled. The insulation for both steel and wood frames is reused (reuse rate = 80%), and the remaining insulation is disposed of in landfills.

Results: Wood saved more CO_2-equivalent emissions and energy than steel (by factors of 3.4 and 1.6, respectively). Steel and wood had similar water savings. The GWP saved by the reuse of steel was equivalent to 30 passenger vehicles driven for one year, according to the average miles a car drives per year in the United States (EPA, 2017). Similarly, the reuse of wood saved CO_2 emissions equivalent to 102 passenger vehicles driven for one year (EPA, 2017).

Implications: Reusing 80% of the wood frame generated a net savings much larger than reusing 100% of the steel frame, especially when it comes to embodied carbon. More efficient methods for assembling and disassembling a wood frame must be developed as an alternative to de-nailing, which is highly time-consuming.

Discussion

Uncertainty and data quality problems are inherent to any LCA method. Hendrickson et al. (1997) well observed that "equally credible analyses can produce qualitatively different results." That said, the hybrid LCA and the process-based LCA generated different results in this study, both in a quantitative and a qualitative manner. This is consistent with the literature and was not an unexpected outcome. For example, Hendrickson et al. (1997) compared the EIO-LCA and the process-based LCA methods and found that some of the results had different orders of magnitude.

This happens because both methods rely on different models and data sources, and thus the results are expected to vary (see the "LCA Methods" section of this chapter). However, the qualitative results are usually the same for both approaches if we are not doing a cradle-to-cradle LCA. For example, if I had not assumed the reuse of steel in this study, the steel frame would have the largest environmental impacts in both hybrid and process-based assessments. But since I compared a reusable material against a single-use material, the method that tends to generate the largest embodied impacts will also generate the largest impact savings due to reuse. Although the hybrid and the process-based approach do not produce directly comparable results, researchers must acknowledge that a hybrid or EIO-LCA will likely create a more "optimistic" perspective on the environmental benefits of reuse. If time and resources are limited, researchers may opt for an EIO-LCA, which is not as costly and time-consuming as a hybrid or process-based approach. However, whenever possible and for the reasons mentioned above, I recommend contrasting the results of both methods when doing C2C LCAs.

Another limitation to keep in mind is the different level of data aggregation in the process-based and EIO methods. The quality of the EIO data is limited by the extent to which the EIO process matches the analyzed process (e.g., "ornamental and architectural metal products manufacturing" is not the as specific as "33mil galvanized steel studs"). The EIO data also had the lowest quality of all data used in this study. As for the time-related representativeness, both process-based and EIO-based data for steel and wood frame manufacturing were assumed representative of the current practices. Factors that may have changed through the years are the recycled content of steel and the renewable energy use of the involved processes.

Besides the considerations about the LCA methods, the better performance of reused steel depended on reuse rates larger than 70% for GWP and primary energy and 40% for water use. These results suggest that we must enhance design practices in the AEC industry to increase the reuse rates of building components. Transportation distances also mattered. Distances larger than 3,000km (1,864mi or the driving distance from Phoenix, AZ, to Chicago, IL) undermined the benefits of reuse. The environmental gains of reuse depend on the creation of local and regional markets for second-hand building components.

Another factor that may weaken the benefits of reuse is the choice of insulation system. In this study, insulation materials had the largest environmental impacts and undermined the benefits of multiple reuses of the steel frame. The pre-use phases of fiberglass and polyiso insulation had the largest shares of water use, GWP, and energy use in both wood- and steel-framed walls. Thus, the reuse of insulation materials is vital to grant the reuse benefits of external wall systems, as shown by the results of the best-case scenario in this study.

Lastly, the uncertainty analysis revealed the value of reusing wood frames. In the best-case scenario, the reuse of the wood frame resulted in GWP savings equal to 102 passenger cars driven for one year. The successful reuse of wood frames depends on the advance of grading techniques that will measure the structural strength of the second-hand wood studs and return them to the market. It also depends on the resources available to de-nail the studs. But first and foremost, boosting the reuse of wood frames depends on the development of a market for second-hand studs that justifies investing time and resources on de-nailing and re-grading the studs.

6. ACCOUNTING FOR THE DURABILITY AND REUSABILITY OF BUILDING MATERIALS IN COMPARATIVE LCA

Goal and Scope

The goal of this analysis is to assess the embodied energy, carbon, and water of materials with different durability and reusability. For this analysis, four roof-covering materials were chosen: one with a short lifespan (asphalt shingles, assumed to last 15 years); two highly durable materials (zinc and copper, assumed to last 90 years); and two materials with medium durability (aluminum and steel, assumed to last 45 years). Zinc and copper were assumed to be reused after a 45-year period, as opposed to the other alternatives with lower durability. This analysis was intended to aid decision-making in earlier phases of design; therefore, the materials were analyzed separately from a building and from a climate zone. This study is meant to complement, as opposed as to substitute, whole-building LCAs that assess the operational energy at later design phases.

The timeline chosen for this analysis is a 90-year period and corresponds to a conservative estimate of the lifespan of copper and zinc roofs. As an alternative, an uncertainty analysis for a 45-year period was performed, as well as a scenario in which no timeline was considered (as the embodied energy studies usually do). Figure 11 illustrates the timeline for each roof-covering material. The figure represents a combined timeline of two buildings that last 45 years each. During this time, I assumed that the copper and zinc coverings would be reused from the first building to the second building. During 90 years, copper and zinc would be produced once, reused once, and then recycled at the end of the 90-year period. I assumed that when the zinc and copper were reused the production of new zinc/copper roofs would be avoided. Aluminum and steel roofs, in turn, would be produced twice and recycled twice (at the end of 45-

year periods). Finally, asphalt shingles would be produced six times and disposed of in landfills six times (every 15 years). The final recycling of materials at the end of the 90-year period was excluded from the system boundaries because there was a lack of reliable data for zinc and copper recycling (Ekman Nilsson et al., 2017).

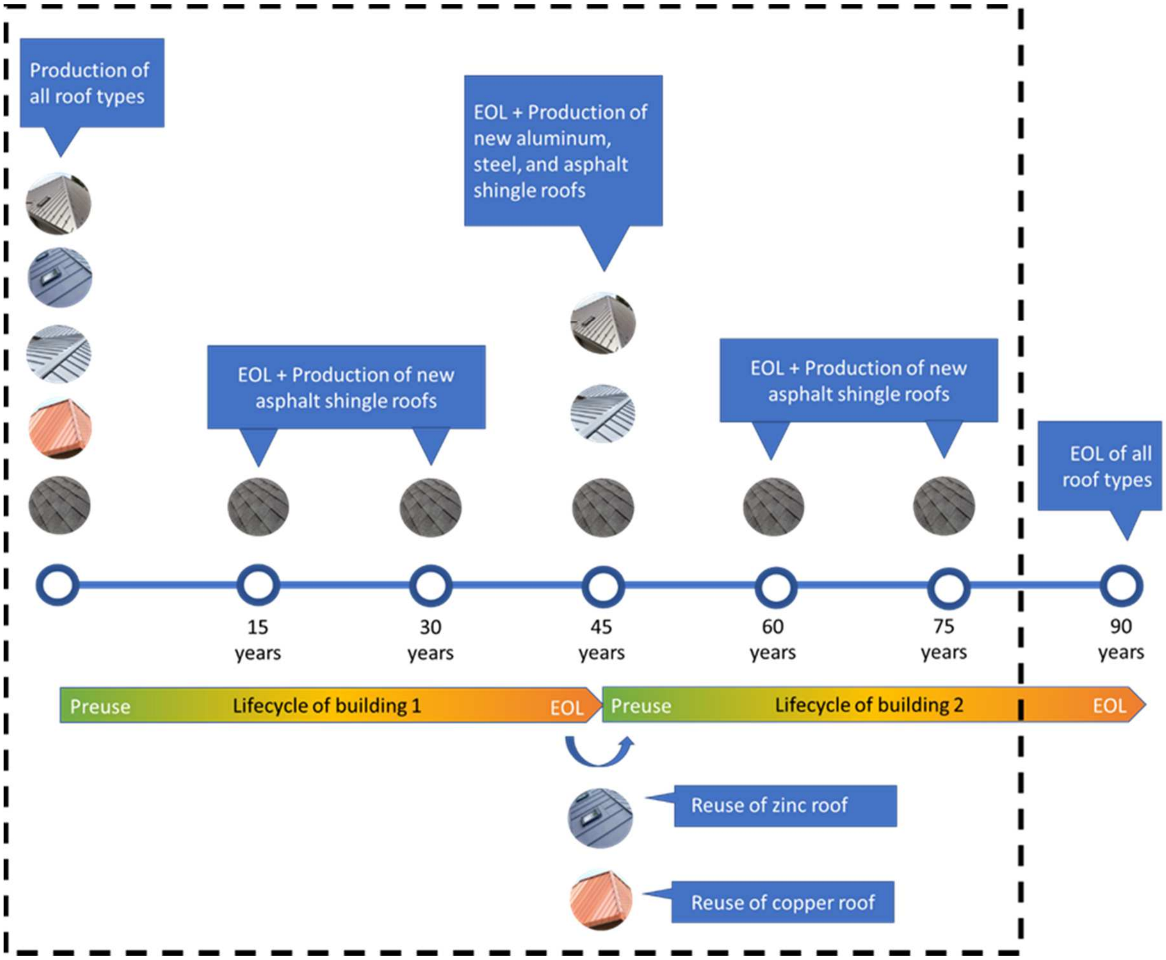

Figure 11. System boundaries (limited by the dashed lines)

The functional unit chosen for this analysis was roof-covering materials necessary to cover one square meter of a roof with slope factor 8/12 (1.20) over 100 years. The roof frame and insulation were assumed to be the same for all roof-covering materials. For example, either metal or asphalt shingle covering can be installed on a system with layers of continuous insulation placed between plywood boards.[6]

Embodied energy and roof materials' lifespan: Past studies

A sample of peer-reviewed LCA studies that compare roof materials is presented in Table 2. I mentioned before that the timeline of the LCAs is not consistent among studies. Note that the timelines for the studies presented in Table 2 range from 20 years to 100 years. Cabeza et al. (2014) found that 50% of the LCA studies in the building sector analyze the environmental impacts over 50 years, which they justify as being the average lifespan of a building. Souza et al. (2015) have the shortest timeline of all studies in Table 2 (20 years). The authors justified that 20 years is the average lifespan of both building materials under study. According to Cabeza et al. (2013), who wrote a review on embodied energy in building materials, the literature on embodied energy does not consider the service life of the building materials, even though several studies have already established the importance of considering the service life in LCAs.

Note, also in Table 2, that not all LCA studies included the EOL as part of the system boundaries. The studies that did include EOL in their comparisons analyzed only the disposal of the materials in landfills and the recycling of some materials. To my knowledge, Aye et al. (2012) were the only ones who have considered the effect of reuse on the embodied energy of building materials so far. The authors stated the importance of the durability and reusability of construction materials to reducing environmental impacts in the building sector. According to the authors, "If a material can be reused after its initial use, the building in which the material is reused should be credited with the embodied energy saving resulting from the avoidance of the

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[6] See http://www.greenbuildingadvisor.com/blogs/dept/green-building-blog/podcast-how-insulate-unvented-roof for an illustrated example of such a system.

energy required for processing and manufacturing new virgin materials". But the analysis made by Aye et al. (2012) did not focus only on the embodied energy of materials; instead, the authors calculated the impact of reuse in the life cycle of a building, including the operational phase. The authors concluded that "prefabricated construction is capable of providing improved environmental performance over conventional construction methods if they are initially designed to be reused, either adaptively or through disassembly" (Aye et al., 2012).

Table 2. Past studies about roof materials and components

Reference	Types of roof	Lifetime	Functional unit	Was EOL included?
(Saiz et al., 2006)	Standard flat roofs and green roofs	50 years	8-story residential building in Madrid	No
(Cubi et al., 2016)	Green roof, white roof, and photovoltaic panels	50 and 100 years	1340m2-office building in Canada (Vancouver, Calgary, and Toronto)	No
(Islam et. al, 2015)	Metal and concrete tile (combined with different ceiling systems)	50 years	A house in Australia	Yes (landfill)
(Napolano et al., 2015)	Different systems of wood and concrete slab	60 years	25m2 of net flat roofing area of an existing building in Italy	Yes (landfill or recycling)
(Souza et al., 2015)	Terracotta versus concrete tiles	20 years	1m2 of roof tiles	Yes (landfill)
(El Bachawati et al., 2016)	Gravel ballasted, white reflective, and green roof	45 years	834m2 of an existing green roof in Lebanon	No
(Lawania & Biswas, 2016)	Concrete tiles, terracotta tiles, and metal profile sheet (along with other envelope options)	50 years	Construction and use of a typical house in Perth, Australia	No
(Pushkar, 2016)	Flat roofs (concrete, ribbed slab with concrete blocks, and ribbed slab with autoclaved aerated blocks)	50 years	1m2 of flat roof that serves 3.7m3 of a building module in Israel (4 climate zones)	Yes (landfill or recycling)
(Contarini & Meijer, 2015)	Gravel and concrete tiles (along with other layers that form roof systems)	30 years	300m2 of roofing of an existing apartment building in Leiden (Netherlands)	No

In the past chapter of this dissertation, I compared the embodied energy, carbon, and water for two different materials used in external wall frames: wood and steel studs. I also compared two different LCA methods and showed how they can drastically change the results. In this chapter, I compared different roof-covering materials regarding their embodied energy, carbon, and water and the effect of including the materials' lifespan in the embodied impacts analysis.

Data collection

This study did not include any primary data; the life cycle inventory (LCI) was collected from previous LCA studies. Table 3 lists the data source for each material and their processes. In this section, the different roof-covering materials were introduced, and their sources' main assumptions were explained. Although most of the sources are peer-reviewed (with the exception of the source for production of zinc sheets), it is important to mention again that the LCI data for embodied energy can vary greatly between sources because of differences in methodology, geography, time, and technology.

Table 3. Data sources for the roof-covering materials

Material	**Process**	**Source**
Asphalt shingles	Extraction of raw materials	BEES (Lippiatt, 2007)
	Manufacturing	BEES (Lippiatt, 2007)
	Transportation + EOL (landfill)	BEES (Lippiatt, 2007)
Steel roll formed cladding with high-performance coating	Extraction of raw materials	MCA (Baer & Koffler, 2012)
	Manufacturing	MCA (Baer & Koffler, 2012)
	EOL (recycling)	ecoinvent
Aluminum sheet with high-performance coating	Extraction of raw materials	MCA (Baer & Koffler, 2012)
	Manufacturing	MCA (Baer & Koffler, 2012)
	EOL (recycling)	AA (PE International, 2013)
Zinc sheet	Extraction of raw materials	IZA (International Zinc Association [IZA], 2016)
	Manufacturing	IZA (2016)
Copper sheet	Extraction of raw materials	ECI (Tikana et al., 2002)
	Manufacturing	ECI (Tikana et al., 2002)
All roof-covering materials	Transportation (truck)	NREL + ecoinvent
	Transportation (ship)	NREL + ecoinvent

Asphalt Shingles

Data from asphalt shingles was collected from BEES (Lippiatt, 2007). BEES stands for Building for Environmental and Economic Sustainability and is an online software[7] created by the National Institute of Standards and Technology (NIST) to aid LCAs in the construction sector in the United States. Asphalt shingles are very popular in the U.S. and are present in more than 70% of all residential roofs (Roof Cost Estimator, 2017). They are made from fiberglass mats, coated with a mix of asphalt and mineral filler, and are typically nailed over an underlayment installed on oriented strand board (Lippiatt, 2007). BEES included the asphalt shingles covering, a felt underlayment, and the steel nails in the analysis. Also, the software assumed that at the end of a 20-year life, a new layer of asphalt shingles would be applied in the whole roof (over cladding). Because the LCI for BEES included two layers of asphalt shingles, I divided the results by two to adjust it to a single layer of asphalt shingles over each 15-year period considered in this analysis. The results from BEES did not allow for separating data from extraction and manufacturing from the data from the EOL (i.e., landfill). For this reason, I did not assume over cladding after each 15-year period; instead, I assumed that the full life cycle (from extraction of raw materials to landfill) would happen every 15 years. Most of the LCI data used in BEES was collected from national sources in the mid-2000s.

Zinc sheet

Zinc sheet is made by combining zinc with alloying elements like copper, titanium, and aluminum, which is then turned into a sheet by a continuous casting/rolling process (IZA, n.d.). According to the International Zinc Association (IZA), zinc sheet is extensively used in the

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[7] BEES can be accessed at: https://ws680.nist.gov/bees/

building industry for roofing and can last for centuries. Zinc sheet is also 100% recyclable (IZA, n.d.). IZA performed a life cycle assessment on zinc sheets and claimed to follow the International Organization for Standardization norm for LCA. However, it is unclear (although assumed) whether the study has undergone a critical review. IZA's goal was to build an LCI for zinc sheet production, from cradle-to-gate (mining to production up to the factory gate). The LCI included the collection of primary data from five sites around the world that, together, produced 225,000 tonnes of zinc sheet per year, which corresponded to more than 50% of the global zinc sheet production in 2006.

Copper sheet

Copper sheet data came from a comprehensive and peer-reviewed report prepared by the Life Cycle Centre in Germany to the European Copper Institute (Tikana et al., 2002). The copper sheet analyzed in the cited study is 0.6mm thick. Their LCI data was based on industry inputs from most European countries and used as reference the year 2000. The authors of the report recommended that, due to the high economic value of copper, LCA practitioners should consider a "full cradle-to-cradle approach." They also pointed out the importance of considering the high durability of the material when comparing the LCA results with other materials likely less durable than copper. The authors claimed that worldwide data were included for the mining and processing phases.

Steel cladding

Another peer-reviewed, comprehensive LCA report was used as a data source for both steel cladding and aluminum sheet. The report was prepared by PE International for the Metal Construction Association (MCA) (Baer & Koffler, 2012). The LCI data for this study used as reference steel roll formed claddings with high-performance coating. The cradle-to-gate LCA includes the mining and manufacturing of 24-gauge steel sheet, the process of coating it, and the roll-forming process. The authors claimed to have used “the best steel and energy datasets available at the time” in their analysis. They used a global average dataset to represent U.S. steel and a few European-average datasets to represent other North American materials that were used in smaller quantities (Baer & Koffler, 2012). Finally, the authors claimed to have reflected the technology for the year 2010 in North America.

Aluminum sheet

The same report prepared and disclosed by MCA was used for aluminum sheets. The study presented LCI data for aluminum-based metal composite material (MCM) panels and sheets. The cradle-to-gate MCM panel manufacturing LCA includes the cradle-to-gate production of 0.020’ aluminum sheets, the gate-to-gate high-performance coil-based coating, the gate-to-gate manufacturing of the MCM sheet, and the gate-to-gate manufacturing of the MCM panel. An MCM panel is a sandwich of two MCM sheets with a thermoplastic core (EPS) in the middle. The total impacts here are for one layer of aluminum sheet equal to the cradle-to-gate MCM panels, minus the gate-to-gate manufacturing of MCM panel (i.e., the addition of the thermoplastic core), divided by two (because two sheets are needed for the panel). In the analysis presented in this chapter, the calculation just mentioned was used to estimate the LCI data for one layer of aluminum sheet with high-performance coating. The LCI data for the aluminum sheet is also based on the technology for the year 2010 in North America.

Other sources

The other sources used in this analysis (i.e., NREL and ecoinvent, for truck and ship transportation) were discussed in the previous chapter of this dissertation.

Results

Three scenarios were analyzed regarding the timeline of the analysis: no timeline considered (as it is common practice among studies on embodied energy), a 45-year timeline (based on a building's lifespan), and a 90-year timeline (based on the most durable materials' lifespan). The "no timeline" scenario accounted only for the cradle-to-gate of the materials, and the EOL was excluded from the analysis. There is a limitation to this method: the data for asphalt shingles was aggregated and did not allow separation of cradle-to-gate from EOL. This limitation should not have major impacts on the results since the EOL usually has a very small share of the total impacts compared to the manufacturing phase (except in the case of a cradle-to-cradle LCA, which is not the case for asphalt shingles). The 45-year timeline assumed only one building life cycle, while the 90-year timeline illustrated in Figure 11 assumed two building life cycles of 45 years each. The 90-year timeline assumed the reuse of copper and zinc from one building to the other. A reuse rate of 100% was assumed. Because there was no reliable data for the recycling of copper and zinc, the final EOL was excluded from the analysis for all materials (except asphalt shingles due to the data limitations discussed above).

The results for the "no timeline" scenario are shown in Figure 12. This scenario includes only cradle-to-gate data (that is, no EOL), and the durability and reusability of materials is not taken into account, as is common practice among embodied energy studies. In these conditions, asphalt shingles (AS) had the lowest global warming potential (GWP), or embodied carbon. It also had the lowest embodied water use. There was no water data for zinc (Zn) production.

Copper (Cu), followed by zinc and steel (ST), had the lowest amount of embodied energy use. The decision of what material to choose based on this analysis depends on the decision-makers' priorities regarding the environmental impacts. Overall, copper had the largest share of impacts due to its very large water use during the production of copper sheets.

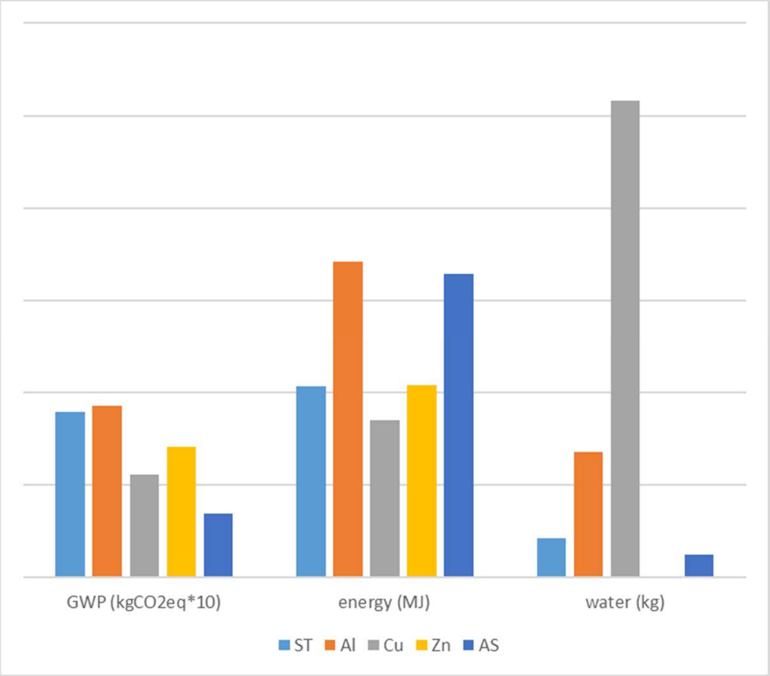

Figure 12. Embodied carbon, energy, and water when no lifespan or EOL were considered

The 45-year scenario accounts for the embodied energy, carbon, and water of the materials during a building's average lifespan. No EOL was considered in this scenario, nor was the reuse of copper and zinc. The 90-year scenario includes the reuse of copper and zinc and the EOL of all materials throughout the life cycle, except after the second building's EOL. The embodied energy results for the 45- and 90-year analyses are presented in Figures 13a and 13b.

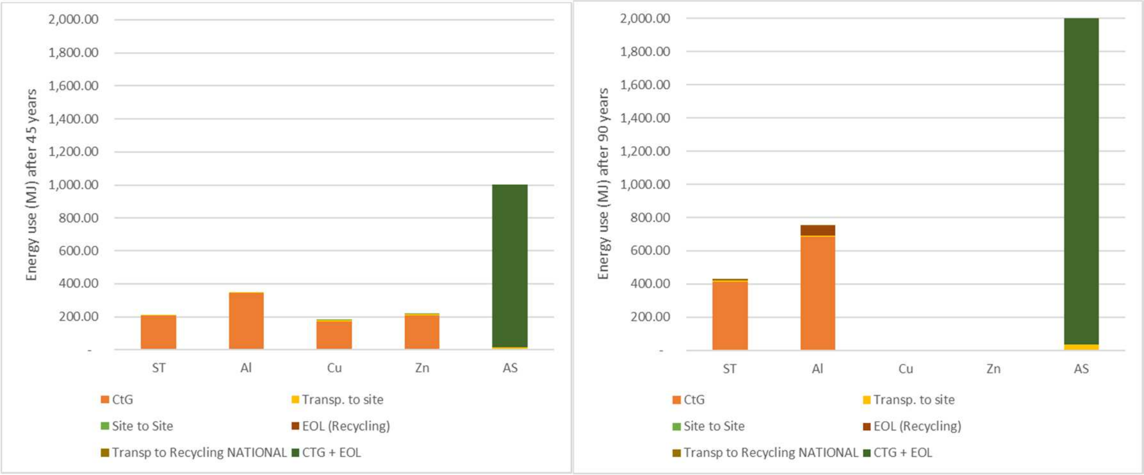

Figure 13 a (left) and b (right). Embodied results for the 45-year analysis and 90-year analysis, respectively.

The figures above show that after 90 years, copper and zinc reach zero energy due to the avoided production of new materials for the second building (assuming 100% reuse). When I accounted for such avoided impacts in the 90-year analysis, copper or zinc were easy choices to make when it came to embodied energy. On the other hand, if one chose to do to a 45-year analysis, the designer's choice would be between steel, copper, and zinc. Due to the high first cost of copper and zinc, steel cladding would likely be the preferred option. Asphalt shingles (followed by aluminum) had the largest embodied energy no matter what timeline was considered. Figures 14a and 14b, below, show the results for embodied carbon between the two analyses.

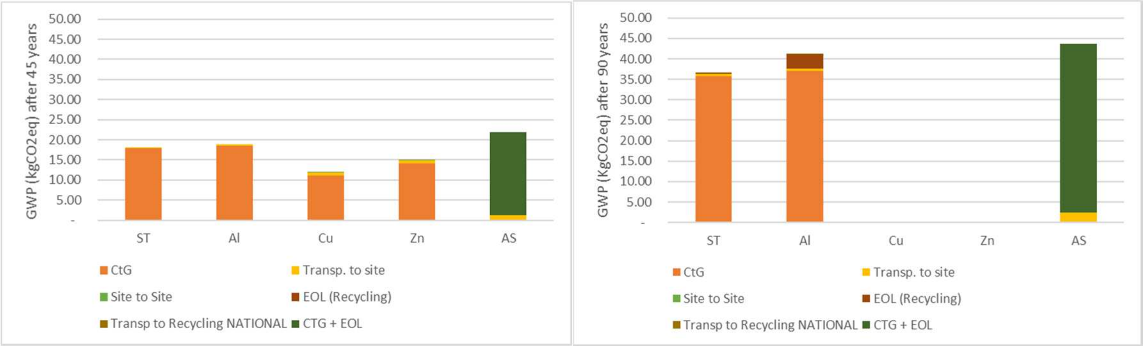

Figure 14 a (left) and b (right). Embodied carbon (or GWP) results for the 45-year analysis and the 90-year analysis, respectively.

Similar to the embodied energy results, a 90-year timeline allowed accounting for the avoided production of new materials for the second building, and copper and zinc reached zero carbon. The non-reusable materials—steel, aluminum, and asphalt shingles— had the same carbon emissions after a 90-year period analysis. If we only take into consideration the 45-year lifespan of a building, copper is more preferable than zinc, and either is more preferable than asphalt shingles, steel, and aluminum, which had similar results (less than 20% difference). However, the difference between copper and zinc, compared to the rest of materials in the 45-year analysis, may not be enough to justify the choice of these materials when other factors come to place (namely, first cost). In other words, when we accounted for the durability and reusability of copper and zinc, it was clear that they were the choice with the lowest embodied carbon (zero carbon). However, had we only analyzed the lifespan of one building without accounting for future reuse, there was little difference between the reusable and non-reusable materials, possibly not enough difference to justify the higher cost of copper or zinc. The results for water use are presented in Figures 15a and 15b below.

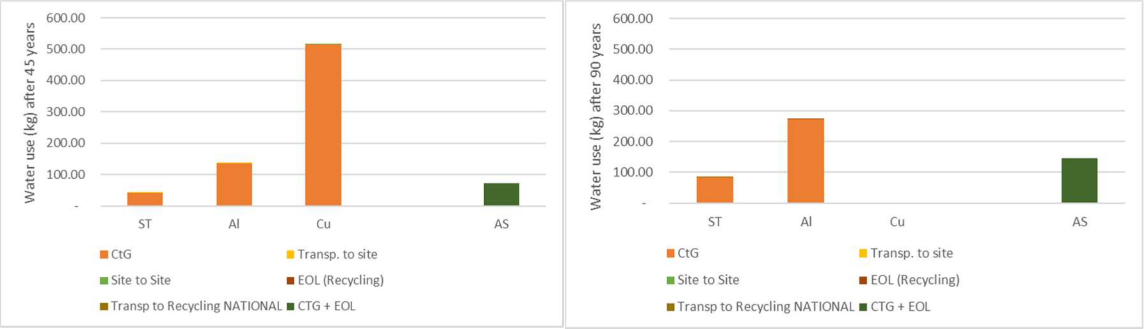

Figure 15 a (left) and b (right). Embodied water results for the 45-year analysis and 90-year analysis, respectively.

There was no water data available for the production of zinc roofs. In a 45-year analysis, steel had the lowest use of water, followed by asphalt shingles, aluminum, and copper. Copper had the largest water use. However, in a 90-year period, copper offset its very large embodied water use through reuse and avoidance of producing new copper sheets. The best copper deposits in the country are located in Arizona, that is, in the desert (Singh, 2010). Thus, reusing copper to offset its embodied water use should be a high priority in the United States, especially in Arizona.

Discussion

The summary of results (Table 4) is presented in order of the lowest to the highest embodied impacts for GWP, energy, and water, according to what timeline was used for the analyses. The table shows how the timeline chosen for the analysis can change the results and the decision-making for specifying roof-covering materials in the early design phase. For example, had no lifespan been considered, asphalt shingles would have the lowest embodied carbon, and copper would have the highest embodied water use. However, when we take into account the durability and reusability of the materials (and the avoidance of the production of new materials through reuse), asphalt shingles had one of the highest embodied carbon outputs, and copper had the lowest embodied water.

Table 4. Summary of results

	No lifespan	45-year lifespan	90-year lifespan
GWP (kgCO2eq)	1. asphalt shingles; 2. copper; 3. zinc; 4. aluminum/steel	1. copper; 2. zinc; 3. steel/aluminum/asphalt shingles	1. copper/zinc; 2. steel/aluminum/asphalt shingles
Energy (MJ)	1. copper; 2. zinc/steel; 3. aluminum/asphalt shingles	1. copper/zinc/steel; 2. aluminum/asphalt shingles	1. copper/zinc; 2. steel; 3. aluminum; 4. asphalt shingles
Water (kg)	1. asphalt shingles; 2. steel; 3. aluminum; 4. copper	1. steel; 2. asphalt shingles; 3. aluminum; 4. copper	1. copper; 2. steel; 3. asphalt shingles; 4. aluminum

It is important to mention, though, that this study has many limitations. First, the data sources for embodied energy in construction materials vary a lot. A study that uses other data sources can come to different conclusions when it comes to what material would be preferable in each situation. Second, because this analysis used data from existing data sources, all the limitations of each data source used are transferred to this study. Third, there are methodological differences between the data sources used in this study (for example, whether it includes ancillary materials or whether most of the data was collected in the United States). However, despite all the limitations, this study has reached its goal of showing how the results of an analysis of embodied impacts will change according to the lifespan chosen. When doing an LCA to study the embodied energy, carbon, and water of building materials, one must consider the durability and reusability of the materials. Based on the results presented in this chapter, I recommend 1) choosing the lifespan of the most durable material for the comparison and 2) making sure that the materials are assembled in a way that allows for their dismantle and reuse in the future.

Finally, because the most durable materials in this analysis were also the most expensive ones (i.e., copper and zinc), the choice for these materials in the design phase will depend on economic factors. Currently, there may not be enough financial incentive for choosing durable (and expensive) materials over the conventional choices like asphalt shingles. However, this may change with the advance of the market for reused materials and with the future rise of the shared economy and product-service systems in construction (e.g., leasing construction materials instead of buying them). In the next chapter of this dissertation, I have explored some of these economic changes, as well as the designers' decision-making process for specifying materials for future disassemble and reuse.

7. DESIGN FOR DISASSEMBLY: WHY NOT? A GROUNDED THEORY

Goals and scope

My initial idea when starting to design this study was to interview architects who have designed for disassembly and to understand what their motivations were. However, I soon realized that there were a little more than a dozen DfD projects that I could find (excluding temporary buildings, such as expo pavilions and emergency shelters). Also, most projects of this type are in Europe, and I wanted to analyze the context of the United States. After contacting[8] two research experts in the DfD field—Bradley Guy and Mark Webster—they helped me realize that I should interview architects in the U.S. regardless of their personal experience with DfD and that I should reframe the goal of this study to understand why they do *not* design for disassembly. This was the goal of the analysis presented in this chapter: to understand why designers do not use DfD strategies in their current practice. As far as scope, I interviewed 13 architects from large design firms in the United States. The participants' demographics are presented in the next section.

Data collection

The architects that were interviewed in this study were selected from the top 160 firms in the U.S., which were ranked by BNP Media using as criteria the firms' revenue in 2013 (BNP Media, 2018). For each firm, I searched for the e-mail addresses of randomly selected architects on their webpage. I sent e-mails to approximately 200 architects, which resulted in 13 interviewees from 12 different firms. A few architects referred to other peers as potential interviewees, and I

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[8] I contacted Bradley Guy and Mark Webster, who agreed to talk to me in informal phone calls to discuss my research objectives and intended contributions to the field. After the hour-long phone calls, their input helped me to shape my interview scripts and frame the objective of this study. I am extremely grateful to both of them.

recruited them as well. The interviews ranged from 25 to 60 minutes long and had an average duration of 40 minutes. Each participant was interviewed one single time. The relevant demographics of the participants (years' experience, the city they work in, and market sectors they design for) are presented in Table 5.

Table 5. Participants' demographics (Note: all participants were given codenames; "xp" = experience)

			Market sectors									
Name*	**xp. (yrs)**	**City**	**Housing**	**Single-family**	**Civic**	**Institutional**	**Retail**	**Commercial**	**Corporate**	**Urban Design**	**Healthcare**	**Nonprofit**
Mark	39	San Diego (CA) / Kansas City (KA)			x	x			x	x		
Kody	17	Chicago (IL)	x			x			x		x	
Dylan	31	Washington DC			x	x					x	
Kevin	32	Tempe (AZ)			x	x						
Louis	30	Philadelphia (PA)				x					x	
Carol	31	Boston (MA)			x	x						x
Roger	41	Norfolk (VA)				x		x	x			x
Jack	20	Greenville (SC)				x	x		x			
Charlie	25	Phoenix (AZ)	x			x	x	x		x		
Mary	3	Phoenix (AZ)	x							x	x	
Brian	38	San Antonio (TX)										
Luke	6	Seattle (WA)										
Will	20	Des Moines (IA) / Madison (WI)	x	x	x	x		x				
Total			4	1	5	10	2	3	4	3	4	2

The large proportion of participants who have clients in the institutional sector (10 out of 13) and the low proportion of participants who have clients in the single-family residential sector (1 out of 13) are likely a result of the firm's revenue as the main selection criteria. The anonymity of the participants was preserved in this study, and they were given codenames.[9] The geographical distribution of the participants is illustrated in Figure 16.

Figure 16. Geographical distribution of participants

The interviews were conducted using a semi-structured script (see Appendix D). At times, I changed the order of the questions according to the flow of the conversation and let the architects spend more time talking about the topics that they seemed more experienced in or enthusiastic about (within the interview topics). I also asked follow-up questions that were out of script but helped me clarify their experiences and even re-frame some questions for future interviews. For example, I changed a question from "what type of market sectors are more interested in [X]" to "what are the common characteristics of clients who are interested in [X]," following the insightful suggestion of one of the participants. As a result, the selective code of

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[9] This research was approved by Institutional Review Board (IRB) of Arizona State University, and the participants signed an informed consent authorizing the publication of the results with the condition that they would remain anonymous.

“Transformational clients and sophisticated clients,” which I did not anticipate during the design of the original scripts, emerged from the data. This is consistent with the grounded theory method that allows for iteration between data collection and analysis. According to Charmaz (2018, p. 90), “your interview guide evolves with your study.” Finally, being an architect myself helped me to engage the participants and enrich the discussion during the interviews. It also helped me understand their language and interpret their statements and experiences.

A sample size of 13 participants may be seen as small for some researchers. However, Guest et al. (2006) concluded that 12 interviews are usually enough for most researchers who aim to study common views and experiences among a relatively homogeneous sample. I consider my sample fairly homogeneous (architects from large firms in the United States, from which 85% had 15 years or more of professional experience). But I did not decide on my final number of interviews based on an arbitrary number. Instead, I stopped recruiting architects based on the theoretical sufficiency of my data (as I explain in the next section).

Data analysis

The data collection and analysis were iterative processes in this study. After the first group of four interviews, I transcribed them and started the process of open coding with the aid of the Dedoose software. Dedoose is a tool to help researchers organize data and apply codes to transcripts. In this step, the researcher must stick closely to the data and avoid relying to preconceived categories (Charmaz, 2014). I had to remain especially conscious preconceived ideas that came from my experience as an architect and my previous studies in DfD. Some grounded theorists even recommend avoiding engaging in literature review before the data collection, which was not possible in the case of this study. Also, according to Charmaz, open codes should be simple and precise and as close to the participant’s language as possible. Open codes that remain close to the data are useful for ensuring that the grounded theory actually fits the data, instead of, for example, fitting the researcher's previous ideas about the phenomena under study.

After finishing the open coding process for the first four transcripts, I reassessed the list of open codes and grouped them into categories that objectivist grounded theorists call "axial codes." Charmaz's take on axial coding is less formal than the objectivist approach from theorists such as Glaser and Strauss: "Although I have not used axial coding according to Strauss and Corbin's formal procedures, I have developed subcategories of a category and showed the links between them as I learned about the experiences the categories represent" (Charmaz, 2014, p. 148).

Similarly, I grouped open codes into constructed categories that summarized the meanings or characteristics of the subcategories. Some examples of the coding process, from open coding to axial and then selective coding, are shown in Tables 6 and 7. I grouped open codes in axial codes and started memo-writing to document my steps and organize my thoughts, and at the same time, I recruited and conducted more interviews. Then, I transcribed the next four interviews and did more open coding followed by axial coding. Repeating this process in groups of four interviews was an experimental approach that worked well to ensure simultaneous data collection and analysis.

Table 6. From open code to selective code (example 1)

Transcript excerpt	Open code	Axial code	Selective code
"I think understanding disassembly means adaptability of the buildings, in terms of a building's structure or interiors. I think there's a really great opportunity to associate disassembly	Understanding disassembly DfD as a means for adaptability Structure and interiors	Disassembly as a means for adaptability and resiliency	Conflicting views about DfD and resiliency

with resiliency rather than temporary”	Associating disassembly with resiliency		
“When we design a building, we hope it’s gonna be there for a long time.”	Hoping that buildings last	Designing for permanency	
“We try to build the building as strong as possible so that doesn’t really lend itself to being able to take it apart.”	Trying to design strong buildings Architects perceive strong buildings as not suitable for DfD	Resilient buildings and DfD as opposite goals	

Table 7. From open code to selective code (example 2)

Transcript excerpt	Open code	Axial Code	Selective code
“I generally feel like everything is set against reusing either components or buildings.”	Everything is set against reusing	Difficulty to justify the reuse of building components	Specifying salvaged materials for subjective reasons
“I kinda think that just by definition salvaged materials are unique and not commercialized.”	Defining salvaged materials as unique Salvaged materials not commercialized	Uniqueness as contrary to commercialization	
“It’s the reintegration of the something of the past, the history, into something new, the future, creates a more interesting project.”	Reintegrating old into new History Past into future Creating an interesting project	Salvaged materials as a means to create an interesting project	
“Try to think of a way of reusing the materials in a new way that kinda make people stop and take notice. Or be kinda entertained by a material being used in a completely different manner.”	Reusing materials in a new way Making people take notice Entertaining building users	Salvaged materials as entertainment	
“And to take those and transform those into a beautiful piece of art,	Transforming salvaged materials Beautiful piece of art	Salvaged materials as art as opposed to ordinary	

that’s kinda the strategy. Versus saying ‘well, we’re gonna re-clad the new buildings with that copper.’”	Using art as a strategy As oppose to Repeating original use Avoiding ordinary uses		

I stopped recruiting participants when I thought that my axial codes had reached what some researchers called “theoretical saturation.” Theoretical saturation “is achieved” when no new properties of the constructed categories emerge from the data and after the researcher has defined, checked, and explained the links between categories and the range of variation within them (Charmaz, 2014). Instead of “theoretical saturation,” I prefer to use “theoretical sufficiency” as defined by Dey (1999). Both terms suggest a comprehensive analysis, but the first implies completion while the second makes it clear that the “sufficiency” depends on the researcher’s judgment and the goal of the study.

After judging my axial codes as theoretically sufficient, I proceeded to selective coding. Selective coding is the process of understanding the relationships between axial codes and selecting one or more core categories intended to produce a theory that connects the categories. I used diagrams to help choose the core categories and refine the relationship between them. First, I drew a “big picture” diagram that connected my axial codes by telling a story. This diagram helped me select the core categories for my theory. Then, I drew individual diagrams for each core category (or “selective code”) to better define these codes and connect them with other selective codes. This process of “zooming in and out” from the big picture to the selective codes was highly experimental and proved extremely beneficial to my process of theorizing. I wrote memos during the process from axial coding to selective coding and theorizing, and the memos helped to frame the writing about each selective code and the links between them (presented in the findings section of this chapter). Figure 17 illustrates the grounded theory process of this study, from the research question to writing the theory. The selective codes and their relationships and characteristics are presented in the next section (Findings and Discussion).

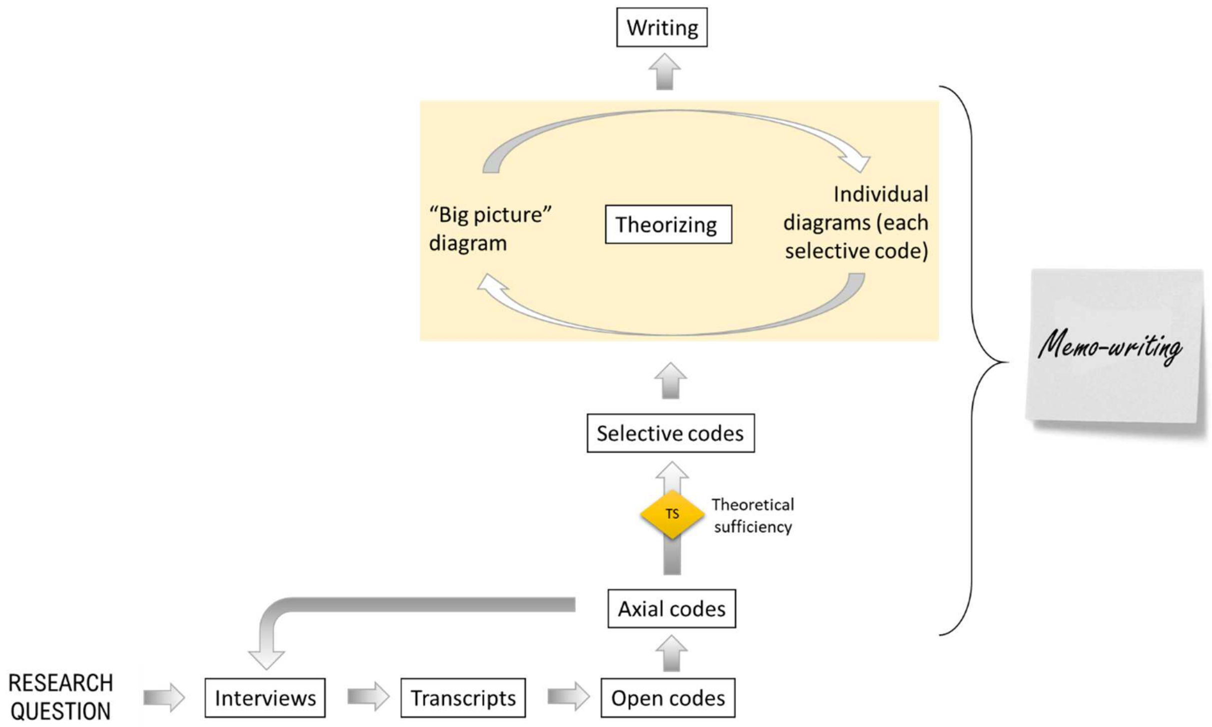

Figure 17. The grounded theory process in this study

Findings and Discussion

In this section, I introduce my five selective codes and the connections between them. Figure 18 illustrates the "big picture" diagram that draws the relationships between the selective codes or core categories of this study. The selective codes (highlighted in bold in the pictures) are as follows:

1. Transformational and sophisticated clients;

2. Conflicting views about DfD and resiliency;
3. Associating subjective reasons to reusing building components;
4. The difficulty of factoring DfD into life cycle cost (LCC);
5. Prefabrication is an opportunity to DfD.

Transformational and sophisticated clients are *in vivo* codes (i.e., words used by the participants) that categorize and describe two groups of clients who are usually interested in sustainable design practices. There are mainly two reasons why clients are interested in sustainable practices: it either makes financial sense in the medium or long term or they believe it is “the right thing to do” according to their individual or institutional mission. The first are the sophisticated clients and the latter are the transformational clients. Sophisticated clients are formed by long-term building owners. Owners who plan to build and sell for a short-term return on investment (ROI) are not sophisticated, but in theory they can be—although the participants believed it is rare—transformational owners. Obviously, there are building owners who do not fit in either group and consequently have little or no interest in sustainable design practices. I decided not to focus this study on these owners, since they will unlikely benefit from DfD for the time being. “Transformational and sophisticated clients” is the first selective code I present individually in this section because it is tightly connected to all other selective codes (see the “big picture” diagram in Figure 18). That makes sense since, as architects, our role is to listen to our clients and understand what they want and then align those goals with our own.

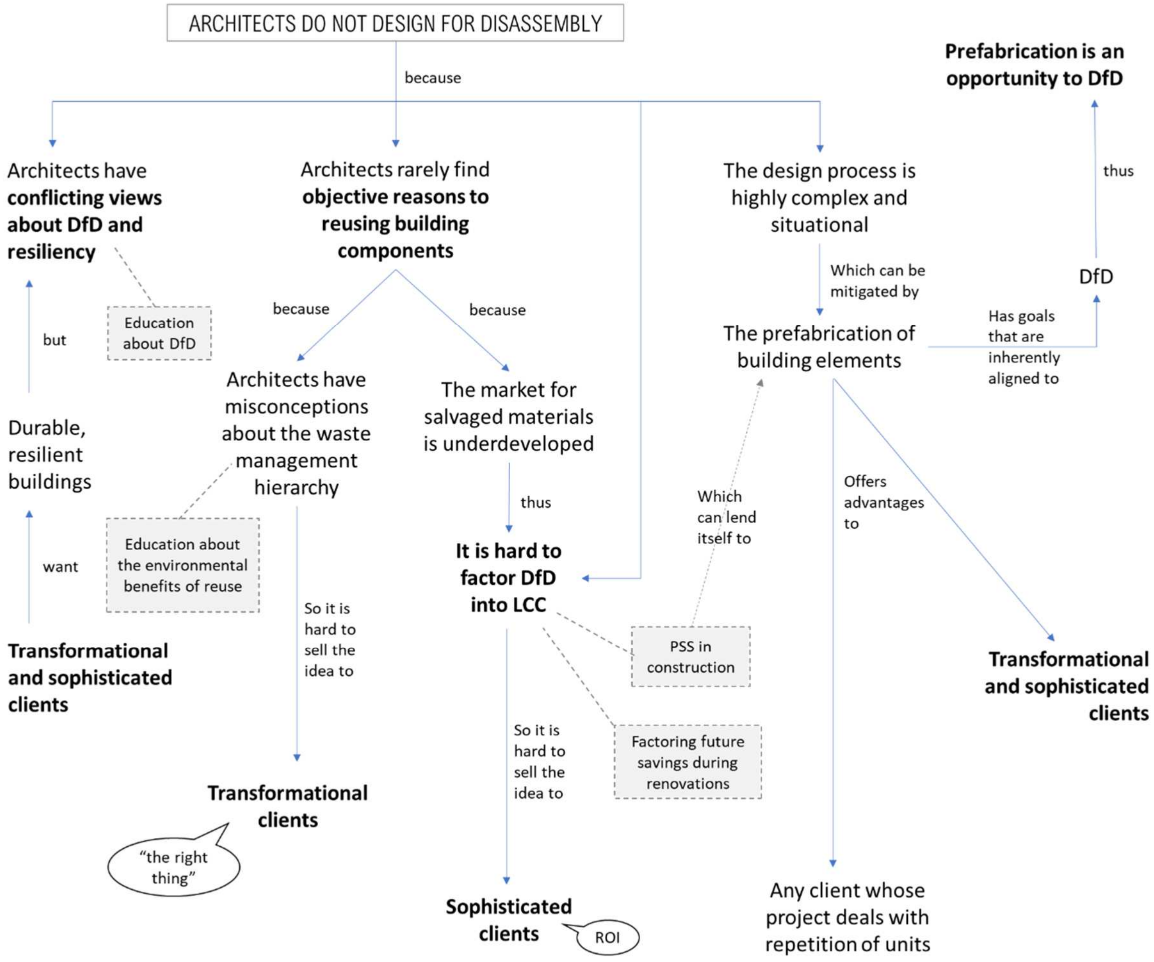

Figure 18. Connecting the selective codes: the "big picture"

The second selective code, "conflicting views about DfD and resiliency," is linked to the architects' take on disassembly. Some architects associated the ability to disassemble a building to a temporary structure, something that is not "made to last." Some went even further and claimed that DfD and resiliency are opposite of each other, that is, a durable, resilient building "does not lend itself to" disassembly. Other architects, like myself, believe that disassembly *allows* for resiliency. This is the case, first, because it allows for a flexible, mutable design that can adapt to future changes in the building's structure, envelope, or interiors and, second, because it allows for the replacement of damaged parts when they reach the end of their useful life or in case of disasters. Thus, there are clearly contrary opinions about whether DfD is an appropriate practice for buildings that intend to last several decades (such as institutional buildings). This is a problem because both transformational and sophisticated clients are interested in durable buildings, either because it is "good for the environment" or because durability is expected in a long-term investment. Hence, such conflicting views are, in my understanding, the first barrier for DfD. The good news is that it may be the easier barrier to overcome; the architects need to be informed and educated about the benefits and purposes of DfD (note, in Figure 18, that the ways to overcome each challenge to DfD is highlighted inside a box with dashed borders). This dissertation is a step toward educating architects about DfD.

The core categories 3 and 4 are tightly interconnected. DfD builds on the assumption that there are enough reasons to reuse building materials in the future. However, the participants associated subjective reasons to reusing building components because they rarely, if ever, find objective reasons to do so. Thus, it is hard for these architects to understand why they should design to ease future disassembly and reuse. By objective reasons, I mean reasons that are not related to aesthetics or sentimental value but are directly linked to financial and/or environmental reasons, that is, reasons that can be quantified and used as data to inform decision-making. And why do architects not find objective reasons to use salvaged materials? First, they have misconceptions about the waste management hierarchy. For example, some participants used the terms "reuse" and "recycling" interchangeably or gave examples of "reuse" when they meant "recycling" and vice-versa. This is concerning because knowing the difference between reuse and recycling is the first step toward understanding the environmental benefits of reuse. Also, in general, there are a lack of life cycle assessment (LCA) studies that aim to quantify the potential benefits of reusing building materials. I covered this issue in Chapters 5 and 6 of this dissertation. These chapters presented the results of cradle-to-cradle LCAs through which I intended to contribute to the general knowledge about reuse and its potential benefits for the environment.

Transformational clients want to “improve the environment” and would be very interested in reusing building materials if we could inform them about such benefits.

The lack of financial reasons to reuse, in turn, is linked to the difficulty of factoring DfD into LCC (selective code 4). As explored in the literature review about DfD presented in Chapter 2, the cost-benefit of reusing depends on the market for salvaged materials, which is currently underdeveloped. There are salvage yards throughout the country, but issues regarding lack of quantity and quality of such materials make it hard to find objective reasons to reuse them. Instead, using salvaged materials is perceived almost like treasure hunting. Factoring DfD into life cycle cost (LCC) is a way to convince sophisticated clients that DfD can have an ROI. There are two ways we can factor DfD into LCC: by accounting for the future resale of building components and by accounting for future savings during renovations in the building. While the first depends on the market for salvaged materials, the second, in theory, can be done right now. There is a need for more studies that investigate ways to estimate these future costs in the most accurate way possible, depending on market sector and possibly a range of other factors. However, the financial benefits of DfD strongly depend on business models that support the CE in construction, such as the product-service-sectors (PSS) discussed in the literature review (Chapter 2). That said, the shift toward a CE in the construction industry will not happen fast. It demands slow changes in design, business models, supply chain relationships, codes, and regulations, among other factors that I am not covering in this dissertation that focus on the role of the design in a CE.

Finally, the complex and situational nature of the design process is another barrier to DfD. In an environment where the teams, the project goals, and the roles of the architects change constantly, it is hard to fit innovative ideas that would add layers of complexity to this process. Prefabrication can help to take away some layers of such complexity, as I discuss in the section designated to the core category 5, “Prefabrication is an opportunity to DfD.” PSS businesses, such as leasing construction materials, also can lend themselves to prefabrication and disassembly. Prefabrication and disassembly, in turn, have many common goals: adaptability, durability, transportability, ability to assemble and disassemble, and use of standard dimensions. But unlike disassembly, prefabrication is gaining ground in the construction industry, and most participants claimed to have specified prefabricated building components at some level. Prefabrication also offers advantages to many clients: transformational clients, who want to reduce construction and demolition (C&D) waste; sophisticated clients, who are interested in cost-effectiveness and faster construction schedules; and any "type" of client who must deal with a high level of repetition in their projects (e.g., hotels, apartments, office buildings). For all these reasons, I believe that prefabrication is an opportunity—and maybe a "shortcut" —to DfD.

The following subsections will further explore each of the core categories individually and present evidence that each of them was grounded on data from the interviews.

Transformational and sophisticated clients

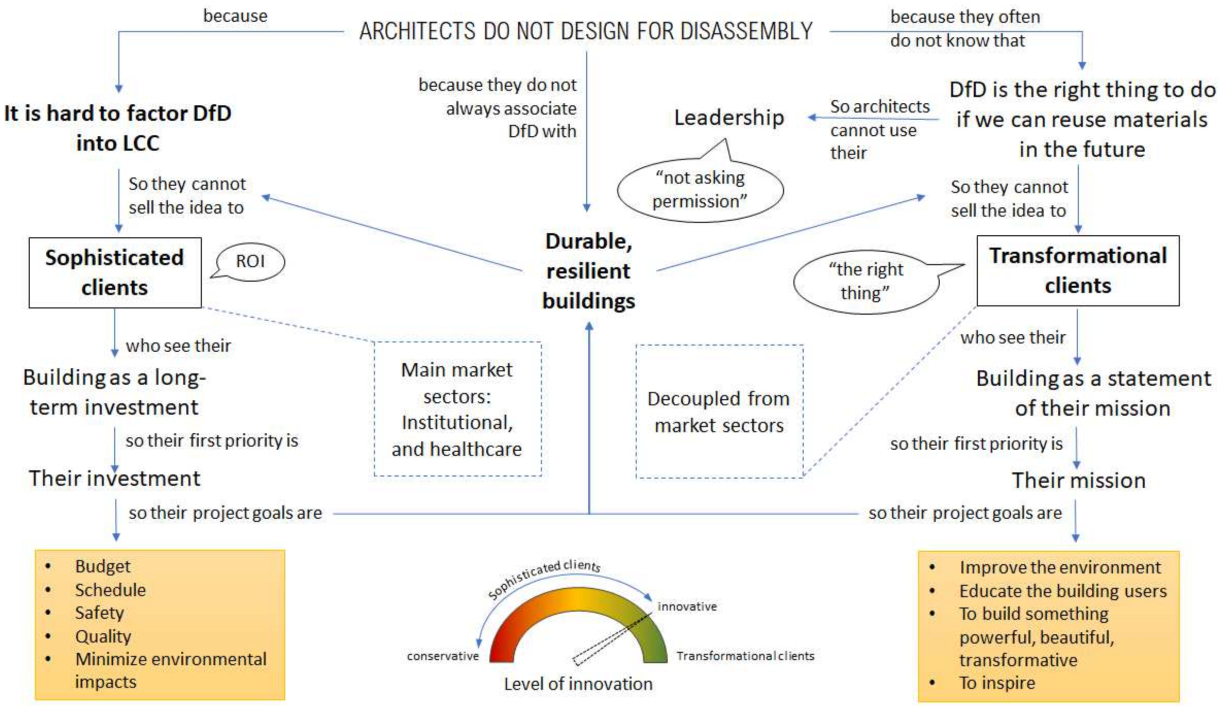

Figure 19. Transformational and sophisticated clients: diagram.

In one of my first interviews, I asked Mark: "In your experience, what type of market sectors would benefit the most from an adaptable design?" We had already talked a bit about adaptability, sustainability, and innovation. His answer helped reshape some of my questions for future participants. He told me that there are "different levels of innovation" between clients and that it does not necessarily depend on the market sector. Later, many other participants would echo his words.

> You know, there are corporate owners that are very innovative, that really design for evolving their organization, to meet the changing needs of the marketplace. And there are owners, corporate owners that are pretty stuck in what's worked in the past, they're gonna stay focused on what's worked in the past—exactly what they need. And the same is true for academic and other users. So, I think you might think about it a little bit differently, you might think about it as "who are those transformational clients, and what inspires them to create environments that

> are adaptable and changeable, that are sustainable, that are doing the right thing? What inspired them to make those decisions?”

In the following passage, Mark described one of his “transformational clients.” The characteristics he described were also brought up in other interviews, and it became clear that these building owners are moved by their personal or institutional mission. They are highly creative, innovative, and often ahead of their time. Their building is more than an investment; it is a symbol of their mission and an educational tool. They want to create something beautiful, powerful, and inspiring. They want to “do the right thing,” and the budget comes second. Transformational clients are “totally open” to the architect’s ideas as long as they are aligned with their social and environmental values. They want to “improve the environment,” rather than minimize environmental impacts like most building owners. In my personal experience as an architect, they are the ones we design for in every single project in the Architecture School (where we do not have a real client) and who most of us rarely, if ever, get to design for during our professional life.

> So the institutional mission of [a certain transformational client] is about world peace, environmental issues, water issues, population... You know, their whole mission is centered on delivering educational programs, that’s about their work. So, if the clients that are interested in sustainability are the far left and the uninterested ones are the far right, well (laughs), they were about 200 miles past the far left. It was a core mission driven idea for them to do something that’s really powerful. We didn’t know them, they reached out to us.… So, we actually started a workshop in the next morning, started exploring ideas of how we could do something really beautiful, really powerful, and start to achieve remarkable results. We didn’t know if they would do Living Building Challenge or LEED Platinum initially until the second meeting. They were totally open. We didn’t have a budget, we didn’t know if we had a budget, because they wanted to understand what the right thing to do was first, and then work towards understanding how much that’s gonna cost. First, find out what’s the right thing to do, what were the benefits of doing that, focusing on how we could achieve, how we could improve the light, water next to the facility, how we could improve the environment, how we could provide education to everyone that came there.... And then we moved in to how we actually accomplish it and how much it’s gonna cost.…Usually, you know (laughs), when you sit around a project you have a lot of parameters to do that. We didn’t have a lot of parameters. It also may have sounded like it was really open-ended and without focus, but it was

> just the opposite; it was very focused. And we came to conclusions very quickly… (Mark)

Roger described a similar experience when working with a non-governmental organization (NGO) whose mission is to preserve the wilderness. His firm designed their headquarters for flexibility, which he defined as finding “multiple uses for spaces.” They were able to reduce building’s carbon footprint by almost 50%. Roger told me that the client came to him and said: “Our space has become a vehicle that we really, truly, can share our mission. Because we did this thing here that, in the long run, preserves the wilderness.” For Roger, the most interesting part of the project was to see how the owner saw their space “as a vehicle to communicate their mission.”

I had an experience with a transformational client of my own. I was acting as the “design facilitator” for a consulting class at Arizona State University. The class was called Designing a Living Building, and it was mostly focused on the Living Building Challenge by the Living Future Institute. In this class, a group of undergraduate and graduate students from the most diverse backgrounds got together to envision a building for a real client. Our client was not institutional or an NGO. It was an entrepreneur who wanted a “circular living building” because he was convinced that the CE was the right thing to do. Similar to Mark’s client, our client had no fixed budget and very few parameters to start with. He was completely open and did not want to limit the design process. He wanted to understand how his building could improve the environment and was committed to “find” the budget to do it. It was an amazing experience for all involved in the project. It was the first time I felt *inspired* by a client.

But Roger also pointed out that, while some building owners are “incredibly enlightened and progressive,” most owners are not like that. It was a common theme between the architects that “sustainable ideas get stripped away by the project’s budget.” Luke stated that “every client wants to do something sustainable until the budget starts happening.” Brian believes that the owner's education about life cycle cost (LCC) and the number of buildings they own are the factor that differentiates sophisticated clients. In his words, "Less sophisticated clients do not understand the complexity of a life cycle cost. So more sophisticated clients that have done multiple projects or multiple buildings, they understand that LCC." Jack also used the term "sophisticated clients" and described it similarly:

> I think sophisticated owners that understand they're not looking at a project as one opportunity to make money, but they're working on a portfolio, that understand the long-term possibilities and the bigger picture value that it might bring from a market standpoint, from a speed of erection standpoint, I mean, I'd just call them sophisticated. Because unsophisticated developers are trying to build a building cheaply, quickly, and get rid of it. Some of the best developers are thinking about it because they know if could really be a differential and really improve their product. (Jack)

In Brian's experience, these owners often come from "institutions that are planning on holding their buildings long term," and they are more interested in sustainability in terms of building performance that can produce operational savings. Carol pointed out that "institutions have a fiscal responsibility" to understand their return on investment (ROI).

> If they are undertaking a project that may meet their institutional goals or reduce their greenhouse gas or reduce their environmental impact, they still need to analyze if there's an increase in cost in order to do that. They want to know how much money in the savings would neutralize that cost. So that's still the norm for analyzing the better windows, better envelope, better insulation, better photovoltaics, all of that. (Carol)

Louis thinks that his healthcare clients are "much more sensitized to the value of it and to the energy performance and energy savings." Because their buildings are very energy intensive, they spend "a huge amount of money" in energy costs. So, it is easy to "sell" sustainable design strategies that will bring down energy costs for these clients. Other participants described their process of educating the client through LCC and trying to show how they can "make decisions differently" so they can save money in the future. Most participants claimed to have internal sustainability goals in the design firm, so they would always try to "advocate for sustainability." For the clients who are not interested in sustainable goals, Dylan's firm will "package it not so much on sustainability but just optimizing the building so it operates efficiently and it's efficient and more inexpensive to own and operate." Kevin also uses LCC as a tool to convince clients to adopt sustainable design strategies by showing them potential long-term savings.

Apart from transformational and sophisticated clients, some participants also mentioned owners who "just don't care," usually because their building is a short-term investment. These owners do not plan on holding the building for long, so the idea of LCC and operational savings does not make sense for their type of investment. Brian believes that these "unsophisticated owners" need to be forced to take sustainable decisions by codes and regulations. I believe that architects should focus their effort on transformational and sophisticated clients to advance the practice of DfD. In the future, when DfD and reuse become more widely adopted in our industry and we have the support of business models that are aligned to a CE, the "unsophisticated owners" will need to catch up with the market and new regulations.

Summing up, "sophisticated clients" are aware of the importance of life cycle cost and will "buy" into sustainable ideas as long as they can bring a return on investment. As any investor, these clients vary in levels of innovation. Some are more conservative, and others are more innovative and less averse to risk. But none of them reach the level of innovation of the transformational clients, for whom the ROI is not the first priority. Their project goals also differ based on their priorities. The sophisticated clients are concerned about budget, schedule, safety, and quality, as they all reflect on the ROI. There is, though, an important goal that is common to transformational and sophisticated clients (and that is somewhat related to "quality"): they all want durable, resilient buildings. I explored this topic more in the section about "conflicting views about DfD and resiliency."

Regardless of the type of client, however, some participants brought up the role of the architect in acting as a sustainability leader. That is, creating a sustainable design "no matter what" or "as a part of [their] work," "without asking permission" from the client. Will asked:

"They don't ask for a beautiful building, but we'll do that anyway. So why not a sustainable building too?" In his work, sustainable design ranges from "water, energy, carbon, community involvement, social equity, waste, life cycle assessment, all of these things." Brian believes that the architects and engineers should make the assumption that the client wants a sustainable building. He thinks it is the architect's role to educate the design team and take control of the sustainability goals from the beginning.

> I think that architects need to become educated to take the time to get the people in the office, you know, educate in terms of what is sustainable and what makes the building sustainable. Both from a short- and long-term life cycle perspective. And then I think that those guiding principles ought to be established upfront. And then I think the firm ought to follow those and ought to provide a leadership to their clients, so then it's not even a discussion. This is just the way it should be. This is the way we do things, this is how we build a building. (Brian)

I share Brian's beliefs in the role of the architect as a leader. Almost all of the architects I interviewed mentioned "leading the design team" as a part of their roles in the design firm. There is a difference, though, between coordinating or managing a team and *leading* a team. My advice to architects: be a leader. Do not ask for permission. Asking whether the client *wants* a sustainable building, offering sustainability as a choice, means that it is acceptable *not* to choose it. It is not acceptable. Not anymore.

Conflicting views about Design for Disassembly and Resiliency

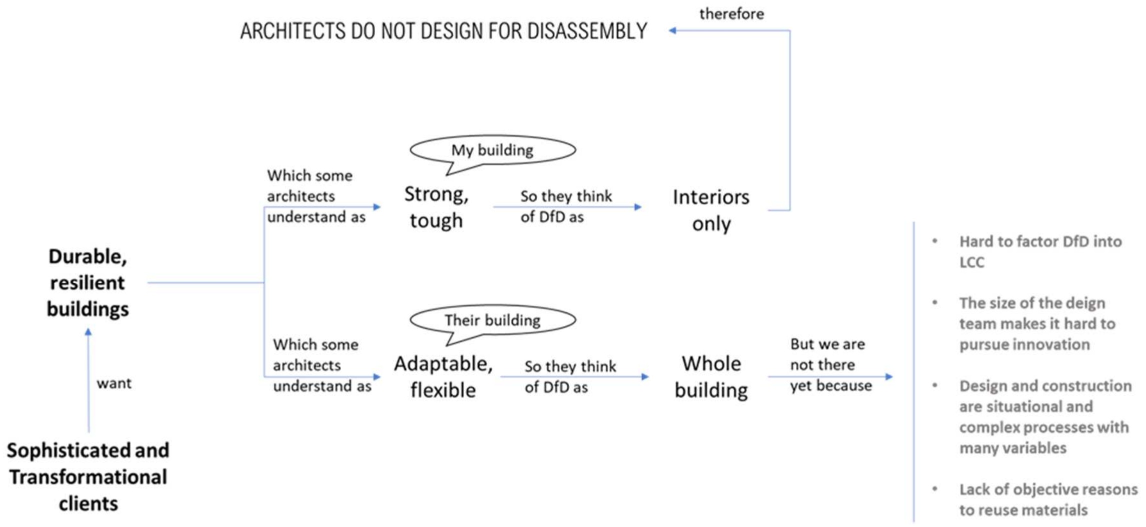

Figure 20. Conflicting views about DfD and resiliency: diagram.

Most long-term building owners want durable buildings. Many participants have designed for institutions (e.g., universities, civic buildings, hospitals), and a resilient design is a common request among such building owners. “It’s always a major ask of them,” said Will. “‘We wanna a flexible project to last fifty to a hundred years.’ And some cases, you know, much longer.” He also thinks that architects can use the concept of resiliency to talk clients into some sustainable design strategies, such as a flexible, adaptable design.

> So when sustainability, climate change, they aren’t part of a lexicon of a particular government or leadership, there are certainly different words you can use to approach the problem from a different perspective. Resilience is huge, you know, the ability of a community to bounce back or even improve after a disaster is universally accepted.

Will stated that he uses flexible design to create durable buildings. Flexible here means “reconfigurable,” adaptable to future changes. “Flexibility” was a recurring topic that emerged from the interviews. When asked about what type of buildings would benefit most from a flexible, adaptable infrastructure, Mark stated that "quick-changing and highly experimental" environments like corporate and educational buildings are the ones that need flexibility the most.

The lack of flexibility may be one of the main reasons why buildings are demolished or abandoned in the United States. Structures that cannot adapt to new program demands and technology are often torn down before the end of their useful life. Dylan brought up the case of office buildings: "It just seems like every time an office building turns over they got it down to the slab and got to start over every time. So it may be useful to see more 'plug and play.'" "Plug and play" is the term that some participants used to describe a modular architecture with prefabricated components that can be easily added or removed from the building. Dylan believes that plug and play can create more flexible buildings that would adapt to new programs that arise every time the building's ownership changes. An adaptable design would bring resiliency to the building; it would not need to be pulled down and rebuilt before its useful life. Kody resents the loss of historic buildings, or what he called "architectural treasures" because they could not adapt to new programs.

In Jack's experience, built-in flexibility can have a higher first cost than a conventional design. According to him, clients invest in flexibility because they *believe* in it or because they are trying to make a return on *investment*. That is, they are either transformational clients, who are moved by their values and beliefs (e.g., what is the right thing to do) or sophisticated clients, who see their buildings as a long-term investment.

> It gets pretty expensive to build in that flexibility, and at some point, you're investing in it because you believe in it or you're just trying to make an ROI. So it's just a balance of trying to plan for that flexibility in the future and the reality of the first cost. (Jack)

The drivers for resiliency and flexibility are connected. When we look for the definition of something "resilient," we find a few common meanings: "strong," "tough," "flexible," and "adaptable." It seems that some people focus on the first two, while others think of the latter two. This statement from Charlie well exemplifies the first case.

> Typically, when we design buildings, we design buildings to be there permanently, to get as long as a life use as possible. So we try to specify durable materials that are gonna last a long time. We try to do mechanical systems that are gonna last for a long time, and so on and so forth. So we are not really looking into deconstructing the building in the future. And you know, we try to build the building as strong as possible so that doesn't really lend itself to being able to take it apart.…[Universities] want you to build a 100-year building. So they'll invest in better materials, stronger structure, better mechanical, plumbing, electrical systems that will last and hold up for years and years.

Charlie clearly associates a durable building with a strong building. Most importantly, he thinks of a strong building as opposed to a building that can be disassembled. He sees disassembly and resiliency as conflicting goals. However, he does acknowledge the need for flexibility—again, in educational buildings—when it comes to the interiors, although he is "*not really doing anything special to make those renovations easier.*" He talked about the possibility of using operable walls as a way of designing for flexibility, which was a recurring example brought up by the participants when asked about disassembly.

Kody reinforces the thinking of DfD as a strategy for the building's interiors. He brought up the need for "adaptability" to allow the reuse of the space for other purposes. He thought of adaptability as something that needs to happen "within the [building's] structural container." In his opinion, the disassembly of the building's envelope makes sense for temporary buildings only. "I would think if you're designing with disassembly in mind it's because you're anticipating that the building is going to outlive its usefulness relatively quickly (Kody)."

Another participant, Louis, claimed that the aim for durability keeps the future EOL of the building away from "the majority of [his] clients' mindset." In Louis's experience, "the ability to demolish and recycle [the building] is trumped by permanency."

Louis's answer also brings light to another issue that will be explored further in this text: he referred to disassembly as "the ability to demolish and recycle [the building]," when the true intent of DfD is to deconstruct and reuse the building and/or its components. This misuse of terms reveals a lack of understanding of the waste management hierarchy, which may reflect a lack of awareness about the importance of preferring reuse to recycling.

While some architects did not intuitively associate DfD with resiliency for the whole building, the majority of participants saw a clear link between DfD, adaptability, and the building's durability. Most of them also mentioned DfD as something "we should be doing," or as an opportunity for sustainable architecture. See, for example, this excerpt from Mary's interview:

> I see where the hesitation comes from with the general meaning of disassembly, but I think understanding disassembly means adaptability of the buildings, in terms of a building's structure or interiors. I think there's a really great opportunity to associate disassembly with resiliency rather than temporary… If they [the building owners] want something permanent, that's gonna be there, I think they need to understand what resiliency means. But I do think it is on the architect and a true collaboration with a cross-discipline to integrate disassembly into the design, because the owner is not gonna know how to do that. So I think we as architects need to understand those design principles of disassembly maybe more so than we do now. I have no exposure to that, but I can start thinking about the idea of disassembly. (Mary)

Mary believes DfD is an opportunity to create resilient buildings through adaptable structures and interiors. Her answer also reveals that she did not know much regarding DfD prior to the interview. This lack of previous knowledge was common in other participants. At the end of the interview, I usually explained the potential of DfD by using the Bullitt Center[10] (Seattle, WA) as an example. The Bullitt Center was designed to last over 250 years, and one of the ways the architects found to make it happen was the design of an envelope that could be easily

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[10] The Bullitt Center was designed by Miller Hull Partnership, and it was completed in 2013. More information about the project can be found at: http://millerhull.com/project/bullitt-center/

disassembled. After listening to this example, some participants immediately understood the benefits of the practice.

> I think that the example that you gave is a good one. There are gonna be materials on the building that will be replaced over that 100-year life, as part of the ongoing maintenance. And of course there are gonna be technologies that change and evolve, so having parts of the building being able to be removed or disassembled from other parts of the building and replaced without necessarily taking the whole building apart... I think that attitude makes a lot of sense. (Kody, who had previously associated DfD with interiors only)

Similarly, when I explained about the potential of DfD to allow for easier renovations throughout the building's life cycle, some architects thought it was "a great idea." Four out of 13 participants mentioned having changed their mind during the interview about the usefulness of DfD when it comes to permanent buildings. Some participants had never heard of the Bullitt Center or knew of any example of a building that was both built to be "permanent" and to ease disassembly. So hearing of an existing example of DfD and the architect's motivations behind it seemed to be enlightening for them. However, I did not include the lack of more examples like the Bullitt Center as one of the reasons why architects do not design for disassembly, and that was a deliberate decision. I did not want to create a "chicken and egg" situation and decided to focus instead on what architects can do right now to advance DfD.

Interestingly, two participants brought up the Bullitt Center on their own. Will related the Bullitt Center with what he calls "design for change." He defined design for change as allowing for "reuse, adaptability, resiliency, functionality, and value over time." He also brought up an important characteristic of a DfD building: its components can be easily replaced after a natural disaster, such as hurricanes or earthquakes. Conversely, "if a welded steel building gets compromised, then you have to tear it down."

Luke used the Bullitt Center as an example of how DfD can create a transformable construction:

> We all strive to build buildings that will be useful for a very long period of time. But you know... In reality, really, buildings transform. Especially, when you turned them over to a client; it's their building. So... I think that [DfD] is, uh, kinda what we should be doing. We really are acknowledging what our role is in our environment and our culture… So, like the Bullitt Center. It's a good example. You know, most of that building can be reused, by limiting the chemicals, utilizing construction techniques that can be disassembled, that building if it needed to be transformed, would be very transformable.

In his answer, Luke acknowledged the transformations that the buildings go through once they are turned over to a client. If we analyze his answer more deeply, we will note that the fact that buildings transform is contrasting with the intent of the architect. We want to design buildings to be useful for very long, "but" buildings transform. They transform because the client makes changes in it over time. When you turn the building over to a client, it's "their" building. Before that, who owns the building? Charlie may have the answer for that:

> As far as disassembling the building, we don't like to think like that. But I do think it's really, really interesting that, uh, I mean, I guess you're doing your thesis on that and I'd love to see you, like, maybe not now but at some point what your findings or like examples of people doing that because I think this is a great idea. But most of my buildings are supposed to last... I get in trouble if my buildings don't last, so... (laughs).

Charlie thinks the idea of disassembly seems great, but he does not "like" to think about disassembly because "his" buildings are supposed to last. Charlie knows he doesn't own the building, but as an architect, he may feel that way over his creation. Charlie is not the only one. We, architects, often refer to the buildings we design as "our buildings." If we Google "Frank Lloyd Wright's buildings," we are going to find a list of the buildings *designed by* Frank Lloyd Wright. It is an artist/art relationship. As a general rule, artists do not want their art to be altered over time. They invested time and effort in that particular creation, and it is a nightmare to imagine it being transformed by another person. The same may happen with architects and "their" buildings. In my personal experience, when casually talking to other architects about DfD, some of them also showed a resistance to think of the disassembly of "their" buildings. They do not like to think of the building's EOL (they hope the building will outlive them by far), and they have a hard time accepting future changes. Changing this behavior depends on changing the way we think as architects and the way we perceive our "role in our environment and culture," as well said by Luke.

In conclusion, thinking of resiliency and the ability of disassembly as conflicting goals is a powerful obstacle for DfD practices. On the other hand, most building owners want to invest in resilient buildings, so there is a great opportunity to associate DfD with resiliency, regardless of the "level of sustainability" for which architects and clients strive. But there are other issues on our way to DfD, and I will discuss them in the next sections.

Associating subjective reasons to reusing building components

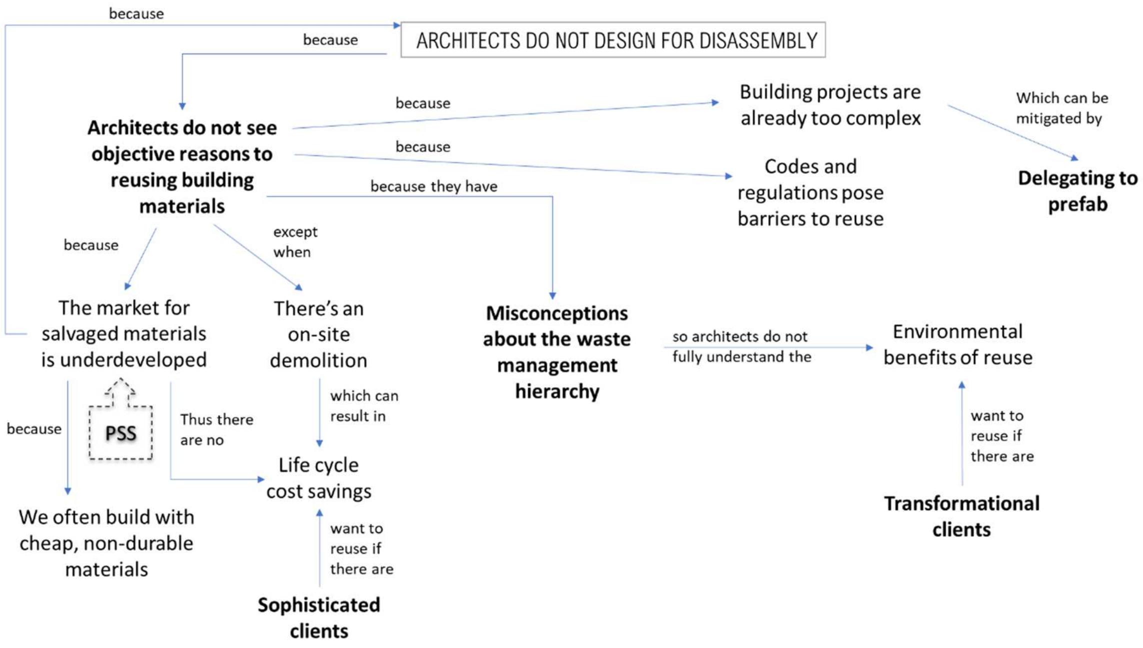

Figure 21. Associating subjective reasons to reusing building materials: diagram

When asked about their motivation, as architects, to reuse building materials, many participants came up with reasons such as "aesthetics," "beauty," "elegance," "unique look," “entertainment of building users,” “sentimental value,” historic value (“selling history”), or artistic value. They associated subjective motivations to reuse. Jack went as far as saying that “by definition, salvaged materials are unique and not commercialized.” The notable exception was when they talked about adaptive reuse, that is, reusing an old building (or its materials) when this building is on the same site as the new project. That said, it was a common theme that they did not find a lot of opportunities to use salvaged materials in new projects. The following excerpts illustrate the subjective meanings given to salvaged materials.

Roger established a causal relationship between the lack of cost-benefit in reusing and the subjective reasons to reuse something.

> R: We are occasionally given the opportunity of, say, we’re going to a site where this existing building’s gonna come down, and we’re gonna do something new. Or for some reason, the owner or somebody has, want to incorporate… but there’s usually smaller, detail kind of thing.…A lot of times the cost of taking something apart and prepping that for reuse is prohibitive, and [we do it] only if there’s aesthetic or sentimental value or some other meaningful reason. It’s a challenge to do that. We’re doing work at a private school.…There was this building that had a kinda Pizza Hut sort of roof, but they were real copper. So we came up with that strategy to make this big screen wall reusing the copper. And we researched to figure out how to do it and the fabricator, everything. And the school just became impatient. So “we’re not gonna do this. We find a big photograph and hang in that place instead.” It was gonna be this screen wall, kinda see through, 16 feet wide by 25 feet tall, it was a substantial thing. They have kept all the copper. They’re looking for another way to reuse it.
> F: Why did they get impatient?
> R: We had this incredibly complicated project. We just had so many things that were demanding everybody’s attention that all of a sudden it came the time where we needed the screen, and it was really a piece of curtain. And we scrambled to figure out how to do it. And it’s really unfortunate that the headmaster just kinda lost patience. They wanted to have a grand opening, and we weren’t able to get this done in time. Maybe it can happen in the future. I kinda doubt it! But anyway, at least in our practice we haven’t found too many opportunities to reuse, you know, a substantial way to reuse...

Because the cost is prohibitive, “we” only reuse if there is an aesthetic or sentimental value to it. That makes sense since being cost prohibitive means that there are no (or very few) objective motivations to reuse building materials. Why is that? His example of the private school illustrates some of the reasons: the complexity of the project and the time pressure from the building owners. In the next fragment, Roger revealed how he prefers to approach salvaged materials: by giving it artistic value.

> …My mindset usually is, try to think of a way of reusing the materials in a new way that kinda make people stop and take notice. Or be kinda entertained by a material being used in a completely different manner. With the copper in my daughter's school, those copper roofs were the primary source of, what's the best word, the most distasteful thing on the campus. Everybody thought: "we have to get rid of those!" And to take those and transform those into a beautiful piece of art, that's kinda the strategy. Versus saying "well, we're gonna re-clad the new buildings with that copper." That probably would have been rejected because of all the coordination and all that. Although it's a perfectly legitimate idea if you can figure out how to accommodate it in your schedule and everything. Because that's what we should be doing anyway.

Although Roger prefers to attribute an artistic meaning to salvaged materials and use them for a "completely different" purpose, he acknowledges the value of reusing materials for ordinary applications. But he believes that, had this been his own approach, the client would have rejected the idea, again, because of the lack of objective reasons to reuse. He thought it would be more reasonable to convince the client through transforming the salvaged copper into a piece of art than by proposing the re-cladding of the new buildings. In the end, he acknowledges that reusing materials is what we, architects, should be doing if we can coordinate "everything." But what is everything? According to Carol, "everything is set against reuse." In her opinion, it all comes down to the economy:

> I think economics continues to be, our economic system continues to impede our ability to improve design and have less environmental impact. And I think you probably find that even as you start talking about a circular economy that there's no real economic incentive for a circular construction system.

Most of the challenges that the participants mentioned about reusing building materials can be traced down to the economy as well. In Will's experience, for example, despite the fair number of existing salvage yards, it is hard to use salvaged materials in large projects because of the lack of a reliable supply. Therefore, he feels that it is easier to reuse materials in smaller projects where there is no need for many elements of the same type. For example, maybe you can find three or four matching salvaged doors, but it is much harder and time-consuming to find 15 of them. Brian reinforced the demand versus supply issue. He mentioned problems in size, quantity, and quality of salvaged materials and agreed that a stronger market for salvaged materials would help to solve these problems. "If somebody would centralize and store these materials and make them more readily available as for size, quantity, that would make it much easier to reuse," he said. He illustrated his point with a personal anecdote about trying to replace his house's clay roof:

> For example, I just had to replace the Italian clay roof on my house that's 100 years old, because of a hailstorm. And only about 10–15% of the pallets were broken, but they were broken uniformly across the whole roof. But because they stopped making that particular tile in that size, in that color, I had to redo the entire roof with a completely new roof. Had I been able to find that particular size stored somewhere, then it'd cost me 30 thousand dollars rather than 300 thousand dollars probably. And now all the roof that was taken off will be taken to the dump. As opposed to be taken to a yard, a storage facility. But I came across an issue where it'd be much more costly to have taken all these tiles down, up and down a ladder, packaged and stored, than it would be for them to just throw them from the roof straight into a dumpster. So it's gonna cost almost 10 thousand dollars more to take it down and salvage for a potential reuse in the future. And then there was storage fee versus just taken to a dumpster and hauled off to the dump. Which is very disconcerting. I thought, "Gosh, there outta be some way you can just use a lift and do it more cost-effectively and store it at a yard so somebody in the future could reuse it." You know what I mean? So anyway, that was very difficult.

One of the reasons why there is no larger supply of such materials is that architects do not design for disassembly. If the building is not easy to take apart, many components will be damaged in the process of deconstruction. Moreover, short-term building owners who are interested in a faster ROI often use cheap, short-life materials in their building renovations or new construction. Carol exemplified this problem:

> It's not unusual in the Northeast to see houses that have roofs that lasted for 100 years, but the ownership on the houses is gonna change every five to ten years so

> the roof when it's gonna be replaced, they're gonna put an asphalt roof on it. And the same thing with the copper in the gutter. You know, they're gonna go for a less expensive material even because of the ownership. They're not gonna get their ROI. (Carol)

Carol's words echoed in Jack's definition of the "Wal-Mart effect."

> And in this country, at least, there is a continuous—I call it the Wal-Mart effect—there is a continuous drive to make things as inexpensive and nondurable as possible. So, a commercial door that's put in a commercial building five years ago probably isn't worth pulling out of a building and reusing. Whereas in 1930s house, the doors were solid wood and well-constructed. So as long as we build cheaply, the materials that we use today aren't gonna be worth to use in the future. (Jack)

When we do not design for disassembly and when we do not use durable materials, we do not allow for reuse. Consequently, the market for salvaged materials does not grow its supply. In turn, architects do not find objective reasons for specifying salvaged materials, do not understand the importance of reuse, and do not design to ease future reuse. But I have already stated my commitment to staying away from "chicken and egg" situations, so I will not explore this further. Instead, I will go back to Carol's statement that "there's no real economic incentive for a circular construction system." Like Carol, I defend that a shift toward disassembly and reuse demands a major paradigm shift in our economy. I discussed this topic in the Introduction chapter: how PSS and the shared economy can help to advance the practice of reuse in the construction sector.

But the lack of support from the market and economy are not the only reasons why architects rarely find objective motivations to reuse building materials. Will brought up problems with building codes and the project's inherent complexity. According to him, "The building codes are a huge barrier [to reuse] because so many of our products have to be UL-listed for fire, smoke, sound, so many other ways... FRC, red doors, windows... It adds layers of complexity to the project." I will explore further in this chapter how the rising use of prefabrication can take layers of complexity off the project and help architects to design for disassembly and reuse. As far as the role of the building codes, Kevin thinks differently:

> I think the codes will adapt to what the industry thinks is important. I don't think the codes will drive how we build. I think the codes react. I remember when there was a whole movement to do straw bale construction... the codes weren't there, and there was a time..., and then they kinda caught up with it. I think the market is gonna drive it. It's just how strong the contractor groups are, the AIA and stuff forcing those things to catch up. But I don't think they're pulling us back. That's not the issue. It's a cost issue.

Kevin believes that the market and economy will drive the changes in the construction sector, and the codes will adapt to it. Following this logic, the development of the market for reused materials will likely make it more cost-effective, in a Life Cycle Cost manner, to reuse building materials. This would attract the investment of sophisticated clients in salvaged materials. As a potential consequence of this scenario, the building codes and regulations will start to adapt to the new reality and remove barriers to salvage building materials—as long as they are safe to reuse.

Last but not least, architects often do not understand the environmental value of reuse when compared to recycling. This is part of what I called "misconceptions about the waste management hierarchy". It is not clear to everyone the distinction between reuse and recycling, what is (and what is not) reuse, and the trade-offs within the waste management hierarchy. The waste management goes like this, in order of the most favorable to the least favorable to the environment: source reduction, reuse, recycling, energy recovery, and disposal. First of all, reuse and recycling are not the same, as discussed in Chapter 2 of this dissertation. As a golden rule, reuse is preferable over recycling because it does not take extra energy to reprocess a material. However, this is not always true. The transportation distances need to be carefully taken into account in both cases, as the environmental impact from the transport can undermine the benefits of reuse and recycling. I have explored this subject in Chapters 5 and 6. That means that the waste management hierarchy is not a static structure and that there may be trade-offs between waste management strategies.

For example, Kevin brought up how his firm uses pre-engineered steel structures as often as possible to reduce the amount of steel in structural sections. This is an example of “source reduction,” but it also limits the possibilities of reuse of the same structure in another building in the future. For example, say we save 30% of steel in a pre-engineered beam designed to attend to a specific building demand, and say that this beam could not be reused in the future because we could not find a building that had the same structural demand it was designed for. We saved 30% of steel now and none in the future. Now, say we have a standard beam designed for a range of structural demands. We are not saving any steel in the present, but we may be able to reuse it in the future and avoid 100% of the production of new steel. Yet, we cannot forget that by using the pre-engineered beam, we are saving resources now, while a reusable beam is subject to future uncertainties out of our immediate control. So, which is better? The point is: there is no one-size-fits-all answer for the waste management hierarchy, and we have to become aware of the possibilities and the differences between them so we can make informed decisions.

Similarly, it is essential to understand the difference between reuse and recycling to truly understand which one is the “right thing to do,” depending on the project, and to be able to interpret life-cycle assessments with clarity. Nonetheless, a few participants used both terms interchangeably. For example, Brian claimed that his team “recycled, for example, copper, when it’s taken off of a building and put into a new building,” because “the recycled copper was much less expensive than buying new copper, and it also had a beautiful patina.” What Brian meant is that he *reused* copper. Later, when asked about where he finds a supply for his “salvaged materials,” he mentioned a large contractor that has the practice of storing the “leftovers” from construction projects to use in other buildings. These materials are not reused because they were never used in the first place. These are still virgin materials that were not used in a project and are sitting in a storage unit waiting for the next opportunity to be used. Other architects understood the recycled content present in some building components as being part of the salvaged materials.

Louis said that his team specified “a certain amount of salvaged material within our steel and our concrete.” This is especially problematic, as architects may think that they are doing their part in contributing to a CE in the construction sector by simply specifying steel structures, which by default have a large portion of recycled content.

Part of the reason for such misconceptions is the lack of understanding of embodied energy and carbon by architects. They have a very good understanding of energy efficiency in terms of the building’s operation and performance but little knowledge when it comes to embodied impacts, as pointed out by Louis:

> I’m finding that clients don’t have a full appreciation of, and I’m not sure design professionals do either, is sort of the embodied energy [impact] in projects. So, what it took to get that out of the ground and all the impacts associated with manufacturing, that sort of thing. I think that’s something that isn’t... it’s a level of detail that I’m not seeing most of our clients interested in and focusing on. And I think that may come from the architects themselves, because I think honestly we don’t have… the majority of us don’t have a great understanding of that embodied impacts." (Louis)

The inability of architects to fully understand and differentiate waste management strategies reflects in their communication with their clients. This way, if a transformational client wants them to design a building that “improves the environment” and “does the right thing,” they will not be able to identify *what* the right thing to do is. It is much easier to fall in their comfort zones and specify materials with recycled content and try to remain guilt-free by believing that they are making a contribution to a CE and sustainable design practices.

The difficulty of factoring Design for Disassembly into Life Cycle Cost

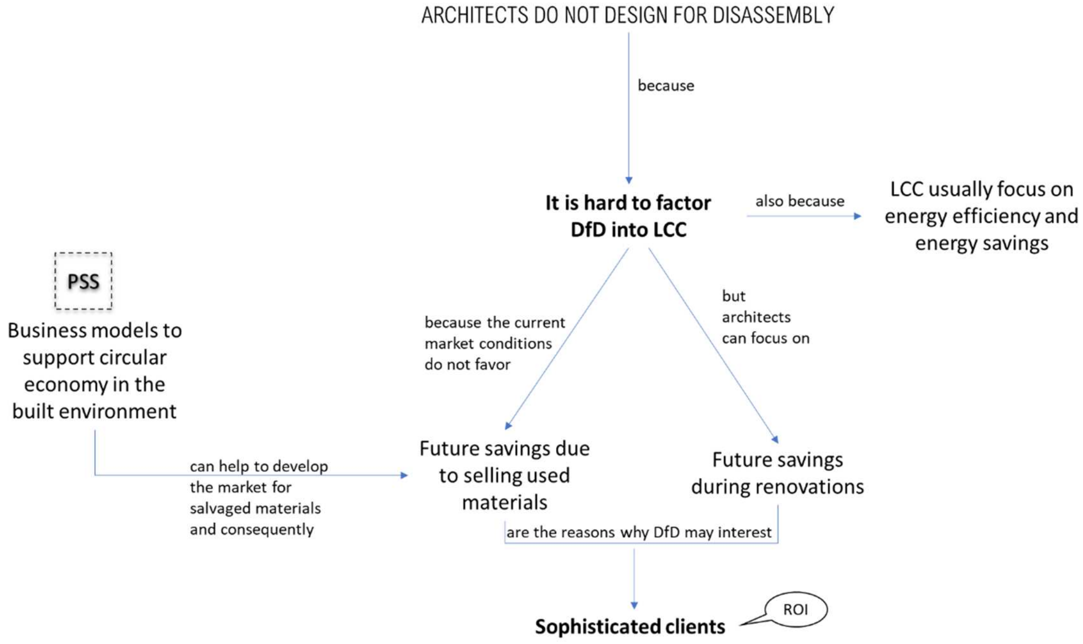

Figure 22. The difficulty of factoring DfD into LCC: diagram

The theme of using lifecycle cost (LCC) as a way to "sell" sustainability ideas to the clients emerged in almost every single one of the interviews. I used the term "emerged" because LCC was not in my original interview scripts, but it proved to be one of the most important factors when discussing the feasibility of sustainable design strategies. LCC involves the balance between first cost (or investment cost) and operational costs (such as energy and water costs and maintenance and repair costs). LCC is an important tool in sustainable design because most of its strategies, especially the most innovative ones, have a higher first cost that can be offset in operational savings throughout the building's lifecycle. It usually focuses on energy performance and energy savings, as maintenance and repair costs are harder to predict. Some participants described the "hurdle of the life cycle [cost] versus the first-time cost" as one of the challenges in their profession. Mary found that “LCC is hard to convey.” She works in the healthcare sector and believes that hospitals’ specific needs makes it more difficult to “find room in the budget.” Luke thinks that such difficulty also comes from the fact that having a client is rarely a part of the architects’ college education.

I could not agree more with Luke. In college, we are taught to free our minds from budget pressures. It is like we are working for “transformational clients” constantly. After we graduate, we realize that such clients are extremely rare to find, and we very quickly become frustrated with our professional reality. That was what happened to me and most of my peers in Brazil, and as I found out by talking to Mary at the end of the interview, it is not very different in the United States. We had this naïve idea that all clients would opt for sustainable design only because it is the “right thing to do.” Similarly, Mark believes that LCC is “backward thinking.” He thinks that, by demanding an LCC analysis, the client is “challenging the right decision at the beginning of the project, when we know that the wrong decision is gonna end up costing more over the life of the project.” Backward thinking or not, many participants agreed that LCC helps to educate the client about sustainable design.

> Some clients aren’t even thinking about [sustainability], and then we’ll have conversations. We’ll talk about life cycle costing, operations, all these things. We make sure they think about the entire lifecycle of the building versus just the capital cost upfront. (Kevin)

Factoring sustainable design strategies into LCC is speaking the language of sophisticated clients who understand the “true cost of material labor,” as said by Luke, or the “real economy,” as described by Mark as the “total value of the building over time.” This value includes salaries, utilities, the cost of tuition in case of educational buildings, and all operation and maintenance costs that are related or not to the design. In Marks’s experience, sophisticated clients understand that the construction costs are a very small part of this total value.

Institutions like universities and government agencies were mentioned as examples of sophisticated clients. Carol mentioned that she likes to work with institutional or academic clients because “we can honestly talk about 50- and 100-year service life, and they appreciate that.” In Luke’s experience, “There’s a better chance sometimes with advocating for sustainable or ecologically sensible designs for larger client groups like municipalities, institutions... even the government. Especially when you can really talk about how the bottom line can be affected.” He described a project for the federal government when they successfully explained LCC to the General Services Administration (GSA) and how they could save money in a short period of time due to water harvesting and solar panels. “Because we advocated for that early and we brought information to the table, they went along with it. And had a charge as a federal agency to minimize the long-term costs of the project.”

It is somewhat straightforward to do an LCC analysis on water and energy savings. Water and energy bills are not so hard to predict, and there are plenty of resources to help with this type of prediction. But factoring the financial benefits of DfD into LCC involves much more uncertainty. There are two ways DfD can bring financial savings to building owners: by easing renovations and by the resale value of building components.

In theory, it is possible to factor the financial savings from easing renovations into the LCC. We would have to compare the cost of future renovations in two scenarios: with and without DfD. DfD would probably pay off when the building went through a major renovation, mainly because the DfD would allow for the building’s adaptability to new space demands. In other words, DfD would make it easier to reconfigure, expand, or downsize the building and, most importantly, would avoid a costly demolition and reconstruction. But factoring these scenarios into LCC involves asking a number of questions. How often would the building go through minor renovations? When would the building go through a major renovation? Are there data to aid such predictions? How much do these renovations cost? And how much can we save with disassembly? Finding data to estimate time and cost of future renovations is probably easier with large, older institutions that have been gathering operation and maintenance data over time. Still, we need more research and databases to make it possible to answer these questions in a more accurate way.

Estimating the resale value of building components is even harder, especially because we currently do not have a strong market for salvaged materials. Certain materials such as metals, wood, and brick, that are being used for a long time and do not depend on technology changes, are more likely to hold their value over time. Yet, in today's market, their resale cost would most likely not be enough to compensate for higher first costs of specifying durable materials, or higher costs of the disassembly process when compared to demolition. In this case, there is no easy way: the economy must go through a major paradigm shift.

In Carol's words, “[The] economy drives everything.” Kevin was very straightforward about it: “It always comes down to dollars. If it doesn’t make economic sense, it’s not gonna happen. It’s really that simple.” As architects, we can take measures to leverage DfD and the reuse of building materials, but we must have economic support to promote a true closed-loop system. We cannot talk about a CE in the built environment if we do not talk about circular business models. As explained in Chapter 2, an example of such business models is Product-Service Systems (PSS). I asked some participants what they think about the idea of applying PSS to construction, as in, for example, leasing building materials. Will found the idea “exciting.” He believes that “any way that the owner can defer first cost and put into operational cost and then maintain like a service contract... I think that’s best for a lot of parties.”

Some participants brought up examples of building materials and components that are being leased by a few companies, mainly in Europe. Carpets and solar panels were the most mentioned examples. “I know a couple of great, sustainable, carpet manufacturers; they will lease your carpet tile to you. And they will clean it on a regular basis, replace it when you need to replace," Mark told me. Carol heard of elevators in Denmark: "The elevator was still a property of the elevator company and leased to the building." In Mark's opinion, "The tax laws can actually favor something like that." He believes that ceiling systems, furniture, demountable walls, and "anything that's not permanently attached to the buildings" are great candidates for being leased to buildings. There are many barriers to overcome, such as the uncertainty of the company's lifespan, as Will pointed out. But Mark is confident: "We'll get there. It's just we're all here, so. You're ahead of your time!"

In summary, architects use LCC analysis to "sell" sustainable design strategies to sophisticated clients. However, factoring DfD into LCC is not easy and involves many uncertainties about the future. DfD will pay off if the cost of durable materials and built-in flexibility are offset by the savings of future renovations and the future resale of used materials. But we need more research and data in LCC for various types of market sectors and locations, and we need business models that support a CE in the built environment.

Prefabrication is an opportunity for Design for Disassembly

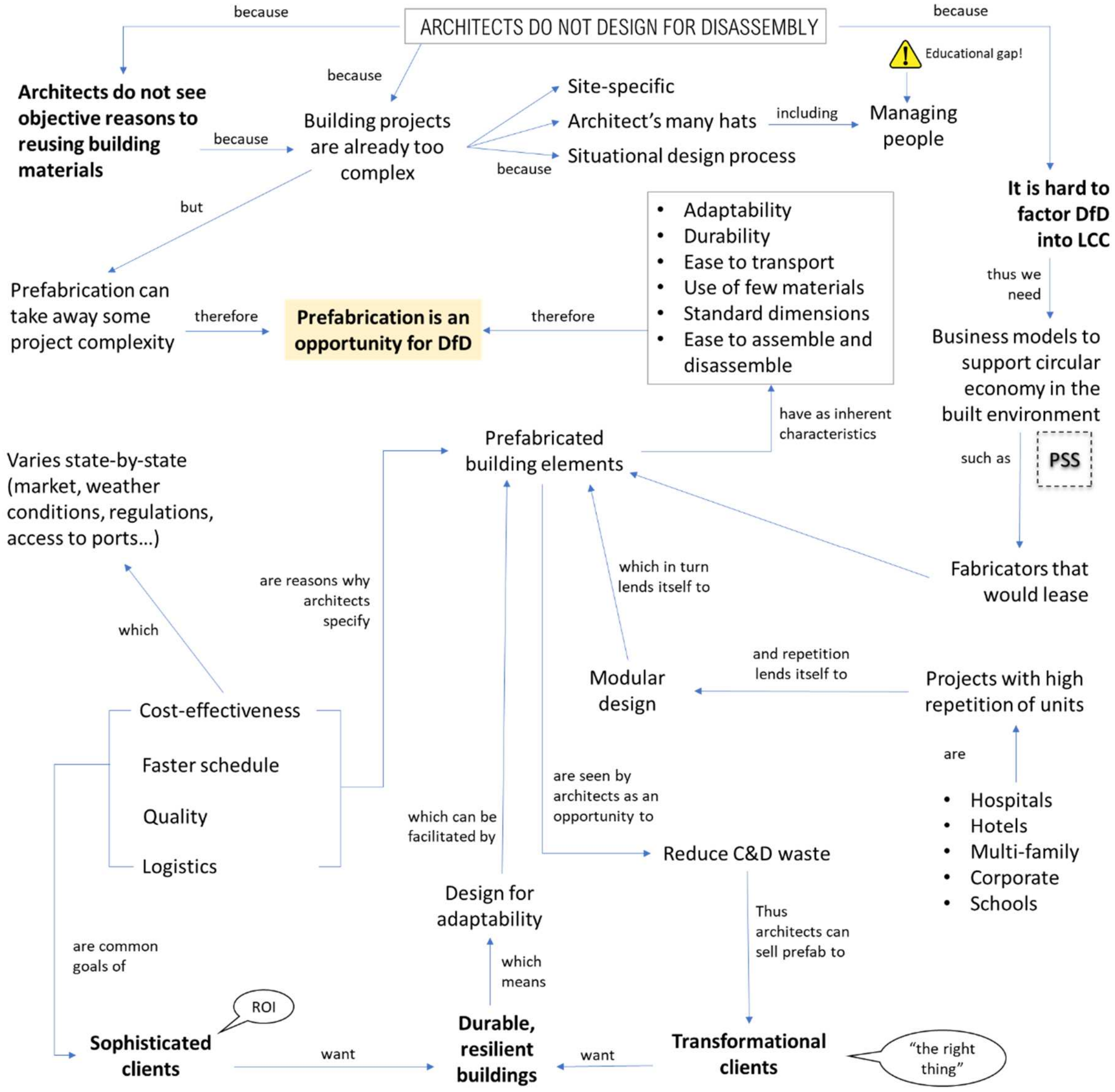

Figure 23. Prefabrication is an opportunity to DfD: diagram

One of the first things I asked the interviewees was to briefly describe their design process and their role in the design team. I had created this question to understand the level of experience of each architect and how they participated in the decision-making and had no intention of analyzing their answers as part of my theoretical categories. However, throughout the data analysis, their answers to this question revealed more reasons why, I believe, the architects do not include DfD in their design process.

First, the question about the architects' role in the design team revealed that architects in the United States (and in many other parts of the planet, I suspect) have multiple roles: managing projects, managing clients, doing research, leading the design team, leading the conversation with consultants, putting the teams together, creating internal sustainability goals for the design firm, ensuring collaboration among team members, teaching co-workers… they wear too many hats! But the main problem is not the number of responsibilities that they must deal with at the same time. It is about the *nature* of such responsibilities. Most of them involve not only the technical skills that architects learn in college but also soft skills like people management. This is true for the most experienced architects (e.g., principals of the design firms), such as Jack, who must "manage projects and manage clients and teach people that work in these projects." And it is also true for some of the least experienced ones, such as Mary, who must "lead the coordination efforts across disciplines with the MEP engineers, structural engineers, any other consultants that we have on the projects." Luke believes that there is a disconnect between education and practice because the education process does not involve a client. In my experience, Luke is right. During college, I never had to defend sustainable design strategies by talking about life cycle cost, for example. My peers and I just assumed that every client would be interested in sustainable design. Similarly, we were free to design without worrying about budget, schedule, or site logistics. We develop our technical skills but not our soft skills. It is not until we join the job market that we face the responsibility of "selling" our ideas to clients, engineers, and contractors. Almost all participants claimed to work in a highly collaborative and multi-disciplinary environment, but as architects, they "lead the conversation" across disciplines. Or, in Carol's words, they "shape the direction of everything that happens." Thus, as Luke, I believe that I think that "one of the skills that we should be trying to help the architects of tomorrow is how to promote these new ideas to clients and how to be advocates for the environment, for modularity, and disassembly."

When asked about their design process, the common answer was "it depends on the project." Kody said that, although there are some issues that he and his coworkers try to consider in every process, they do not have a "set process" to follow. Luke found the question "hard to answer." He said that the firm he works in shuffles teams around from project to project, so his design process "does vary quite a bit." Jack and Will also answered that their roles change a lot on a project basis: "It happens differently every time depending on the client, depending on the project."(Will). Later, Will brought up the size of the team and the complexity of the project as factors that limit the architect's role in preventing C&D waste.

I will exemplify such limitations with the decision-making process that leads to welded or bolted connections in steel structures. One of the interview questions was whether the architects feel that they had a role in deciding if a steel structure would be welded or bolted. It was a consensus among the participants that it depends on the project, but they rarely have had a say in this type of decision. In Kody's and Dylan's experience, the architect has a role in this decision only if the connections are going to be exposed.

> "I think the only time the structural engineers are willing to listen to us in terms of if something is welded or bolted if it's going to be exposed and we have concerns about how it looks. I think if it's concealed construction they don't necessarily even ask us." (Kody)

In Will's experience, there are "good" and "bad" structural engineers. In his opinion, the good ones show up to the sustainability discussions, are proactive, and come up with innovative solutions. "The bad ones tend to rely on what they've done before or what they are familiar with. It's less work. There's a lot of institutional inertia that we need to overcome." Will believe that our role as architects is to choose "the right partner" early on the project. Several times, I have witnessed the "institutional inertia" Will refers to, both among engineers and architects, as well as contractors. In my experience, many construction stakeholders are stuck to the “tested and true” methods and are very conservative when it comes to taking the risk that is inherent to innovation, especially if it involves a higher first investment in capital and/or level of effort.

The structural engineers and architects are not the only ones involved in this type of decision (bolting versus welding). Mary and Kevin brought up the role of the contractor in such decisions. In Louis’s experience, the structural engineers design the strength of the connection, but the individual fabricator decides whether the connection is bolted or welded. The architect only has a say when there is a need for disassembly.

> “The only time we weigh in right now heavily on that is when we need something to be removable. There needs to be a section, you know, it’s one floor of the building, and in order to get equipment in the future, we need to be able to remove a section of floor. That’s when we will typically weigh in and require a welded or bolted connection.” (Louis)

Louis’s answer suggests that, if architects design with disassembly in mind, they would have a heavier role in some structural decisions, such as welded versus bolted connections. But that would add one more hat to the architects’ wardrobe and one more responsibility to deal with during the design process. What if, instead, we could delegate some of the waste management responsibilities?

Prefabrication can be an answer to these questions. When the architect specifies a prefabricated component to a building, s/he delegates some of her or his waste management responsibilities to the fabricators. For example, architects can choose a fabricator that reuses and recycles its own waste. Roger exemplified how prefabrication can help to reduce C&D waste:

> You know, the construction waste is an issue. One of the things that you sort of led into was the idea of prefabrication and modular design, which does help progress that, because in a factory setting there’s more control. And oftentimes the waste can be reincorporated in the project or other areas. When you got sort of one entity doing everything and creating say modules or something, there’s more control than five different companies each throwing away their scrap, instead of one company. So, there’s definitely more control, and it’s probably more effective in terms of using fewer materials and, hopefully, developing

> higher quality when you build in a controlled environment versus on the job site. (Roger)

There are many ways that prefabrication can create an opportunity for DfD. The following is a fragment of Dylan's interview where he described some of his projects in the healthcare sector.

> …And then these hospitals, Netzero water and energy hospitals, they're all modular and made from a single building material. And this material is panelized and can be put together adhesively and can support up to two stories. So, it's one of those things when we are very conscious of the dimensions. So we're thinking about: ok, this needs to get there in a truck or a shipping container. So, 2.2 meters is the limit. So, you start to think about the logistics of bringing materials to the site and how to get there and how efficient you can be.
> Me: So, it is a modular floorplan.
> Dylan: It is. It is. And that module can be used for a patient bed, it can be used for a delivery ward, it can be used for a surgical emergency room or a pharmacy. So we can adapt any part of the hospital that we need to. So, because it's the same size, made with the same size panels, it goes together in a lot less cost and as a composite. So it's just a more efficient way to do it. And in a part of the world that couldn't afford the kind of hospitals we build in this country and... I'm not sure we can afford the hospitals we build in this country (laughs). So we need to have a different solution, and I think that's what's driving that. And so, designing construction materials and processes are part of the solution. Not just the design itself.

Dylan described a modular floor plan that was built with prefabricated components. The combination of a modular design and prefabricated elements forced the architects to think about the dimensions of the project, so everything can be easily transported to the site. It also allowed for a highly adaptable design, so the hospital can transform according to future spatial demands. Adaptability, transportability, the use of standard dimensions, and the use of few types (in this case, a single type) of materials are all DfD strategies. Similarly, prefabricated elements are built off-site and assembled on-site, so they are inherently easy to put together—and likely to take apart. Also, the site logistics needed to disassemble the building is the reverse of the logistics used to assemble its components. All these factors show how prefabrication can work together with DfD. Another factor is the use of durable materials. Prefabricated building elements need to resist potential damages caused by their transportation to the site, so they should be built with durable materials. The fabricators also take away part of the higher cost of durability from the building owners, because they procure such materials in much higher quantities than what would be needed for one single project. Thus, durability is another DfD strategy that is inherent in prefabrication.

Fortunately, and unlike DfD, architects currently specify prefabricated components for building projects. Seven out of 13 participants stated that they use prefabrication on some level in their projects. Louis claimed to use prefabrication "all the time" for "certain aspects of the building." He used as examples curtain walls, precast panels, metal wall systems, and pre-manufactured stud walls. While many times the decision for prefabrication is driven by financial reasons, Louis affirmed that sometimes the main reason is site logistics. In a certain project, he said that "the site is so tight that they don't have the room on-site to fabricate, so they're going to build—this is a hospital project—so they're gonna build the patient rooms offsite and plug them into the building."

Another reason why architects specify prefabrication is the potential schedule benefits. According to Roger, prefabrication "can reduce the time of construction… [because] it's not a linear process, you have multiple tasks being done at the same time, and theoretically, the quality should be better." In Roger's experience, the quality of prefabricated elements depends highly on the fabricator. The desire for flexibility and the inherent repetition of certain types of buildings are also part of the motivation for prefabrication. Buildings like hotels, multi-family housing, student housing, corporate buildings, hospitals, and schools commonly repeat the same unit along the floor plan (e.g., apartments, offices, patient rooms, and classrooms). In Roger's opinion, repetition lends itself to modularity, which can be more efficiently built with prefabricated elements. Other architects drew a connection between flexible design and demountable walls for buildings' interiors.

Jack believes that prefabrication and modular design combined are a great opportunity to "build smarter, better, faster, and cleaner." Indeed, a few participants listed prefabrication as one of the design strategies that architects can use to reduce C&D waste. Carol believes that "modular and prefab have a reduced impact on the environment because of the reduced waste and quality control." Roger justifies the importance of a controlled environment in reducing construction waste:

> "In a factory setting there's more control, and oftentimes the waste can be reincorporated in the project or other areas when you got sort of one entity doing everything, and creating say modules or something, there's more control than five different companies each throwing away their scrap, instead of one company. So there's definitely more control, and it's probably more effective in terms of using fewer materials and, hopefully, developing higher quality when you build in a controlled environment versus in the job site." (Roger)

Kody mentioned demountable walls as an example of how prefabrication can reduce demolition waste. According to him, one of the reasons why DIRTT's [www.dirtt.net] demountable walls became popular is because they allow for disassembly and reuse, besides reducing construction waste when compared to "in-the-field assemblies."

When it comes to the cost-effectiveness of prefabrication, the opinions were divided between participants. While some found that prefabrication was a "pretty big win for a client" (financially), others could not talk the clients into prefabrication because "it didn't pay off." My conclusion, based on their other observations, is that the cost-effectiveness of prefabrication varies state-by-state. The architects mentioned several factors that impact the cost-benefit of prefabrication. Factors that drove the cost of prefabrication down were, as mentioned by the participants: the high cost of labor, the faster construction schedule, the high levels of repetition, the availability of local contractors, the connections with ports (because many parts come from Europe), and the possibility of a more stable workflow in a controlled environment (especially in adverse weather conditions such as heat, cold, and rain).

While some regional markets are more developed than others, most participants are optimistic about the future of prefabrication. Roger believes that the more “nationally and internationally acclaimed architects” adopt prefabrication in their design, the more credibility the practice will get. He also believes that the market for prefabricated building components will evolve. “I think we’re definitely gonna see more of this. You know, it’s sustainable, the more it’s done, the more the fabricator’s cost will go down, just like everything (Roger).”

Jack’s design firm has a personal drive for finding opportunities for prefabrication. He compared the barriers he has found with the barriers to sustainable design in general:

> “Again, a lot of the same issues that we encountered with sustainability early on: it’s difficult to find people who do modular construction, people who understand it, people who are able to price it competitively and to find an owner who’s willing to try something new that they have never done before, because there’s a whole lot of different issues when you come up when you do those.” (Jack)

Despite the difficulties, he believes that “once regions adopt it and see the benefit, it’ll then be adopted much more quickly.” Brian echoed Jack’s words. He believes that prefabrication will become more and more available and cost-effective across the U.S., although the process will likely be slower than in other countries. “We have a lot of rules and regulations and practices already in place. So innovation sometimes is slower here than it is in a country where there is not as many rules and regulations.”

The development of the prefabrication market may create opportunities not only for DfD but also for business models that support the CE, such as PSS. As mentioned in the literature review section of this thesis, a potential application of PSS in the construction sector is the leasing of building components by fabricators. Such building components would inherently be prefabricated and designed for disassembly, in order to allow for future take-back and reuse by the fabricators. Thus, there is a symbiotic relationship between prefabrication, DfD, reuse, and PSS, and this symbiosis is key to closing the loop and eliminating C&D waste in the construction industry.

In summary, prefabrication can be an opportunity—and even a shortcut—for DfD in many ways, such as by delegating part of C&D responsibilities to fabricators and by allowing adaptable, easy to assemble/disassemble/transport structures that use fewer materials and standard dimensions. Although architects still do not design for disassembly, they do specify prefabricated components for building projects. Some drivers for prefabrication are environmental benefits, a faster and more reliable schedule, quality control, site logistics, and cost-effectiveness (depending on regional factors). While the market for prefabrication is still under development, most architects were optimistic about its future and think we are headed in the "right direction." This is fortunate, since more prefabrication and disassembly will be essential in a shift toward product-service-systems and CE in the built environment.

8. DISCUSSION OF RESULTS

Chapters 5 and 6 of this dissertation attempted to estimate the environmental benefits (i.e., embodied energy, carbon, and water use) of reusing building materials in multiple life cycles. The materials chosen as scope for the analyses were part of the building's envelope, which is the building component that has the largest embodied energy. Chapter 5 compared a wood frame against a steel frame as external wall alternatives for a tiny house. The wood frame was assumed to be single-use not because it is less durable than the steel frame but because it is not usually designed for disassembly. Contrary to wood frames, steel frames can be bolted, which eases their future reuse. Chapter 5 accomplished its goal of showing how a hybrid LCA and a process-based LCA can produce qualitatively different results when analyzing the environmental benefits of reuse. In the same chapter, uncertainty analyses showed how reuse rates, transportation distances, number of reuses, and waste management scenarios can affect the results of a closed-loop LCA. The benefits of reuse depended on aggressive reuse rates (larger than 70%), which illustrates the impact of DfD on increasing reuse rates and waste diversion. The steel frame had to be reused twice to offset the larger embodied impacts of steel when compared to wood. All these considerations can inform future research in LCA and closed-loop systems in the built environment.

The reuse of wood, addressed in Chapter 5 as an uncertainty scenario, produced the lowest environmental impacts. Thus, house owners concerned about their environmental footprint should opt for second-hand wood studs available regionally, so they could de-nail and reuse them by themselves. If the owners opt for reusing a steel frame, they must make sure to reuse as much of it as possible and to ease its second reuse at the end of its life cycle (e.g., by choosing to use bolts as opposed to welding). Regardless of the framing system, house owners should avoid fiberglass and foam insulations unless they are reused and should prefer materials with large recycled content, such as cellulose- or denim-based insulation.

In Chapter 6, the material with the lowest embodied impacts depended on the timeline of the LCA. For example, in a study in which no lifespan was considered, asphalt shingles would have been the preferred material when it comes to embodied carbon, and copper would have been the material with the highest water use. But when the durability and reuse of copper were considered in the LCA (90-year analysis), the savings from the avoided production of new copper made the material preferable to asphalt shingles, aluminum, and steel, for example. In the same 90-year analysis, asphalt shingles were one of the materials with highest embodied carbon, energy, and water use due to its short lifespan and constant need for replacement. Designers must be alert to whether the durability of materials is considered in embodied energy LCA studies. Also, when performing comparative LCAs, practitioners must consider the durability of the material with the highest lifespan as the analysis timeline and ensure that the analysis accounts for the future reuse of durable materials.

Because the most durable materials in Chapter 6 were also the most expensive ones (i.e., copper and zinc), the choice for these materials in the design phase will depend on economic factors. Currently, there may not be enough financial incentive for choosing durable (and expensive) materials over the conventional choices, such as asphalt shingles. However, this may change with the advance of the market for reused materials and with the future rise of the shared economy and product-service systems in construction (e.g., leasing construction materials instead of buying them). Another consideration must be made here: choosing a material with lower embodied energy and carbon regardless of its lifespan is a way to control the reduction of such impacts in the present. Conversely, choosing a material with higher embodied energy and carbon but high durability and reusability allows for future reuse and avoidance of production of new materials but is subjected to the uncertainties of the future. However, as the CE evolves, so will the market for salvaged materials, and future reuse will become more feasible and less uncertain.

Finally, in Chapter 6, I proposed that building-related LCAs are divided into two steps. The first step would be to perform an analysis of the embodied impacts of different materials, such as it was done in Chapter 6. This type of analysis would analyze building materials as products, separately from a building, and would account for their durability and reuse (or remanufacturing) in multiple life cycles. The purpose of this first analysis would be to inform decision-making during early design when the building has not taken shape yet. The second analysis would be a whole-building LCA, as it is common practice in the building-related LCA literature. This analysis would be done in later stages of design and would allow the designers to assess the consequences of their materials' choices in the building and its specific climate zone. Currently, the second analysis is often the only one. As a result, building-related LCAs are very difficult to compare.

In Chapter 7, the grounded theory about the empirically based barriers to DfD in the current design practice attempted to answer the question of why architects do not currently design for disassembly. Through my interviews with 13 architects from large design firms in the U.S., I have discussed many answers to this question. First, the building owner's priorities will create opportunities or barriers to DfD. "Transformational owners'" priority is "doing the right thing," while sophisticated owners' priority is the return on investment (ROI). Estimating the financial benefits of DfD through the building's life cycle cost is a hard task because it depends on the savings during future renovations and the value of the future resale of building components. The latter is harder to predict due to the currently undeveloped market for salvaged materials, which is another barrier to DfD. Transformational owners, on the other hand, would value DfD if they understood that promoting reuse creates a positive impact on the environment. However, there is a lack of studies that estimate the environmental benefits of reuse in the built environment.

Another challenge to DfD lies on the architects' view of disassembly. Some architects associated the ability to disassemble a building to a structure that is not "made to last." Some even claimed that a resilient building "does not lend itself to" disassembly. More education on the benefits of DfD and reuse is essential to promote these practices in the AEC industry. For example, some architects' lack of understanding about the differences between reuse and recycling is one of the factors in why they do not find objective reasons (e.g., financial or environmental reasons) for specifying salvaged materials.

Finally, the complex and situational nature of the design process is another barrier to DfD. Prefabrication can help to take away some layers of such complexity. Also, PSS business models can lend themselves to prefabrication and disassembly. Prefabrication and DfD have many common goals: adaptability, durability, transportability, ability to assemble and disassemble, and the use of standard dimensions. For these reasons, prefabrication is an opportunity for a CE in the construction sector if combined with DfD, PSS, and the other factors discussed in Chapter 1 (see Figure 4). Thus, the shift toward a CE in the construction industry demands slow changes in design, business models, supply chain relationships, codes and regulations, and technology.

Limitations of this research

Chapters 5 and 6 of this dissertation were built on life cycle assessments. Although authors claimed that LCA is the most complete methodology to support CE assessments to date, it does have many limitations and inherent uncertainties. As Hendrickson et al. (1997) pointed out, "equally credible [life cycle] analyses can produce qualitatively different results". Also, LCA studies are often not comparable because of inconsistencies related to the method, scope, and data quality. In the built environment, this problem is augmented by the fact that many LCAs are building-specific, that is, use a certain building as the scope of the analysis, which makes it even harder to compare different studies. The limitations of an LCA are also related to the quality of its data sources. Thus, the limitations of each LCA presented in this dissertation were addressed in Chapters 5 and 6. Despite their limitations, the LCAs in this study have served their purpose. In Chapter 5, it became clear how different LCA methods and variables (e.g., reuse rates, transportation distances) can change the results of a cradle-to-cradle LCA. In Chapter 6, the results showed how the embodied energy, carbon, and water use can change according to the timeline used for the study and how accounting for the materials' durability can qualitatively change the results in a comparative LCA.

It is also important to mention that, in Chapters 5 and 6, the reuse of materials was assumed to happen "as is," that is, without the remanufacturing of materials. Therefore, the energy needed to remanufacture components was not included in the analyses. However, not all materials are suitable to reuse without remanufacturing. The materials assumed to be reused in this study tend to hold their value and properties over time and do not change technology often. Conversely, building components that are under constant upgrade and depend on fast-changing technologies should be assumed to be remanufactured into new components. For these studies, the environmental impacts involved in the remanufacturing process should be estimated.

Chapter 7, in turn, built on grounded theory to explain the barriers to DfD in the current designers' practice in the U.S. The analysis had a few limitations. First, because only architects from large design firms were interviewed, their experiences were mostly focused on institutional buildings and larger clients. The findings may have been different if architects from other market sectors have been interviewed (e.g., single-family residential sector). Another limitation is related to the sample size and theoretical sufficiency. In grounded theory, the researcher's claim of having sufficient data to start theorizing is a judgment call. Such judgment may evolve with the researcher's experience of the grounded theory method. Although my professional background as an architect has helped me to judge the theoretical sufficiency of my data, this was the first time I developed a grounded theory, and my lack of experience with the method may have affected my judgment in ways that I cannot predict. Finally, the interview participants have not yet been asked to provide feedback on the findings of this research, although I intend to do so in the future. Asking for participants' feedback is optional in grounded theory, but it is a way to improve the credibility of the results.

9. INTELLECTUAL MERIT

This dissertation contributes to the emergent fields of CE in the built environment, reuse, and DfD. The literature in these subjects is still scarce, especially in the United States and in the construction sector in general. To the best of my knowledge, this was the first study to:

- Compare hybrid and process-based LCA methods in the context of a cradle-to-cradle LCA (i.e., considering the impacts of reusing building materials);
- Show how different variables (transportation distances, number of reuses, reuse rates) affect the results of a comparative cradle-to-cradle LCA;
- Compare the effect of different LCA timelines on the embodied energy, carbon, and water of construction materials;
- Propose that building-related LCAs should be divided into two stages, according to the design development (i.e., early design phase and advanced design phase);
- Interview architects about the empirical barriers to DfD in their practice; and
- Identify challenges to DfD, such as conflicting views about resiliency, misunderstanding of the waste management hierarchy, the association of subjective meanings to reuse, and the difficulty of factoring DfD into life cycle cost analysis.

This research was also one of the rare studies that used LCA to assess the CE strategies of integrating a product into multiple life cycles and accounting for the product's durability in a comparative LCA. This research made considerations for how different LCA methods and assumptions regarding variables can affect the results of a cradle-to-cradle LCA. These considerations are a contribution to future research that aims to assess the environmental impacts of reuse through life cycle assessment. Finally, the grounded theory presented in Chapter 7 identified empirically based barriers to DfD that were not part of the literature on the topic.

10. BROADER IMPACT

A shift toward CE could reduce greenhouse gases emissions by 70% and increase the workforce by 4% (Wijkman & Skånberg, 2015). This dissertation aimed to contribute to the CE in the sector that uses the most resources in the world: construction. Very few companies have adopted CE business models in the built environment, and the emergent research in this field is led by Europe and China. DfD and materials' reuse can drastically reduce:

- Resource consumption;
- Construction and demolition (C&D) waste; and the
- Embodied energy and carbon of the building sector.

Contrary to the incremental changes caused by materials' recycling, DfD promotes the reduction and reuse of resources, while CE advocates for highly durable materials that can stay in the resource loop for longer through multiple life cycles. Shifting to a CE demands that we change the way we think in the construction industry, from design to business models to procurement of construction materials. This is not a fast change, but it is a radical one. It may be the only effective way to deal with the problem of resource scarcity in the future.

11. CONCLUSIONS AND RECOMMENDATIONS

Despite the threats of resource scarcity and climate change and the potential benefits of a circular economy (CE), the building sector has shown little progress in the field. The environmental impacts of reusing building materials are not fully understood, and the industry still relies on recycling as a resource efficiency strategy. In addition to that, the current business models favor an economy based on ownership and the right to destroy, and there are no financial incentives for reusing materials and diverting waste. Finally, the design of products for disassembly and reuse has a central role in the CE, but the practice of design for disassembly (DfD) is extremely rare in the construction sector. This dissertation investigated the environmental impacts (i.e., embodied energy, carbon, and water) of reusing components of the building's envelope, namely external wall frames and roof-covering materials. The analyses were made through cradle-to-cradle life cycle assessments (LCA) and focused on the effect of different LCA methods and variables in the results. A hybrid LCA and a process-based LCA were compared and produced opposite qualitative results. The benefits of reuse depended on aggressive reuse rates (larger than 70%), transportation distances, and on the embodied energy of insulation materials. The steel frame had to be reused twice to offset the higher embodied impacts of steel when compared to wood. The embodied energy, carbon, and water results also varied according to the time frame chosen for the analysis. I recommend that researchers in the construction field consider materials' reuse in multiple life cycles and the durability of the materials when doing comparative LCA between building materials. Also, I propose that LCA practitioners do more comparative LCA of building components as products, that is, separately from a building so the analysis can inform early decision-making in design. This type of analysis would complement whole-building LCAs that are becoming more common in the building but are done in later design stages.

Besides researchers and LCA practitioners, several stakeholders play a role in advancing materials' reuse; policy-makers, designers, manufacturers, and building owners must work together. For example, policy-makers can eliminate regulations that make reuse unfeasible and create incentives for the market of reused materials. Manufacturers and owners can partner up to create extended producer responsibility (EPR) strategies and PSS business models in the U.S., such as leasing high-quality, reusable, and prefabricated building components. Finally, the development of information and communication technologies, such as Building Information Modeling (BIM) and Radio-Frequency Identification (RFID), can aid the integration of the supply chain in the design and procurement of construction materials.

Finally, the designer's role is central for a shift toward a CE. This dissertation also investigated the reasons why architects currently do not design for disassembly (DfD) and the roles of the designer to promote a CE in the built environment. Several challenges were found, from conflicting views of resiliency to a misunderstanding of the waste management hierarchy. Designers must seek information about DfD and its potential benefits and about the environmental impacts of reuse when compared to other waste management strategies, such as recycling. Specifying materials with high recycled content is an incremental measure that is not enough to contribute to closing the loop in the construction sector. Second, architects must account for future renovations in the building's life cycle cost analysis. Accounting for future renovations is a way to financially justify DfD to clients who seek an ROI as a priority. Third, architects should specify prefabricated building components whenever they judge adequate and should work with the fabricators to ensure DfD practices in their design. Also, architects should seek out information about product-service system business models in the construction industry and be supportive of PSS manufacturers whenever possible. Finally, designers should acknowledge the responsibility for the environmental consequences of design decisions and exercise what some participants called "leadership," that is, *not asking permission* for designing with sustainable practices in mind. In the words of Brian: “This is just the way it should be. This is the way we do things, this is how we build a building.”

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APPENDIX A

SYSTEM BOUNDARIES (CHAPTER 5)

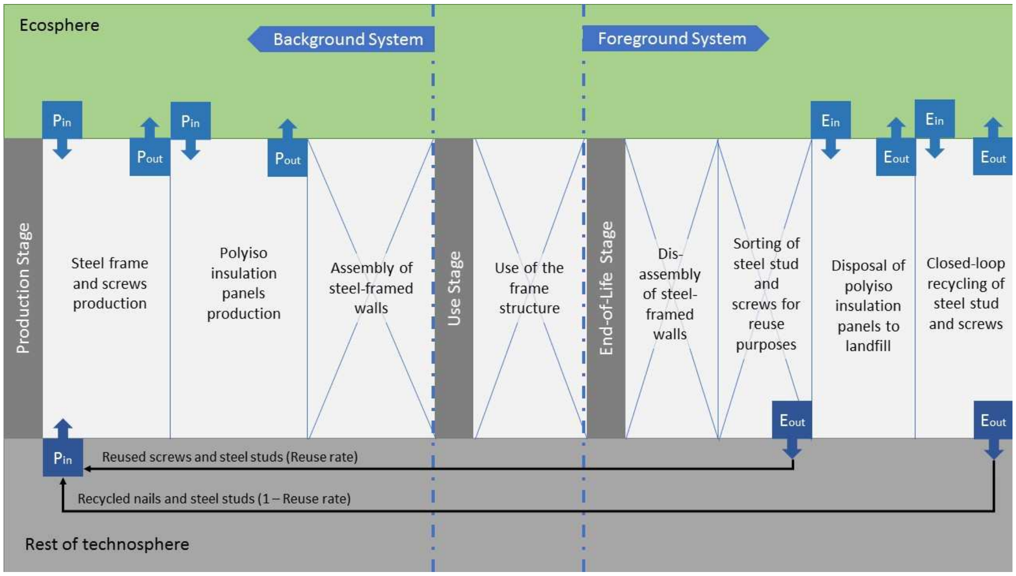

Figure 24. System boundaries for steel frame design. Notes: T=transportation; the processes analyzed are within the dashed lines

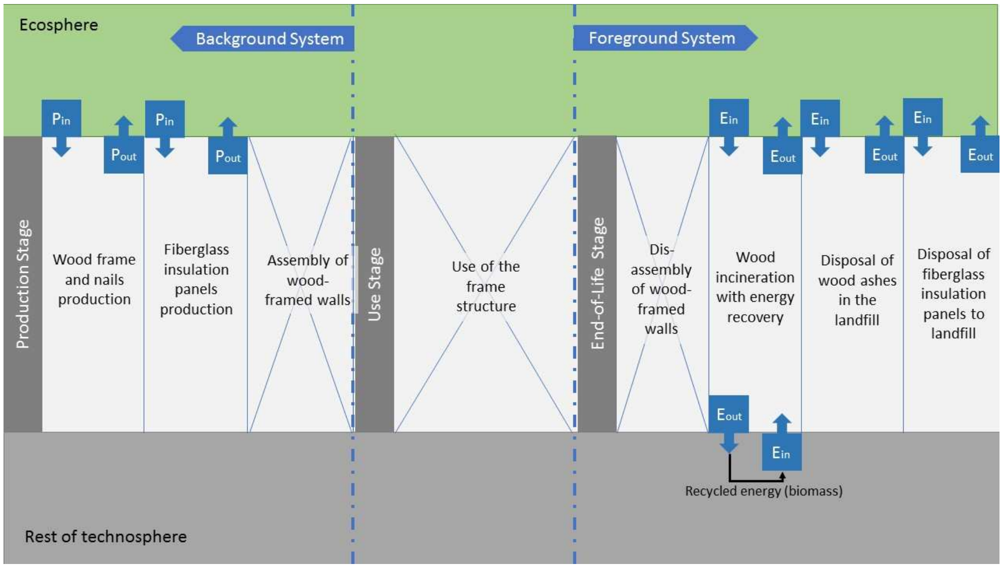

Figure 25. System boundaries for wood frame design. Notes: T=transportation; the processes analyzed are within the dashed lines.

APPENDIX B

DATA SOURCES AND QUALITY (CHAPTER 5)

Table 8. Unit Processes (UP) reference numbers

UP #	UP Description
1.1	Extraction and manufacture of steel frame
1.2	Transportation of steel frame from manufacturing to construction site
1.3	Extraction and processing of raw materials for polyiso rigid insulation panels
1.4	Transportation of polyiso's raw materials from processing to manufacturing
1.5	Transportation of polyiso panels to construction site (includes NREL and ecoinvent data)
1.6	Manufacturing of the polyiso panels
1.7	Transportation and disposal of poliyiso panels to landfills
1.8	Transportation of steel frame to next construction site, according to reuse rate
1.9	Transportation of steel studs and screws from old construction site to recycling facility (not suitable for reuse)
1.10	Recycling of steel frame that is not suitable for reuse
1.11	Transportation of steel studs from the last construction site to recycling facility
1.12	Extraction, manufacturing, and transportation of new steel frame to new construction site (to match the percentage that could not be reused from last construction site)
1.13	Recycling of steel frame after final use (2nd reuse)
2.1	Extraction and manufacturing of wood frame
2.2	Transportation of wood frame from manufacturing to construction site
2.3	Extraction and manufacturing of fiberglass batts
2.4	Transportation of fiberglass batts from manufacturing to construction site
2.5	Transportation of wood studs to incineration facility, and Incineration
2.6	Transportation of nails from construction site to landfill
2.7	Disposal of nails in the landfill
2.8	Transportation and landfilling of fiberglass, from construction site.
2.9	Disposal of wood ashes in the landfill

Table 9. Data sources for each Unit Process

UP	Source	Original Source	Period	Locat-ion	Notes / Assumptions
	Process-based LCA				
1.1, 1.2	BEES 4.0. (NIST, 2010)	AISI[11] and IISI[12] (extraction and manufacturing), and U.S. LCI Database (transportation)	Late 1990s (efficiency rate from 2016)[13]	World	"late 1990s world-wide production and account for recycling loops". Assumptions (BEES model): no weighting, user-input transportation distance to site (50mi), untreated wood. BEES assumes 33mil galvanized studs placed 24'' from each other, on center (Lippiatt, 2007, pp. 117-119).
1.3, 1.4, 1.6,	PIMA (Pavlovich, Phelan, & Jewel, 2011, pp. 131-154)	Mix of primary data (from all 33 polyester polyol plants in U.S.) and data from GaBi database (ecoinvent, NREL, and data on demand).	2003-2010	US	The PIMA report is very comprehensive and included the comments of a Critical Review Panel composed by Ms. Deana Matthews, PhD, Mr. John Clinton, and Ms. Amy Costello. A table listing all data sources can be found at page 21.
1.7	PIMA (Pavlovich, Phelan, & Jewel, 2011, pp. 131-154)	GaBi database (ecoinvent, NREL, and data on demand)	2003-2008	EU	"*based on disposal of commercial waste in a municipal landfill modeled after European processes but considered representative of such landfills in U.S.*" (Pavlovich, Phelan, & Jewel, 2011). Includes transportation to landfill.
1.5, 1.8, 1.9, 1.11, 2.4,	U.S LCI Database (NREL, 2012).	Franklin Associates	2001	US	NREL process: "*Transport, combination truck, diesel powered*". NREL provides the input data in liters of diesel. I used the ecoinvent

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[11] American Iron and Steel Institute (https://www.steel.org/)

[12] International Iron and Steel Institute (https://www.worldsteel.org/)

[13] AISI reported that, in 2016, structural steel (with 98% recycling rate at the time) was produced using 31% less energy and releasing 36% less greenhouse gases emissions than in 1990 (AISI, 2016). I added such efficiency gains to the BEES' original data to reduce temporal uncertainties caused by older data.

2.6					database to gather the inputs and outputs needed to produce diesel and added them to the transportation process.
	(ecoinvent Centre, 2014)	(Jungbluth, 2007)	2005-2014	EU	Ecoinvent process: "*petroleum refinery operation*" (product: 1kg of diesel). Includes outputs at the refinery and waste water treatment. Allocation: cut-off by classification. Average technology.
1.10, 1.13	(ecoinvent Centre, 2014)	(Doka, 2007)	1994-2014 (extrapol at-ed from 2000)	CH	Process: *"Treatment of waste reinforcement steel"*. Limitation: includes energy for dismantling, while the dismantling of the tiny house frame is a manual process.
1.12	10% of (1.1 + 1.2) processes combined.				
2.1, 2.2	BEES 4.0 (NIST, 2010)	Logging and growth: (Bowyer, 2004); Emissions associated with production and combustion of gasoline and diesel: (NREL, 2012);	Not specified (various sources)	US / EU	BEES assumes 2x4 or 2x6 (does not specify between both) wood frame, placed 16'' from each other, on center (Lippiatt, 2007, pp. 119-123). I assumed 2x4 wood frame for weight calculations. Service life: 75 years. The lumber production data was collected from the Pacific Northwest and Southeastern U.S. Species: Douglas Fir, Western Hemlock, and Southern Yellow Pine. The wood is untreated.
2.3	(ecoinvent Centre, 2014)	(Kellenberger, Althaus, Jungbluth, & Kunniger, 2007)	2000-2014 (extrapol at-ed)	EU	Process: "*Glass Fibre Production"*. Data for recuperative or oxy-fuel fired furnaces (26 furnaces at 12 sites).
2.5	WARM (EPA, 2016)	(Doka, 2013)	2006-2014	US	Data for wood combustion with energy recovery. Includes transportation to incineration facility. WARM assumes that the biogenic carbon (from wood biomass) does not count as carbon emissions because it

					is offset by the carbon absorbed by reforestation. The GHG data are based on the N20 emissions, transportation emissions, and avoided utility emissions – since the energy recovered is reused by the incineration facility (EPA, 2016).
2.7	(ecoinvent Centre, 2014)	(Doka, 2007)	1994-2014 (extrapolated from 2000)	CH	Process: *“Treatment of scrap steel; inert material landfill”*. No direct emissions from inert material (negligible). The data “contains only exchanges to process specific burdens (energy, land use), and infrastructure”. Landfill with renaturation after closure.
2.8	WARM (EPA, 2016)	Transportation: (NREL, 2012); Equipment emissions: (Franklin Associates, 1994)	1994, 2001	US	Data specific for the disposal of fiberglass batts insulation. Includes GHG emissions (carbon dioxide and methane) from the transport to landfill and from landfill equipments (ICF International, 2016).
2.9	(ecoinvent Centre, 2014)	(Doka, 2007)	1994-2014 (extrapolated from 2000)	CH	Process: *“Treatment of wood ash mixture, pure, sanitary landfill”*. Short-term emissios to air from gas incineration and leachate. Note: for the Douglas-Fir wood type, 1.82% of the wood mass is converted to ashes during incineration (Misra, Ragland, & Baker, 1993).
	EIO-LCA. Model: “US 2002 Benchmark (428 sectors), Producer Price”.				
1.1	(Carnegie Mellon University, 2002)		2002	US	Process: *“Ornamental and architectural metal products manufacturing"*
2.1					Process: “*Prefabricated wood building manufacturing”*

Table 10. Data quality indicators and calculation. Based on ILCD (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010, p. 329)

Unit Process	Technological representativeness	Time-related representativeness	Geographical Representativeness	Completeness	Precision/ Uncertainty	Methodological appropriateness and consistency	Quality
	Process-Based LCA						
1.2	1	2	3	1	1	1	2.1 (Basic)
1.2	1	4	1	1	1	2	2.5 (Basic)
1.3	1	2	1	1	1	1	1.5 (High)
1.4	1	2	1	1	1	1	1.5 (High)
1.5	2	4	3	1	1	2	2.9 (Basic)
1.6	1	2	1	1	1	1	1.5 (High)
1.7	2	2	3	1	1	1	2.2 (Basic)
1.8	2	4	3	1	1	2	2.9 (Basic)
1.9	2	4	3	1	1	2	2.9 (Basic)
1.10	2	2	3	1	1	2	2.3 (Basic)
1.11	2	4	3	1	1	2	2.9 (Basic)
1.12	1	4	3	1	1	2	2.8 (Basic)
1.13	2	2	3	1	1	2	2.3 (Basic)
2.1	1	1	3	1	1	1	2.0 (Basic)
2.2	1	4	1	1	1	2	2.5 (Basic)
2.3	2	2	3	2	1	1	2.2 (Basic)
2.4	2	4	3	1	1	2	2.9 (Basic)
2.5	1	4	1	1	1	1	2.5 (Basic)
2.6	2	4	3	1	1	2	2.9 (Basic)
2.7	2	2	3	1	1	1	2.2 (Basic)
2.8	1	4	1	2	1	2	2.7 (Basic)
2.9	2	4	3	1	1	2	2.9 (Basic)
	EIO-LCA						
1.1	3	4	1	0	0	0	3.4 (Estimate)
2.1	3	4	1	0	0	0	3.4 (Estimate)

Notes: “0” = N/A

APPENDIX C

ASSUMPTIONS (CHAPTER 5)

Table 11. Transportation distances

Itinerary	Distance	Notes
Steel/wood frame: from production facility to construction site	**80km**	Modeled in BEES, based on (Guggemos & Horvath, 2005)
Insulation: from production facility to construction site	**750km**	Based on (Guggemos & Horvath, 2005)
Steel frame: from deconstruction to reuse	**160km**	Tested for uncertainty
Wood/Steel frame and insulation: from demolition site to recycling, incineration, or landfill facilities	**32km**	Based on WARM default values

Table 12. Density of construction materials

Material	Density	Source
Wood frame	1.1lb/ft2	(Boise Cascade: Engineered wood products, 2018)
Steel frame	0.82lb/ft2	(Bolin & Smith, 2011)
Fiberglass[14]	0.64 lbs/ft2	(Knauf Insulation, 2014)
Polyiso panels	0.5lb/ft2	(Pavlovich, Phelan, & Jewel, 2011)
Galvanized nails	0.04kg/ft2	(Lippiatt, 2007)
Steel screws	0.0056kg/ft2	(Lippiatt, 2007)

Table 13. Prices of materials in 2002 used in EIO-LCA calculation

Material	Price in 2002	Source
Wood frame	U$5.16/sf of living area	(PATH, 2002)
Steel frame	U$7.41/sf of living area	

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[14] Percentage of wall insulation in relation to frame: 70% (Hereford, 2015)

APPENDIX D

SEMI-STRUCTURED INTERVIEW SCRIPT (CHAPTER 7)

Thank you for your time to participate in this interview. A little about me: I graduated in architecture and urban planning from the federal university of Brazil in 2012, and now I am doing a PhD in construction engineering at ASU with a focus on sustainable construction.

The focus of my thesis is in design for disassembly and reuse of construction materials. This interview is the second step of this study. The first step was the life cycle assessment of reusable building components, and the next step will be a simulation of how design factors, market factors, and policy factors can impact on the future reuse of building materials. I expect to graduate on next summer, and my dissertation will be published on the second half of 2018.

I expect to call about 15 architects from major design firms in the United States and report the findings in my dissertation and maybe a journal publication after that. Your participation is voluntary, and all the participants will remain anonymous. Your time will benefit industry understanding of design practices that help reducing construction waste, their uses, importance, gaps and variation in current practice. I am recording and transcribing the interview, but recordings and transcripts will not be shared with third parties.

Do you have any questions about the study before we begin?

Interview questions

1. Can you tell me how many years of experience you have as an architect, and what market sectors you have worked with?
2. Can you walk me through your design process? What is your main role in the design team?
3. What would you say are the main factors that make the client, and/or the architect opt for sustainable design? Which one do you think is the single most important factors? What are the challenges along the way?
4. Do you think architects have a role in preventing construction waste? Why/What role?

5. Do you work closely with a structural engineer? When it comes to decisions such as opting for prefabricated components or structural connections such as bolts or welding, do you play any part in these decisions?
6. Have you ever used modular design? In what project(s)? What were your drivers and difficulties?
7. How often do your design team specify prefabricated components? What drives this decision-making? Any difficulties/barriers?
8. Have you ever specified salvaged materials to be used in new construction? Why?
9. When it comes to permanent buildings (i.e. non-temporary buildings), what do you think of the idea of designing to ease the future disassembly and adaptability of the building?
    a. Have you ever designed with the intent of easing disassembly? Why? (If yes, in what project, and what strategies did you use?)
    b. What type of building/clients/market do you think would be interested in designing for disassembly (if any)? Why?
10. Is there anything else you want to add to this interview? Is there any question I did not ask? Do you have any questions about my work?