Quantifying the Impact of Circular Economy Applied to the Built Environment:

A Study of Construction and Demolition Waste to Identify Leverage Points

by

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ABSTRACT

The built environment is responsible for a significant portion of global waste generation. Construction and demolition (C&D) waste requires significant landfill areas and costs billions of dollars. New business models that reduce this waste may prove to be financially beneficial and generally more sustainable. One such model is referred to as the "Circular Economy" (CE), which promotes the efficient use of materials to minimize waste generation and raw material consumption. CE is achieved by maximizing the life of materials and components and by reclaiming the typically wasted value at the end of their life. This thesis identifies the potential opportunities for using CE in the built environment. It first calculates the magnitude of C&D waste and its main streams, highlights the top C&D materials based on weight and value using data from various regions, identifies the top C&D materials' current recycling and reuse rates, and finally estimates a potential financial benefit of $3.7 billion from redirecting C&D waste using the CE concept in the United States.

I dedicate this thesis to my mother and my father who gave me everything to help me succeed and taught me to work hard and not to give up under any circumstances.
I dedicate this thesis to my Sisters Dania and Dima, my brother Mahmoud, and my partner Adriana for always giving me the support I needed throughout my personal life and my career. I am grateful for all your efforts.

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CHAPTER 1

INTRODUCTION

Current global population growth and increasing standards of living are putting more demand on, and depleting, natural resources. The architecture, engineering, and construction industry is striving to have more sustainable facilities and communities, but it is consuming large amounts of raw materials and generating large amounts of waste. The construction industry is the world's largest raw materials consumer (World Economic Forum (WEF), 2016). For example, the construction industry is responsible for 50% of the global steel production, and it consumes more than 3 billion tons of raw materials (ARUP, 2016; WEF, 2016). Construction and demolition (C&D) waste constitutes a large percentage of the total municipal solid waste (MSW). China, for instance, is the largest producer of MSW in the world, since it produces 29% of the world's MSW (Zhang et al. 2010), and forty percent of that comes from the construction industry (Wang et al. 2008), but their recycle rate is below ten percent (Yan 2018). The construction industry's consumption of raw materials and waste generation is draining natural resources and producing high amounts of greenhouse gases (Kucukvar and Tatari 2013).

According to a white paper by the Construction and Demolition Recycling Association (CDRA), C&D waste in the US alone requires 4,356 acres of landfill area 50 feet deep every year (Townsend et al. 2014). This large amount of landfilled waste starts as generated waste from construction sites and goes through multiple phases to finally reach the landfilling phase. Yuan et al. (2011) developed a conceptual model for the C&D waste chain. This model represents the life of C&D waste. Starting from the generation phase, C&D waste undergoes different waste management activities that minimize the volume of waste at each activity until the disposal of the remaining waste. Their model also displays some of the typical factors affecting C&D waste management activities. This model is shown in Figure 1.

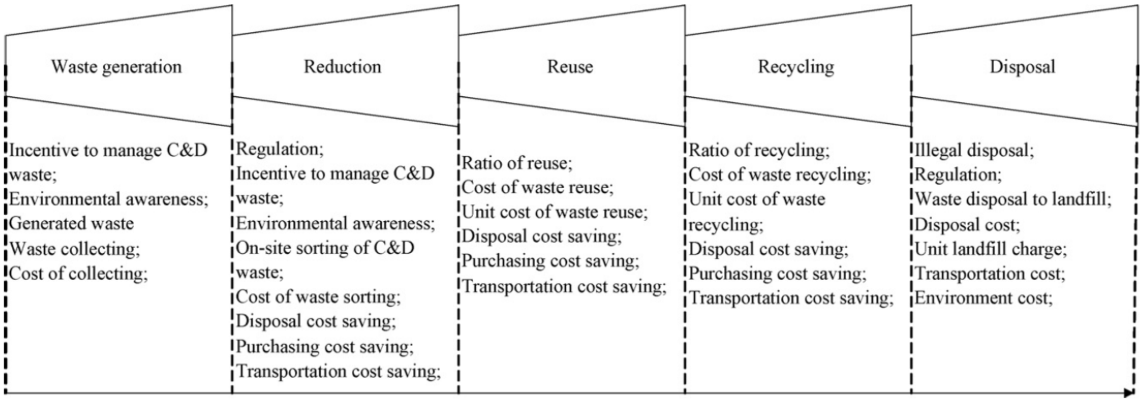


Fig. 1. C&D waste chain (Yuan et al. 2011)

As can be seen from Figure 1, there are five phases in the waste chain. The first piece of the chain is the waste generation phase. The definition of C&D waste may differ slightly from one study to another, but typically includes waste generated from construction, demolition and renovation activities, and it can also include infrastructure waste (Sandler 2003). These activities produce high volumes of MSW that end up in landfills, which is not considered sustainable practice, especially in an industry known to be continuously innovating to achieve higher levels of sustainability. In addition, this waste is costing the industry billions of dollars due to constantly rising landfill costs driven by governmental regulations trying to overcome the problem of shrinking landfill space.

The second piece of the chain and the best C&D waste management practice is reducing the amount of waste (Peng et al. 1997). However, in the construction industry, avoiding waste generation and reducing waste is difficult (Yuan and Shen 2011).

The third and fourth pieces of the chain and the next best options to reduce the environmental impacts of the C&D waste are reusing and recycling the waste (Peng et al. 1997). Currently not all C&D waste ends up in landfills. A considerable amount is being recovered to be reused or recycled. C&D waste from construction sites can be managed in three different ways: (1) it can either be sorted on-site where part of the waste is recovered to be reused on-site or taken to recycling facilities, while the rest is taken to landfills; (2) the C&D waste can be sorted off-site; or (3) the last and least sustainable way would be hauling the waste to landfills directly (Hossain et al. 2017). The choice of on-site sorting vs off-site sorting depends on the advantages and disadvantages of each process. According to Kourmpanis et al. (2008), on-site sorting advantages include: (1) lower material handling and transport costs, especially if the materials will be used on-site, and (2) lower machinery capital costs. Off-site sorting advantages include: (1) Better sorting equipment, (2) lower per ton cost, (3) easier quality control of recycled materials, and (4) ability to hold material stockpiles. Disadvantages of on-site sorting include: (1) space limitation on site, (2) less flexibility on where/when recycled materials can be used, and (3) possible construction delays. Off-site sorting disadvantages include: (1) high transport and handling costs, and (2) high fixed costs and starting capital costs. Some studies have shown that on-site sorting is the best option for C&D waste management and can actually reduce the environmental impacts of the waste by 63%, as an average of multiple impacts, due to the possibility for secondary reuse on-site (Hossain et al. 2017; Hossain and Thomas Ng 2019). According to Wang et al. (2010), successful on-site sorting requires: (1) manpower, (2) market for recycled materials, (3) waste sortability, (4) better management, (5) site space, and (6) equipment for sorting of construction waste.

The last piece of the chain is the disposal of the waste, which should be minimized as much as possible through all the previous steps. Construction waste recyclers generate profit from this process because the value gained from the landfill tipping fees can be the main source of a recycler's income (Peng et al. 1997).

One important factor for a successful C&D waste management strategy is the economic incentive, which is important for construction industry stakeholders involved when considering conducting more sustainable C&D waste management and would encourage them to undertake environmentally friendly construction practices. A lack of economic incentive can hinder the waste management activities. Conducting waste management activities can provide benefits for construction companies, which can be used to provide competitive bids and gain a better public image (Yuan et al. 2011).

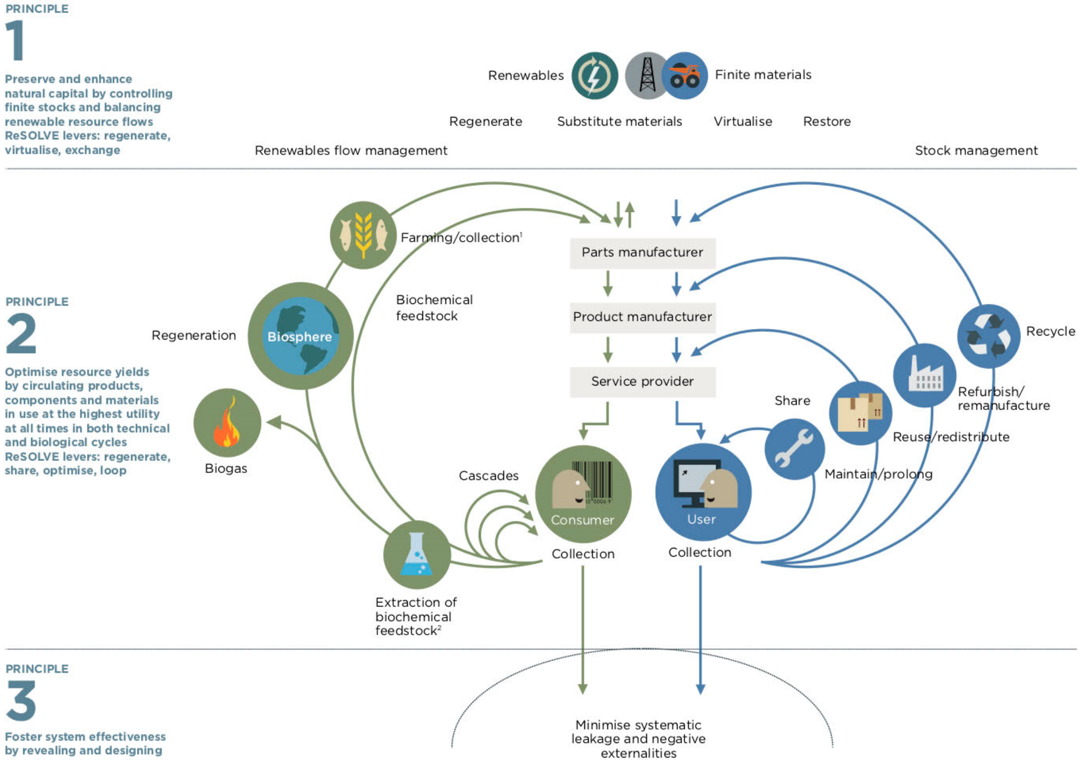
The high volume of C&D waste is a motivator for this research, which studies how the large waste streams can become financially beneficial through applying the concept of Circular Economy (CE) to the built environment. El Asmar et al. (2018) state that if recycling and reusing C&D MSW can generate significant monetary benefits, then it is important to estimate these benefits to further drive CE adoption.

CHAPTER 2

THE CONCEPT OF CIRCULAR ECONOMY

The Ellen MacArthur Foundation (EMF) (2017) defines a CE as one that keeps products, components, and materials at their highest value and in use. The term circular in CE means keeping the resources in closed loops where waste is considered a valuable output and is matched with a process to which it can add value as an input. Figure 2 shows an outline of the CE concept. CE contains three major principles: preserve and enhance natural capital, optimize resource yields, and foster system effectiveness. With these principles, biological cycles, presented on the left side of the cycle in Figure 2, and technical cycles, presented on the right side, are considered to minimize waste and negative externalities. The construction industry focuses more on the technical side through sharing, maintaining, reusing, refurbishing, and recycling strategies to achieve a CE (ARUP 2016). According to Liu et al. (2017), CE has been considered to be a more efficient way to conduct waste management and is becoming a dominant concept to reach a sustainable environment.

Three different business models can be applied to the current value chain in the built environment: (1) circular design, (2) circular use, and (3) circular recovery (Carra and Magdani 2017). A business model is the way an entity does its business (Magretta 2002). Circular design reframes product design from its current linear process to a circular process by exploring opportunities for social, cultural, natural, and human capital (Ellen MacArthur Foundation and IDEO 2017). In the built environment, circular design can be applied by attempting to select circular materials during the design stage. Circular use works on retaining the value of built facilities. Some examples of circular use in the built environment are lifetime expansions and platform sharing. Circular recovery is applied to products at the end of their lifecycle (Gregson et al. 2015; Singh and Ordoñez 2016) and can be applied in the built environment by managing reverse logistics and reusing materials at their highest value.



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

Fig. 2. Overview of CE (EMF, 2015)

According to Bocken et al. (2016), a circular business model aims not only to close resource loops, but also to narrow and slow resource loops. Narrowing resource loops is reducing the resources used to produce products. Slowing resource loops is extending the life of products, which can be done by (1) designing long-lasting products (2) using product-life extension measures such as repairing, maintenance, remanufacturing, etc., and (3) reusing products. Lastly, closing resource loops is recycling materials and products, which will result in no waste. These action items represent the “3R” action items; narrowing represents reducing, slowing represents reusing, and closing represents recycling. Ultimately, the goal is to maximize each of these action items to reach a circular economy.

According to Nasir et al. (2017), the concept of circular economy was spread through the industrial ecology literature as a way to transform products and supply chains to achieve environmental and economic growth. A circular economy requires green supply chains that maximize resource utilization, reduce consumption and enhance operation performance (Zhou and Li 2011). An experiment was done by Nasir et al. (2017) to test whether the use of a circular supply chain for insulation materials would result in better environmental performance at the whole supply chain level. They found that it reduces the environmental impact of the material compared to a linear insulation material supply chain.

CHAPTER 3

C&D MATERIAL REUSE AND RECYCLING PRACTICES AND CIRCULAR ECONOMY APPLICATIONS IN THE BUILT ENVIRONMENT: A REVIEW OF LITERATURE

The EMF (2013) highlights the life cycle of C&D waste estimated in the US. Figure 3 shows 26% of the total waste is C&D waste, and about three quarters of the total C&D waste is being discarded. The discarded waste includes lumber (40%), asphalt products (14%), concrete and brick (11%), and others. Recovering these materials will be critical to applying CE in the built environment. These values were based on United States Environmental Protection Agency (USEPA) data from 2008 (USEPA 2009); new EPA data came out in 2014 (USEPA, 2016b) and will be used in this thesis.

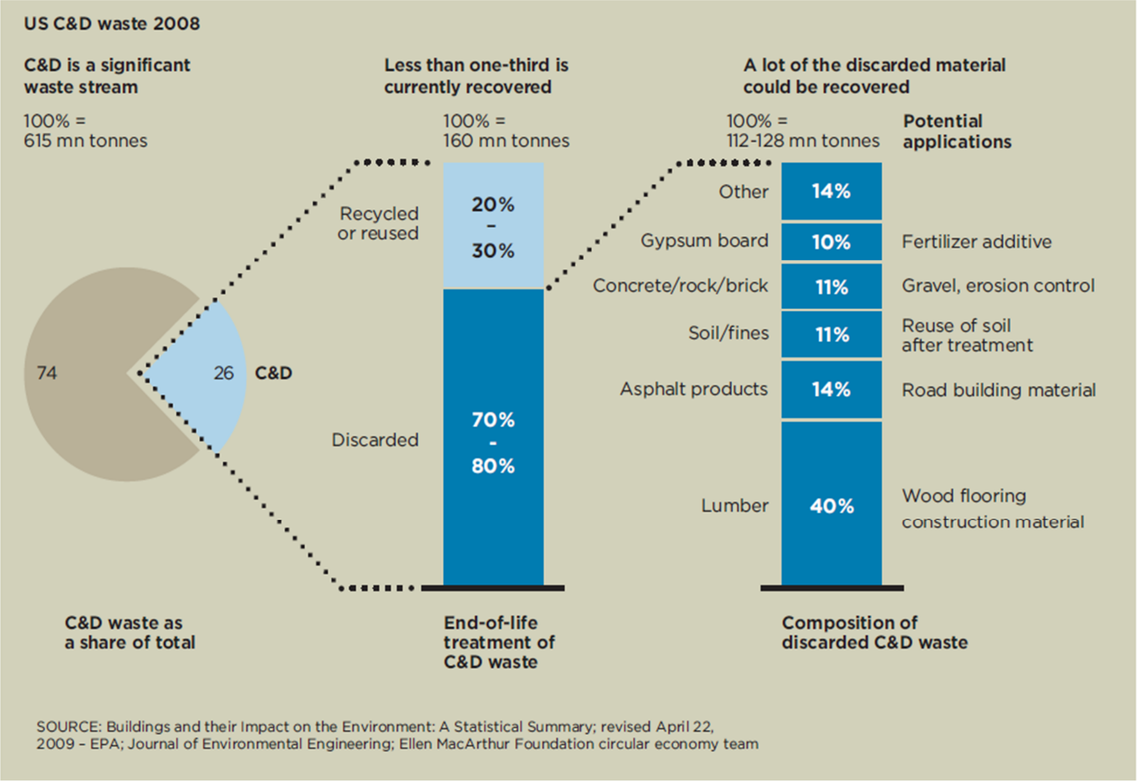


Fig. 3. C&D: a noteworthy opportunity (EMF, 2013)

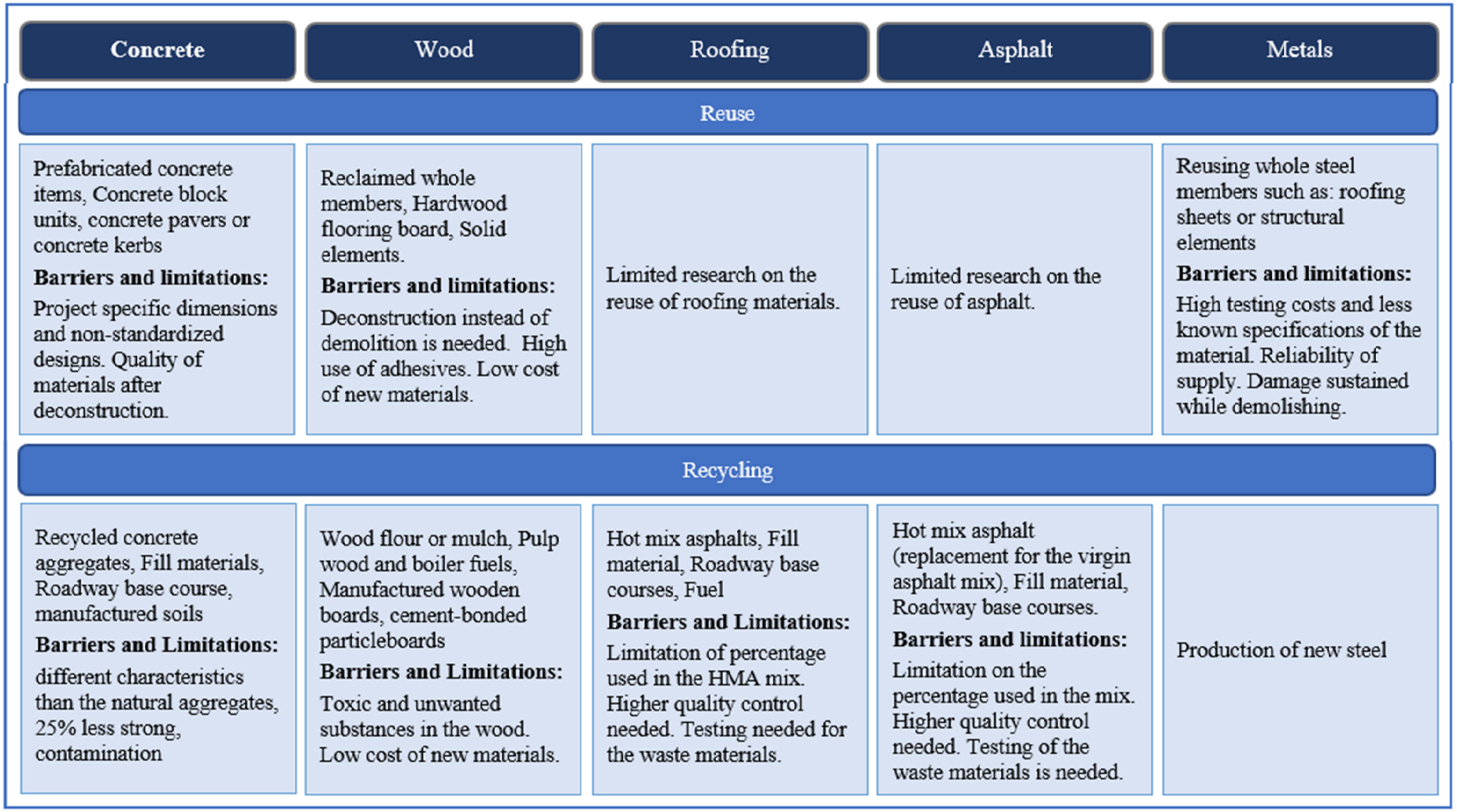
As shown in Figure 3, some materials are reused and recycled more than others, leading to less discarded waste. For example, the figure shows concrete and asphalt products to make up a significant portion of the discarded waste, highlighting an interesting opportunity because recycled aggregates for lower quality applications are the most commonly recycled material (Tam and Tam 2006). The disparity between different materials' reuse or recycling rates is partly because of the factors affecting the choice of reclaimed materials instead of virgin materials. These factors include, (1) the price of the reclaimed material, especially in a free-market situation; (2) the shortage of virgin materials; (3) the shortage of suitable deposit sites for C&D waste; (4) the availability of a reliable supply of ready-to-use reclaimed materials, and (5) the competitive quality of reclaimed products (Kartam et al. 2004). According to Shahria Alam et al. (2013) and Yeheyis et al. (2013), the high quality of products made from recycled C&D waste can be a reason for the high recycling rates in the Scandinavian countries. On the other hand, a lack of comprehensive standards may hinder C&D waste recycling efforts (Brooks et al. 1994). The waste management options for specific C&D waste materials are affected by different criteria for reuse and recycling, which in turn would affect the reuse and recycling rates. Table 1 include some of the general criteria for the reuse and recycling of the major C&D waste. These criteria can be different for each material.

Table 1. C&D waste materials reuse and recycling criteria

Material	Criteria for reuse and recycling	Reference
Concrete	The availability of contaminant materials such as lead-bearing paints, which can prohibit the reuse of the concrete waste completely because of the fear of water contamination risks.	(WDNR 2017)
Wood	Contamination, physical location of the material, the size and the condition of the material.	(Falk and McKeever 2004)
Roofing	The original shingle binder material type.	(Zhou et al. 2013)
Asphalt	The variability in the Recycled Asphalt Pavement (RAP) materials. This variability might come from: 1) The sources of RAP 2) Asphalt content in RAP, which might vary because of the milling processes used, asphalt layer thickness, and types of mixtures used. 3) Dust contents 4) Aggregate gradation 5) The maintenance history of milled pavement	(Arredondo 2018)
Metals	The structural integrity and properties of the reused members.	(Gorgolewski et al 2006)

3.1 C&D material reuse and recycling practices

Some traditional reuse and recycling activities are already being implemented, especially for the common C&D waste materials. These include asphalt, concrete, wood, steel, and roofing materials. All of these materials will be considered in this thesis' analysis to estimate any wasted financial potential from not recycling all the waste. In this literature review section, the reuse and recycling general criteria, reuse and recycling practices, barriers/limitations and solutions for the different C&D waste materials are researched to identify the opportunities for applying CE to these practices. Figure 4 shows some of the recycling and reuse practices that are being implemented for the top C&D waste materials. In the next sections, these reuse and recycling practices will be discussed.



Concrete	Wood	Roofing	Asphalt	Metals
Reuse				
Prefabricated concrete items, Concrete block units, concrete pavers or concrete kerbs **Barriers and limitations:** Project specific dimensions and non-standardized designs. Quality of materials after deconstruction.	Reclaimed whole members, Hardwood flooring board, Solid elements. **Barriers and limitations:** Deconstruction instead of demolition is needed. High use of adhesives. Low cost of new materials.	Limited research on the reuse of roofing materials.	Limited research on the reuse of asphalt.	Reusing whole steel members such as: roofing sheets or structural elements **Barriers and limitations:** High testing costs and less known specifications of the material. Reliability of supply. Damage sustained while demolishing.
Recycling				
Recycled concrete aggregates, Fill materials, Roadway base course, manufactured soils **Barriers and Limitations:** different characteristics than the natural aggregates, 25% less strong, contamination	Wood flour or mulch, Pulp wood and boiler fuels, Manufactured wooden boards, cement-bonded particleboards **Barriers and Limitations:** Toxic and unwanted substances in the wood. Low cost of new materials.	Hot mix asphalts, Fill material, Roadway base courses, Fuel **Barriers and Limitations:** Limitation of percentage used in the HMA mix. Higher quality control needed. Testing needed for the waste materials.	Hot mix asphalt (replacement for the virgin asphalt mix), Fill material, Roadway base courses. **Barriers and limitations:** Limitation on the percentage used in the mix. Higher quality control needed. Testing of the waste materials is needed.	Production of new steel

Fig. 4. C&D Material Reuse and Recycling Practices

References: Kuehlen et al. (2014), Leal et al. (2006), Earle et al. (2014), Cooper (1999), Jeffrey (2011), Lennon (2005), Gorgolewski (2006), Nakajima (2014), Yang et al. (2015), Arredondo (2018)

3.1.1 Concrete

Concrete reuse is generally limited to smaller applications such as prefabricated concrete items, concrete block units, concrete pavers or concrete curbs. This is mainly because of the uniqueness of the construction industry, which has project-specific dimensions and non-standardized designs (Kuehlen et al. 2014; Leal et al. 2006). Thus, concrete recycling is the more common practice and is usually done by crushing the concrete waste and using it as recycled concrete aggregates (RCA), fill materials, roadway base course, or manufactured soils.

Concrete recycling might be a simple process because there is no need for standardized or flexible designs. Tam (2008) highlights the importance of recycling concrete waste because of its large amount compared to the total C&D waste. This large amount and the simplicity of the process can make recycling concrete for new production a cost-effective method. However, recycled aggregates have different characteristics compared to natural aggregates. It could be 25% less strong (Earle et al. 2014) and its properties should be accepted before it is used in concrete production. According to Marie and Quiasrawi (2012), concrete production from RCA will result in (1) lower workability compared to normal concrete, (2) adverse effects on concrete compressive and tensile strength, and (3) high absorption rates compared to natural aggregates. There is still some doubt about the use of recycled aggregates in asphalt pavement because of recycled aggregates' lack of resistance to water actions, which could lead to stripping. Recycled aggregates could be used feasibly in flexible pavement with low to medium traffic (Pérez et al. 2010). The contamination of the recycled aggregates can also be a barrier for its use.

However, according to Silva et al. (2014), one solution for this barrier is selective demolition, which would help to obtain materials with minimum levels of contamination.

3.1.2 Wood

Compared to concrete, wood tends to be more difficult to recycle or reuse. According to Burgoyne (2003), wood recycling requires labor-intensive disassembly to remove fasteners and finishes. As can be seen in Figure 4, recycling options for wood can include (1) wood chips or wood flour, (2) composite or engineered lumber products, (3) mulch, (4) animal bedding, (5) compost, (6) particle boards, or other products. In Japan, C&D wood waste constitutes almost 70% of all particle board material (Nakajima 2014). According to Cooper (1999), there is a high potential for the use of treated wood waste to make siding, sheathings, and even flooring boards. Finally, unseparated wood can be burned to produce electricity.

The size and condition of the material will affect the recoverability and usability of wood waste (Falk and McKeever 2004). One challenge to the use of recovered wood waste is the low cost of virgin wood materials. Another challenging aspect of recycling wood is the added adhesives and chemicals, which make the deconstruction process harder. Recycled wood with high adhesive content is no longer suitable for mulches. Wood waste should also be screened for lead paints and other treatments.

3.1.3 Roofing

According to the Connecticut Department of Energy and Environmental Protection (2014), asphalt shingles comprise almost 85-90% of the C&D roofing waste. Therefore, asphalt shingles are assumed in this thesis to represent the total roofing materials. Interestingly, 65% of the total production of roofing shingles is used for restoration works and only 35%

for new construction. This means that these 65% are likely replacing old shingles. Tearing off the roofing shingles requires a careful process to separate the contaminants and nails from clean roofing shingles waste (Brock 2007).

According to Jeffrey (2011), no clear reuse practices are currently done for the roofing materials, but more research is ongoing on the subject. Recycling of the roofing waste is the more predominant practice. Roofing shingles can be recycled as fill material, roadway base course, or fuel, and little to no limitations can be found for these recycling options. However, the best way to recycle roofing shingles can be to use it in Hot Mix Asphalt (HMA) (Jeffrey 2011; Lennon 2005). Recycling roofing shingles waste into HMA is found to result in lower energy requirements than disposing of the old shingles and using virgin materials instead (Cochran 2009).

3.1.4 Asphalt

Asphalt is one of the most reclaimed materials in the US (National Asphalt Pavement Association (NAPA) 2017) with recycling and reuse rates higher than 95% (Arredondo 2018; Hansen and Copeland 2015; Townsend et al. 2014). Reclaimed asphalt is mainly used as fill material, aggregates, and RAP. US states and cities are recovering asphalt waste and reusing it in various ways. Some states and cities are enforcing regulations regarding the mix designs of new asphalt pavements to include RAP. However, challenges exist for the reuse of RAP and RAS, especially in severe weather conditions. For example, the city of Phoenix, Arizona, and Arizona State University studied the possibility of increasing the reuse of RAP and RAS in new asphalt pavements. According to Arredondo (2018), the city of Phoenix uses only up to 15% RAP in their mix because of severe weather in the area, which affects the performance of the asphalt mixes at higher RAP percentages. However, this 15% results in an asphalt performance equal to that of standard mixtures and has saved the city $3.9 million in the first year of adoption. The reclaimed value of asphalt as aggregate is $9/ton (C&E Excavating 2018). According to Hansen and Copeland (2015), assuming 5% of the total recycled asphalt pavement (RAP) is liquid asphalt worth $550/ton, and the remaining 95% is aggregates worth $9/ton, the mixed value of the RAP would be around $36/ton, which is four times more valuable than asphalt as aggregates. In fact, this high value is leading to higher reuse rates of RAP in warm mix asphalt (WMA), from 15.6% in 2004 to 20.4% in 2014. Asphalt is a great example of how to start adopting circular economy to promote sustainable performance while considering resource efficiency and resource recovery altogether (Hossain and Ng 2018).

3.1.5 Steel

Structural steel systems can present a major opportunity for possible element reuse. Whole members such as roofing sheets and structural elements can be reused successfully but with some limitations and barriers, such as: (1) high testing and quality control costs, (2) reliability of supply, and (3) costs of any damages sustained through the deconstruction or demolition processes (Gorgolewski et al. 2006; Lennon 2005). According to Gorgolewski et al. (2006), these limitations and barriers can be mitigated by improving the demolition and deconstruction processes in addition to having better supply chain management, which will allow for better quality of reused steel. Pongiglione and Calderini (2014) state that one way to reuse steel can be using reused elements in conjunction with new elements that need to be over-dimensioned to guarantee the safety of the reused elements. This would result in steel savings of around 30%. *Reuse-steel.org* is a website that facilitates the reuse and exchange of reusable steel construction components. This is one example of a better supply chain management method that can improve the reuse process of steel. Steel recycling, on the other hand, is the process of using old steel to produce new steel (Jeffrey 2011; Kuehlen et al. 2014; Leal et al. 2006).

3.1.6 General reuse/ recycle barriers and limitations

The barriers and limitations for material reuse and recycling can be either general or material specific. Some of the general barriers and limitations for waste material recycling and reuse include the need for strict quality control, high costs of testing and low costs of virgin material. In general, all barriers and limitations can be categorized into two main parts that are interconnected. These are:

1) Supply barriers such as the quality and strength of the reclaimed C&D waste materials and the unpredictability of the supply sources. These affect the materials offered to the market.
2) Demand barriers such as project specific dimensions and specifications for the needed materials and the need for flexible designs. These affect the materials needed for a specific project because each project has separate material requirements.

One solution that can be considered applicable for most barriers and limitations for all materials is to improve the demolition and deconstruction processes to ensure the quality of the reclaimed materials. The increased quality will ensure a strict adherence to required material conditions and specifications. In some cases, barriers will be forced by regulations. For example, according to Weil et al. (2006) the civil engineering C&D waste in Germany is largely reused as loose bed material. However, new regulations on water for soil and ground water protection will limit the old reuse paths and the landfilling possibility of the civil engineering waste when contaminants are found in the materials because these contaminants could leak into the ground water. This can result in either illegal dumping of the waste if no new paths are found or it can result in improving the demolition processes to improve the quality of the waste materials.

3.2 CE applications in the built environment

Circular economy research in the built environment was slightly limited specially when considering whole systems. However, much of the research on the subject is focused on the end of pipe C&D waste management practices, which improved the management of C&D waste (Adams et al. 2017). Figure 5 provides a holistic view of a possible circular business model in the built environment where the linear consumption model is replaced by a circular consumption model. Various studies may propose different actions to transform the built environment to a circular one, but their main approach is generally the same (Crowther 2001; EMF 2013). Figure 5 shows four types of action: recycling, reprocessing, reusing, and relocation. In this circular model, materials and resources keep circulating in the system and do not lose all their value (in contrast to common practice). The best way to reach a CE is to reduce the waste through a whole building relocation, which is a fairly aggressive strategy that may not be easily attainable in most applications. A little less aggressive than relocation is the reuse of components, which is applicable to many more situations and can be accomplished by disassembling whole building components and reusing them for the same function served in their first life. The next layer down is reusing with some reprocessing of materials, which would require reassembling the salvaged materials into system components. A last resort on the path towards CE is the recycling of materials, which would turn old building materials into base materials that require reprocessing and remanufacturing. Using this CE model would conserve energy, save processing costs, and may provide high financial feasibility for waste reuse and recycling. This model represents a closed-loop system where all materials and resources are kept in the built environment domain.

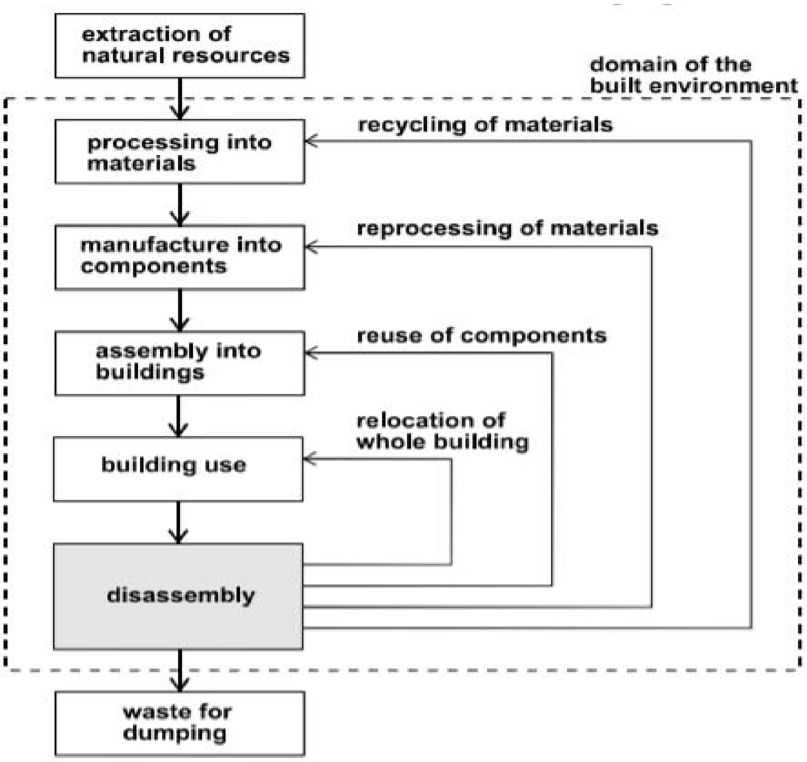


Fig. 5. Possible end of life scenarios for the built environment (Crowther 2001)

In general, C&D waste materials are recycled in either closed-loop or open-loop recycling processes. A closed-loop system can be defined as a recycling system that puts the materials back into the same product, whereas open-loop recycling uses the material in products different than the preceding ones (Haupt et al. 2017). As was seen in Figure 5, a closed-loop will achieve the circularity goal in the domain of the built environment. Open-loop recycling can achieve the circularity goal by keeping the waste materials outside of the landfills, not necessarily only in the built environment domain, providing more options for circularity. As an example, waste generated by the construction industry can be used in other applications such as using C&D wood waste in landscaping or feedstock (Lennon 2005). Another example is using waste from outside of the construction industry in the built environment such as using powdered glass waste in concrete production (Deschamps et al. 2018; Ellen MacArthur Foundation 2016). A higher priority is given to the reduction of waste from both a resource efficiency and waste management perspectives (Hossain et al. 2017; Pacheco-Torgal et al. 2013), requiring both closed-loop and open-loop recycling to reduce waste as much as possible. Geyer et al. (2016) state that closed-loop recycling should not be favored over open-loop recycling and that there should not be any distinction between the two. In different applications, depending on the materials' qualities and quantities, the benefits of either system can vary (Zink and Geyer 2017). In the end, all of this would result in maintaining the value of C&D materials to be reused at the end of their lifecycles, which would make construction a much more sustainable industry.

The CE in the built environment is not only achieved by reusing end products like concrete, but also by incorporating other waste materials in the production supply chain. The concrete industry is using by-products of other industries as cement substitutes (e.g.; fly ash; slag) reducing the cost of concrete by 2-10%, and its CO2 footprint by 25-40%. These substitutes improve the material properties of concrete as well (EMF 2016). Fly ash and slag can cause health concerns that discourage their use. In addition, the transition towards cleaner electricity generation can reduce the availability of the fly ash, which might require transporting it from farther locations. Due to these potential issues, ground glass may be used to replace fly ash and slag. Such a shift would help reduce landfilled recyclable glass and the CO2 footprint of concrete production. However, one downside is the increase in concrete production cost by around 2-5%.

Changing the existing frameworks and philosophies in the built environment to CE will have some challenges (ARUP 2016), these challenges hinder pushing the C&D waste management toward CE. Some of the challenges are in the design and construction using reclaimed materials and components. That would require the designers to be far more flexible in their design (Fathifazl 2008), also, there may be unpredictable material supply sources, possibly limited product innovation, as well as depreciation issues (Gorgolewski 2008). All of this might also introduce cost or time constraints that need to be considered in construction documents, cost estimates, and project schedules (Gorgolewski et al. 2006). Other challenges are related to the materials themselves. According to Waste Robotics Inc. (2018), the recovered materials may face challenges including a lack of markets, in addition to transportation, sorting and cost management complexities and the risk of contamination in mixed materials. However, the efforts may be worthwhile because reducing the amount of C&D waste discarded in landfills would conserve landfill space, reduce greenhouse gases, save energy (Townsend et al. 2014), and possibly generate monetary benefits, as will be quantified in this thesis.

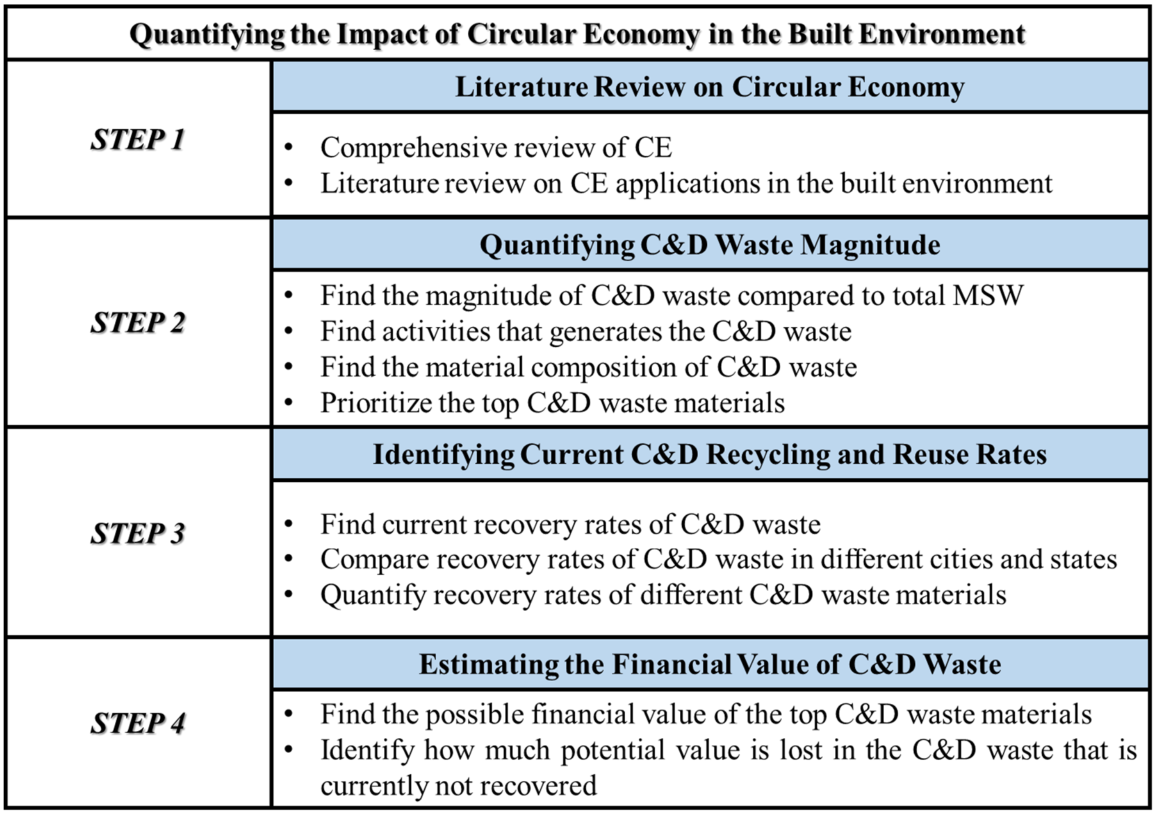
The existing literature can be broken down into two parts. First, there is an abundance of literature focusing on the CE as a new business model to protect resources and control waste, inching closer toward sustainability and the application of CE in the built environment (Carra and Magdani 2017). Second, there is a rich literature focusing on C&D waste management, which includes the amount, generation, reusing, recycling and barriers to the reuse of C&D waste. According to Yuan and Shen (2011), Five developed countries and regions contribute the most to this literature. These countries and regions are, Hong Kong, Australia, USA, UK, and Sweden. The total number of research papers published on the subject of C&D waste management between the years 2000 and 2009 were 87 papers in total, Hong Kong being the most contributing region with 23 papers. However, limited literature focuses on the economic aspect of managing C&D waste, with only 3 papers published on the subject between the years 2000 and 2009, out of the 87 papers as reported by Yuan and Shen (2011). These 3 papers used a cost-benefit analysis method as part of their data analysis to identify the feasibility of the C&D waste management. However, these 3 papers did not find a specific conclusion for what materials can result in the best financial benefits neither they found how much that financial benefit might be. This was identified as a research gap and will be tackled in this thesis.

CHAPTER 4

RESEARCH OBJECTIVE AND METHODS

This thesis aims to address the gap identified in the literature review, investigating the magnitude of C&D waste by weight and then estimating its monetary value. The objective is to highlight the opportunities available to allow the built environment stakeholders to identify where the leverage points are, along with the financial opportunities associated with changing their business model to a circular one. In other words, the author studied the C&D waste makeup to identify key materials that are responsible for the major portion of C&D waste. Then they estimate the potential monetary value being wasted to shed the light on opportunities that may incentivize the industry to take on this CE challenge. Identifying significant financial benefits may drive built environment owners and contractors, as well as material suppliers and manufacturers, to consider investigating CE as a possible alternative to current linear supply chains in which materials end in landfills.

The first step was the literature review and background work, which consisted of analyzing existing literature around the reuse and recycling of C&D waste, what criteria is used to determine the goodness of the waste materials, what are the current practices for the reuse and recycling of C&D waste and what are the challenges for these reuse and recycling practices, through identifying illustrative examples of reuse and recycling for some C&D materials. Then the literature was searched for the application of CE in the built environment. Once this first step was complete, three major steps were undertaken to accomplish the research objective of finding leverage points to apply CE to the built environment. All these steps are shown in Figure 6.



Quantifying the Impact of Circular Economy in the Built Environment	
STEP 1	**Literature Review on Circular Economy** • Comprehensive review of CE • Literature review on CE applications in the built environment
STEP 2	**Quantifying C&D Waste Magnitude** • Find the magnitude of C&D waste compared to total MSW • Find activities that generates the C&D waste • Find the material composition of C&D waste • Prioritize the top C&D waste materials
STEP 3	**Identifying Current C&D Recycling and Reuse Rates** • Find current recovery rates of C&D waste • Compare recovery rates of C&D waste in different cities and states • Quantify recovery rates of different C&D waste materials
STEP 4	**Estimating the Financial Value of C&D Waste** • Find the possible financial value of the top C&D waste materials • Identify how much potential value is lost in the C&D waste that is currently not recovered

Fig. 6. Research method

The intent of the second step was to research the existing publications and statistics of C&D waste in different countries as well as different states and cities. The literature and statistics were mined for C&D waste data, type of activities that generated the waste, and the material composition of the C&D waste. The collected data was first used to compare the magnitude of the C&D waste to the MSW in different locations. Then the author compared the activities that generated the waste to see whether construction or demolition has the highest impact on waste generation. Finally, materials were organized and classified according to their contribution to the total weight of C&D waste to highlight the top waste materials generated from C&D activities. The key goal of this analysis is to identify a limited number of leverage points that are responsible for the largest portion of the problem, according to the Pareto principle.

The third step investigated the current C&D waste recycling and reuse rates to gauge which waste materials are already being highly recovered and which materials have a high potential for more recycling and reuse. Therefore, the author investigated how these two groups of materials can achieve higher levels of circularity through identifying different options that maximize the efficiency of reusing and recycling these specific materials. Then the recovery rates of C&D waste in different states and cities in the US were compared and contrasted to identify which areas of the US are achieving higher levels of recovery and further study how these states and cities are separating themselves from the crowd to achieve such high recovery rates. The author then highlighted best practices that other states and cities can adopt to improve their performance.

Finally, in Step four, once the amount of the C&D waste and the current recycling and reuse rates have been established, the author studied the potential monetary value that could be recovered from this waste. Data was collected for possible resale values of the top C&D waste materials. Data was also collected on landfill tipping fees that could be avoided. Then the material resale value and the tipping fee savings were multiplied by the total generated waste for these materials to get the total potential market value of the top C&D waste materials. Then the different costs for handling waste materials were estimated. These costs included collection, transportation, and processing costs. This data allows one to estimate the possible financial benefits resulting from reusing or recycling each ton of C&D waste. The rates were then applied to the amount of C&D waste that is currently not being recovered to estimate potential financial benefits of recovering C&D waste in the US.

For this thesis, literature and statistics on the subject of C&D waste management from different regions of the world were used. This can be seen in Figure 7. Hong Kong, Australia and USA had the greatest number of research papers on the subject and USA had the greatest number of data and statistics on the magnitude and cost of C&D waste.

Fig. 7. Literature and Statistics Geographical Distribution

CHAPTER 5

FINDINGS PART 1: C&D WASTE MAGNITUDE

The author investigated the magnitude of C&D waste from four perspectives to develop a comprehensive understanding of the problem as well as the origin of the top C&D waste materials. These four perspectives are discussed next, in the following order: C&D contributions to total MSW; construction versus demolition; C&D waste material composition; and identifying the top C&D waste materials by weight.

5.1 C&D contributions to total MSW

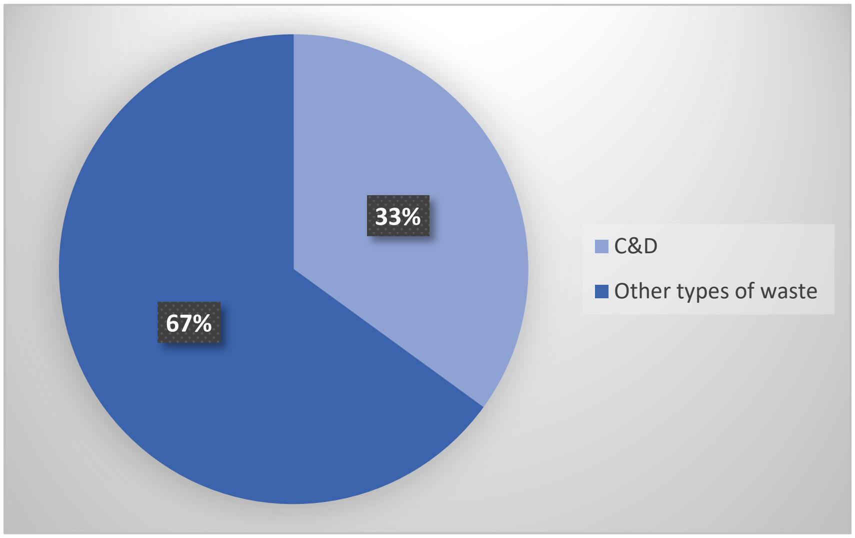


Fig. 8. Average Percentage of Construction and Demolition (C&D) waste as a component of the total MSW, by weight (Sources in Table 2)

The collected data shows C&D waste is responsible for a large percentage of the total solid waste generation, regardless of the geographic location. As can be seen in Figure 8, on average, C&D waste makes up about 33% of the total MSW. Table 2 shows the collected data for different regions. Although using an average of states, countries, and continents is not ideal, it is adequate to indicate that C&D waste is responsible for about a third of the total MSW and varies based on the location. Most of the data found was in the same range. In the case of the UK number being higher than all others, one main reason for this difference is the inclusion of other materials in calculating C&D waste, such as excavation and dredging waste (UK Department for Environment Food and Rural Affairs (UKDEFRA), 2018).

Table 2. The percentage of C&D waste compared to total MSW, by weight

Europe (Eurostat 2017)	China (Suocheng et al. 2001)	UK (UKDEFRA, 2018)	India (Ghosh et al. 2016)	Canada (Yeheyis et al. 2013)	California (CalRecycle 2015a)	Australia (Craven et al. 1994)	Hong Kong (EPD 2017)	Avg
33%	40%	59%*	30%	27%	24%	20%-33%	27%	33%

5.2 Construction versus demolition

After indicating that C&D waste is responsible for about a third of the total MSW, specific activities that generated this waste were investigated further. There are three major types of activities that generate C&D waste: construction, demolition, and renovation. In this comparison, only construction and demolition activities are considered because most of the available data did not include renovation. The results show that demolition is responsible for 90% of C&D waste generated, on average.

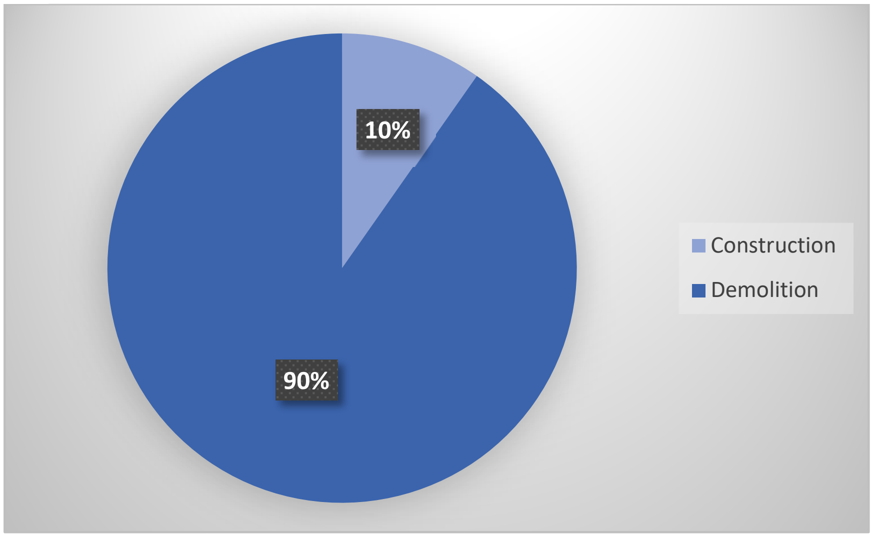


Fig. 9. Average construction versus demolition waste, by weight (Sources in Table 3)

Figure 9 shows an average percentage of the breakdown of C&D waste by the type of activity that generated the waste. It can be seen that around 90% of the total C&D waste comes from the demolition activities. Table 3 provides the detailed data for countries and states, all hovering around 90% for demolition waste. As discussed earlier, averaging values for different locations might not be the most accurate method, but it is adequate to provide an indication of the major source of C&D waste. All the values recorded do not deviate much from the average. This finding helps understand the importance of managing the demolition process to improve the recovery of the typically wasted materials. Effective demolition techniques, or ideally deconstruction techniques, are needed to recover valuable demolition waste. When discussing leverage points, multiplying the 35% found for C&D waste by the 90% attributed to demolition, one can estimate that a little less than a third of total MSW may be attributed to demolition activities in the built environment. Identifying this leverage point may help devise pointed strategies to tackle this growing problem.

Table 3. The percentage of construction waste versus demolition waste, by weight

Activity	Spain (Martínez Lage et al. 2010)	USA (USEPA, 2016b)	California (CalRecycle 2015a)	Connecticut (USEPA, 2016a)	Iowa (USEPA, 2016a)	Average
Construction	4.8%	5.4%	19%	11.5%	8%	10%
Demolition	95.2%	94.6%	81%	88.5%	92%	90%

5.3 C&D waste material composition

As one would expect, C&D waste consists of numerous types of materials generated in varying amounts. Thus, it is important to identify which materials make up the bulk of the waste, in the spirit of identifying leverage points as discussed earlier. Table 4 shows the relative distributions (by weight) of the C&D waste materials generated in different locations.

Materials	Location													
	Countries					Regions	States					Cities		
	US	Thailand	Spain[c]	Canada	Australia	Northeast US	CA 1	CA 2[a]	CT	FL[b]	MN	Des Moines, IA	Shanghai	Avg
References	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	
Concrete	70.30%	46.00%	29.30%	24.30%	80.00%	12.70%	11.20%	17.00%	9.00%	32.00%	9.70%	7.00%	32.75%	29%
Wood	7.20%	14.00%	5.40%	41.20%	-----	47.90%	23.30%	15.00%	34.00%	15.00%	22.70%	28.00%	9.80%	20%
Roofing	2.50%	-----	-----	-----	-----	15.50%	16.90%	15.00%	11.00%	6.00%	17.10%	21.00%	-----	8%
Drywall	2.50%	6.00%	3.60%	-----	-----	14.10%	9.30%	-----	10.00%	-----	11.60%	-----	1.60%	5%
Brick	2.30%	-----	-----	-----	-----	-----	-----	-----	-----	-----	5.60%	-----	51.05%	5%
Metals	0.80%	1.00%	8.80%	6.70%	5.10%	7.00%	1.30%	4.00%	5.00%	5.00%	3.40%	5.00%	4.80%	4%
Rocks, gravel, sand, and dirt	-----*	-----	0.20%	4.80%	-----	-----	16.80%	8.00%	-----	-----	16.10%	8.00%	-----	4%
Asphalt	14.30%	-----	0.10%	-----	-----	-----	11.50%	10.00%	-----	-----	-----	-----	-----	3%
Ceramic	-----	-----	44.60%	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	3%
Electrical waste	-----	-----	-----	-----	-----	-----	-----	8.00%	-----	12.00%	0.10%	13.00%	-----	3%
Paper	-----	3.50%	3.40%	5.20%	0.30%	-----	-----	3.00%	-----	-----	4.20%	6.00%	-----	2%
Plastics	-----	1.50%	3.80%	1.90%	0.30%	2.80%	-----	1.00%	2.00%	-----	4.30%	5.00%	-----	2%
Other C&D including glass and carpet	-----	28.00%	0.80%	16.10%	14.30%	-----	9.70%	9.00%	29.00%	30.00%	5.20%	10.00%	-----	12%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100%

Notes: Dashed cell values represent materials that are not found in the C&D waste stream in that location or there is no available data for it in the original source. These are all used as 0.00% to avoid problems in the total calculations.

(a) Cascadia Consulting Group data represents only the four major metropolitan areas of the state: the San Diego area, Southern California/L.A. Basin, the San Francisco Bay Area, and the Central Valley.

(b) Calrecycle and Foth Infrastructure & Environment data did not add up to exactly 100%, likely due to rounding errors, so the authors had to divide the numbers by a factor of 0.994 to make the sum exactly 100%.

(c) Spain data set shows a very high value for ceramic waste; there was no clear justification for this in the data source.

References: (1) (USEPA, 2016b) (2) (Kofoworola and Gheewala 2009) (3) (Martínez Lage et al. 2010) (4) (Yeheyis et al. 2013) (5) (Hyder-Consuting 2011) (6) (Griffith 2009) (7) (Cascadia Consulting Group 2006) (8) (CalRecycle 2015a) (9) (USEPA, 2016a) (10) (Foth Infrastructure & Environment 2007) (11) (Fisher 2008) (12) (Foth Infrastructure & Environment 2007) (13) (Ding and Xiao 2014)

Averaging values for different cities, states, regions, and countries, is certainly not ideal, especially that some locations did not have any data reported for specific materials, which impacts the average values calculated for the given material. One example is asphalt; asphalt waste values are not included in several sources, resulting in a lower average value than expected. On the other hand, very high percentages were reported in some occasions, such as ceramic in Spain. These were considered outliers specific to one data set or one location. Notwithstanding the abovementioned issues that impact the accuracy of average numbers, the analysis is still very useful in highlighting the top handful of materials that make up a significant component of the waste, which is the intent of this work.

5.4 Identifying the top C&D waste materials by weight

Now that the material composition of C&D waste has been identified, one can point to the top materials. Finding the top materials can help identify leverage points that address a large portion of the waste problem. Most of the existing research focuses on the reuse and recycling of specific C&D waste materials. In contrast, this thesis analyzes and compares all the materials together to understand which of them have the highest leverage. This intent is in accordance with the Pareto principle, which in essence states that roughly 80% of the effects come from 20% of the causes.

For this research, the top five materials were identified as: concrete, wood, roofing, asphalt and metals. Concrete, wood, and roofing are the top three C&D waste materials by weight, and they make up more than half of the total C&D waste as seen in Table 4. If these three materials alone make up half of the C&D waste, which was estimated earlier as contributing to about a third of the total MSW, then these three C&D materials alone may be responsible for about 15% of the total MSW, which perhaps is the most significant leverage point to minimize landfill use. Even small reductions in these materials contribute significantly to solving the global waste problem.

Additionally, asphalt appears to only have a small 3% contribution (by weight) because of the lack of asphalt data in most surveyed locations. However, asphalt is responsible for more than 14% of the total C&D waste in the US, so it is considered one of the top C&D waste materials (USEPA, 2016a). Finally, metals were added to the list of top materials because of its significantly higher monetary value per weight and hence its direct connection to potential monetary benefits that may lead metals to be reused.

CHAPTER 6

FINDINGS PART 2: CURRENT C&D RECYCLING AND REUSE RATES

Five specific materials were identified in the previous section as holding the most leverage in C&D waste. This section will investigate them further, starting with their current recovery rates. A portion of these materials is being recovered for recycling and reuse. Table 5 shows the recovery rates of the five major C&D waste materials in the US. Three references were found for metals and asphalt to ensure accuracy. For other materials there was one significant reference due to limited data availability; however, the source is the reputable, CDRA (Townsend et al. 2014). These results will be broken down further by location and will be compared and discussed in this thesis.

Table 4. Recovery rates of major C&D waste materials

Material	Average Percent of Reuse and Recycle (%)	Range of Reuse and Recycle (%)
Concrete	77%	77% (Townsend et al. 2014)
Wood	46%	46% (Townsend et al. 2014)
Roofing	9%	9% (Townsend et al. 2014)
Asphalt	98%	95% to 99% (Townsend et al., 2014; Hansen and Copeland, 2015; Arredondo, 2018)
Metals	98%	96% to 99% (Sansom and Avery 2014; Steel Recycling Institute 2017; TATA Steel 2018)

6.1 Top highly recovered materials versus less recovered materials.

In order to achieve a true CE in the built environment, C&D waste materials would need to be treated as resources. An assessment of the current state of practice is beneficial to understand how CE can be applied practically. Specifically, the author highlighted top materials that are being recycled and reused at a relatively high rate, versus those that have significant room for improvement.

Table 5 helps group the top materials into three groups based on recovery rates. The first group is for materials that are highly recovered. It includes metals and asphalt. A little less than 100% of the metals and asphalt C&D waste are reused or recycled according to the sources found. Splitting these based on the way they are recovered (reused versus recycled) provides more insight. Reused materials fulfill the circularity goal in a closed-loop system with minimal effort for processing. Recycled materials require major processing and treatment to make them reusable and will require additional resources, cost, and time. The result might be an open-loop system with the materials possibly used in a lower quality application, a process often called “downcycling” (Geyer et al. 2016). Although downcycling provides significant environmental gains and is better than landfilling, it is preferred to recycle in high quality application when possible (Di Maria et al. 2018). Reclaimed asphalt is mainly used as fill material, aggregates, and as Recycled Asphalt Pavement (RAP) in new asphalt mixes, which can save significant costs.

The second group only includes concrete as a relatively high-reclaimed material. Concrete is mostly reclaimed and crushed as aggregate to make new concrete, but has some limiting factors such as harder mix designs, affected concrete strength and slump values (Fathifazl 2008). More efficient reuses of concrete can include reusing prefabricated concrete items, concrete curbs, blocks and pavers (International Council for Research and Innovation in Building and Construction 2014; Vossberg et al. 2014). CE strategies can also be applied to the mix design of concrete such as using fly ash, slag or even ground glass, which can reduce the cost of concrete by 2-10% and its CO2 footprint by 25-40% (EMF, 2016).

The third group consists of the top C&D waste materials that are not heavily recycled or reused. This group includes wood and roofing materials (shingles). In this group, the recycling and reuse rates can still be considerably improved from their current state. These materials need to be diverted from the landfills. According to the Institutional Recycling Network (Lennon 2005), “almost all job site wastes are recyclable”. Understanding the causes for the differences in recovery rates between the three groups may help find solutions to increase wood and roofing materials’ recovery rates. Some of the main causes for the differences in rates include easier recycling or reuse requirements, higher monetary value of recovered materials, and the availability of a market for these materials.

6.2 C&D waste recycling/reuse differences between various cities and states

In addition to the variations in recycling and reuse rates for different materials, recycling and reuse of C&D waste vary greatly from one location to the next. Table 6 shows the recycling rates of C&D waste in different states and cities in the US. Some states are achieving high levels of recycling of C&D waste (e.g.; Massachusetts) while other states have much lower recycling and reuse rates (e.g.; Texas; Virginia). This discussion will highlight the actions implemented by states and cities with high recovery rates to achieve these high rates. Then these successful models are formalized as good practices that states and cities with low recycling and reuse rates can adopt to enhance their material recovery rates.

Table 6. Sample of C&D recycling rates in the US

City or State	C&D disposal (Tons)	C&D recycled (Tons)	Total (Tons)	% recycled	References
Florida	4,422,861	3,097,791	7,520,652	41%	(Townsend et al. 2014)
Maine	329,562	54,960	384,522	14%	
Maryland	1,452,670	196,164	1,648,834	12%	
Massachusetts	440,000	2,250,000	2,690,000	84%	
South Carolina	2,894,242	690,826	3,585,068	19%	
Texas	4,972,998	408,256	5,381,254	8%	
Virginia	3,476,690	309,996	3,786,686	8%	
Washington	2,115,982	3,655,698	5,771,680	63%	
New York	2,125,422	2,075,174	4,200,616	49%	(Griffith 2009)
San Francisco, CA	-----	-----	-----	65% (Mandatory)	(Lee and Raphael 2014)
Portland, OR	-----	-----	-----	75% (Mandatory)	(Elder Demolition 2015)

Two cities and two states with high recycling and reuse rates are studied further to identify strategies or good practices adopted to enhance recycling/reuse rates. These are the states of Massachusetts and Washington and the cities of Portland, OR and San Francisco, CA, as shown in Table 6. They are ordered in decreasing recovery rates in the table.

Table 7. Used C&D waste recovery strategies in Massachusetts, Portland OR, San Francisco CA, and Washington State.

State or City	MA	Portland, OR	San Francisco, CA	WA
Current C&D waste recovery rate	84%	75%	65%	63%
Identified Strategies				
1. Governmental regulations determining the minimum diversion percentages		X	X	X
2. Waste disposal ban	X			
3. Increased landfill tipping fees	X	X	X	X
4. Local funding to recycling and waste management programs		X	X	
5. Well-developed and growing recycling industry with many recycling facilities	X	X	X	X

The strategies listed in Table 7 are not meant to be comprehensive, but rather illustrative of the types of good practices that could be adopted by other cities or states. Some of these strategies used by the high-performing states and cities are discussed next. They are grouped by regulatory strategies and economic strategies.

Regulatory strategies include regulations on minimum diversion rates from the landfills, as used in Portland, Seattle, and San Francisco (Lee and Raphael, 2014; Elder Demolition, 2015; Seattle Public Utilities, 2017). The city of Portland began regulating C&D waste in 1995. They first specified that all projects valued $25,000 or more have to recycle at least half of their waste. This requirement was later raised to projects more than $50,000 in value. Builders receive benefits associated with recycling C&D waste, including tax deductions when donating salvage materials, lower tipping fees, and financial benefits from selling the recovered materials (City of Portland 2018). This regulation was applied to metals, cardboard, wood, land-clearing debris, concrete, and masonry. The city of Portland now has a 75% mandatory diversion rate, and a stricter 85% diversion rate for city owned buildings and buildings abiding by its green building policy (Elder Demolition 2015).

Another regulatory strategy in Portland included banning some specific C&D waste types. The Massachusetts Department of Environmental Protection amended its waste disposal ban regulations in 2006 to add asphalt pavement, brick, concrete, metal and wood to its waste disposal ban, meaning these materials are not allowed in landfills (DSM Environmental Services 2008). The wood disposal ban resulted in recovering 667,000 tons of wood waste sent to landfills, which is responsible for 31% of the total C&D waste in Massachusetts. However, this amount of wood waste includes the waste diverted through Waste-to-Energy (WTE), not just materials sent to recycling and processing plants. States are currently trying to reduce WTE facilities, especially those facilities that receive wood waste from out-of-state sources. Similar C&D waste disposal bans are enforced in Vermont, West Virginia, and Washington, DC. According to Zhao et al. (2010), economic and political tools must be used to enhance the feasibility of C&D waste recycling, such as landfill bans for unsorted waste, which should be carried out only when effective recycling systems are available. Otherwise, it’s advisable to create “mono” landfills for recyclable materials, which can be used as resource reservoirs of the recycled materials in the future (Symonds Group 1999).

The third regulatory strategy is local funding to recycling and waste management programs. The city of San Francisco provides funding to their waste management programs entirely through garbage bills to city residents (Resource Recycling Systems 2017). In

Portland, financial grants are given to encourage deconstruction as an alternative to mechanical demolition of housing projects. These grants are worth $2,500 for full deconstruction and $500 for partial deconstruction (City of Portland 2018). According to the Northwest Economic Research Center (2016), deconstruction, on average, would cost $8,500 more than mechanical demolition, so including the grant makes the average cost of deconstruction $6,000, without considering any value of the salvaged materials. These materials can have a significant monetary value, which may offset the higher costs of deconstruction. More research is needed to identify this value and clarify it to residents in order to turn deconstruction into a financially viable option.

In addition to regulations, economic strategies are also being implemented successfully. First, increasing landfill tipping fees directly reduces the amount of landfilled waste. Massachusetts, San Francisco, and Portland have 350 to 750 percent higher tipping fees compared to the average fees in the US, and therefore their recycling rates are also higher than average (CalRecycle 2015b; DSM Environmental Services 2008; Rathmann 1997).

In addition, a well-developed and growing recycling industry helps increase recycling rates. The city of Portland has an exceptionally well-developed recycling economy, with forty to fifty recycling facilities that support the growth of the recycling economy, which contributed to the high rates of C&D recycling (Rathmann 1997). In Massachusetts, the direct impact of the recycling economy is about $3.2 billion. The Department of Ecology (n.d.) at the State of Washington is developing new uses and markets for recycled materials such as paint and carpet, aiming to further enhance the recycling rates in the state. In San Francisco, new heavy materials recycling lines were built to meet the 75% mandatory recycling rates (Quillen and Reed 2004)

The author identified five C&D waste recovery strategies implemented by states and cities that achieved high recovery rates. Replicating some of these strategies in other states or cities could help boost C&D waste recovery rates. The author's recommendation is for states and cities to investigate which of these strategies may be applicable based on their unique context.

CHAPTER 7

FINDINGS PART 3: ESTIMATING THE MONETARY VALUE OF C&D WASTE

Organizing the C&D waste materials by weight shows the materials with the largest impact on landfills. However, some other C&D materials with lower weight contribution might have a higher monetary value and hence a stronger business case for their reuse; these materials will also be considered here. For example, steel has a monetary value of $335/ton (Scrap Monster 2018) compared to recycled concrete at $14/ton (C&E Excavating 2018).

The value of the C&D waste materials will strongly depend on the state of the material itself and the kind of treatment and effort needed for the recovery process. Reclaimed wood values can be as low as $35/ton when recovered and used as pulpwood (Carter 2013) and can be as high as $1700/ton when recovered, treated, and used as flooring boards (Falk 2002). This large range introduces many variables that need to be leveled and compared in order to assess reuse feasibility. Ideally, one would want to use materials at their highest possible value.

To estimate the potential monetary value of the C&D waste, assumptions were made regarding the state of the recovered material and the treatment and processing required. The assumptions used are conservative and likely underestimate the potential value of the C&D waste. The value can also be raised significantly if the C&D waste materials can be treated correctly. Some of these assumptions are:

1) Roofing materials are assumed predominantly as asphalt shingles since asphalt shingles comprise almost 85-90% of the roofing C&D waste (Connecticut Department of Energy and Environmental Protection 2014).

2) Concrete was assumed to be reused as RCA, assigning it a low potential value ranging of \$9/ton to \$14/ton (C&E Excavating 2018).

The amount of landfilled C&D waste materials used in the estimate is for the US only because of the available data regarding the cost and weight of waste materials. Table 8 shows some resale values from different sources and uses of the C&D waste materials in addition to average landfill tipping fee savings. When accounting for the total generated waste for these materials, one can start estimating the total potential value of these five C&D waste materials in the US. An average tipping fee value was used here, but tipping fees vary considerably between regions. The resale value and the landfill tipping fee savings are considered a value to be gained from recovering the waste. These two values are added and then multiplied by the total amount of waste generated in the US to give the total potential value of the generated waste in the US based on the 2014 EPA data. This is calculated using *Equation 1*. The total potential value of the top five C&D waste materials is estimated to \$33.57 billion in the US, which is more than the \$23 billion estimate for the EU's market saving by resource efficiency (European Commission, 2016).

Table 8. Estimated potential value for the top 5 C&D waste materials in the US

Material	US waste (tons/year) (USEPA, 2016b)	Material potential resale value ($/ton) *Average, (range), references*	US avg tipping fee ($/ton) (Rosengren 2017)	Total potential value ($/year)
Concrete	375,252,026	$10.92 ($9.00 to $14.00) (C&E Excavating 2018; East Valley Sand and Gravel Co. Inc. 2018)	$49.00	$22.48 Billion
Wood	38,675,365	$40.00 ($18.00 to $67.00) (Turley, 2002; Carter, 2013; Ghent Wood Products & Meltz Lumber, 2018)	$49.00	$3.44 Billion
Roofing	13,350,000	$18.37 ($5.50 to $42.50) (Brock, 2007; Zhou et al., 2013; Yang et al., 2015)	$49.00	$0.90 Billion
Asphalt	76,555,825	$18.65 ($9.00 to $36.70) (Hansen and Copeland, 2015; C&E Excavating, 2018; East Valley Sand and Gravel Co. Inc., 2018)	$49.00	$5.18 Billion
Metals	4,348,479	$312.73 ($243.20 to $360.00) (Scrap Monster 2018; Scrapregister 2018; SteelConstruction.info 2018)	$49.00	$1.57 Billion
Total				**$ 33.57 billion**

Equation 1. Total Potential Value = US waste * (Material potential resale value + US avg tipping fee)

Table 9 shows the breakdown of the costs and savings of recovering and reusing the C&D waste materials. Adding up these values provides an estimated net cost or savings for each material. The total costs or savings achieved through recycling/reusing C&D waste materials can be estimated using *Equation 2* by adding the materials' resale value and the tipping fees savings, then deducting the collection costs and the processing cost. A positive value means that profit can be generated. A negative value means it will cost money to recycle or reuse these materials. It is interesting to see that all materials in the table have a positive net savings, which means that recovering these materials for reuse or recycle would provide a monetary benefit.

Table 9. Breaking down the cost of recovering five C&D waste materials in the US (units: Dollars per ton)

Costs and Savings	Concrete ($/ton)	Wood ($/ton)	Roofing ($/ton)	Asphalt ($/ton)	Metals ($/ton)
Collection costs	$25.80 (Sobotka and Sagan 2016)	$6.60 (Sobotka and Sagan 2016)	$9.30 (Sobotka and Sagan 2016)	---	$0.00 (Sobotka and Sagan 2016)
Transport costs	$11 (Lennon 2005)[a]	$29 (Lennon 2005)	$32 (Uecker 2014)	$0.25/ton/ Mile (ConcreteNetwork.com 2018)	$12 (Lennon 2005)
Processing (Recycling) costs	$10 (Lennon 2005)	$40 - $60 (Turley 2002)	$36 - $46 (Lennon 2005)	$10 (Lennon 2005)	$15 (Lennon 2005)
Tipping fees savings	($49.00) (Rosengren 2017)	($70 - $84) (Turley 2002)	($49.00) (Rosengren 2017)	($49.00) (Rosengren 2017)	($49.00) (Rosengren 2017)
Resale value (From Table 8)	$10.92	$40.00	$18.37	$18.65	$312.73
Net cost/savings	**$24.12**	**$60.40**	**$17.07**	**$57.65**	**$346.73**

Equation 2. Net Cost/ Savings = Resale value + Tipping fees savings – Collection costs – Processing costs ➔ Positive = benefits; Negative = Cost

Note: transportation cost for asphalt was assumed equal to that of concrete for lack of better estimates regarding the average for hauling distance. Transportation costs would be incurred anyway if the C&D waste were to be landfilled.

[a] Lennon (2005) numbers are based on the prices in Boston, MA.

It is important to highlight the following regarding the estimates provided in Table 9. The numbers in the table may vary significantly between various states or cities, especially the tipping fees. The numbers in the table were sourced from different states and cities depending on data availability, and all references ae provided in the table and at the end of this document.

Knowing that some materials are already being highly recovered, such as steel and asphalt, the lost recycling potential can be determined by taking into account how much material is ending up in landfills. The total weights of the C&D waste materials in the US were multiplied by the percentage of the waste currently landfilled for each material to estimate the weight of waste landfilled for each material. This weight was multiplied by the estimated monetary value gained from recycling/reusing that material as presented earlier. This simple calculation is illustrated in Table 10, which provides a rough estimate for the total value for each of the top C&D waste materials. Note that this calculation just accounts for bringing the top five materials up to a 100% landfill diversion rate.

Table 10. Monetary potential from landfilled C&D waste in the US

Materials	Total C&D waste generation in the US (Tons/year)	Waste recovery rate *from*	Amount landfilled (Tons/year)	Net savings from recovery ($/ton)	Total savings possible ($/year)
Concrete	375,252,026	77%	86,307,966	$24.12	$2.08 Billion
Wood	38,675,365	46%	20,884,697	$60.40	$1.26 Billion
Roofing	13,350,000	9%	12,148,500	$17.07	$0.21 Billion
Asphalt	76,555,825	98%	1,531,117	$57.65	$0.09 Billion
Metals	4,348,479	98%	86,970	$346.73	$0.03 Billion
Total					**$3.67 Billion**

Equation 3. Amount landfilled = Total C&D waste generated * (1 – Recovery rate)
Equation 4. Total savings possible = Amount landfilled * Net savings from recovery

Table 10 brings together all the values provided in this thesis to provide a rough conservative estimate of how much value is lost every year in C&D waste. First step, the amount of waste landfilled was calculated using *Equation 3*. The generated waste amount was multiplied by (1 – waste recovery rate), then the total savings possible was calculated using *Equation 4* by multiplying the amount of C&D waste landfilled (outcome of *Equation 3*) and the net saving from recovery. The total yearly potential is on the order or $3.7 Billion, most of which (about $3.3 Billion) is coming from two materials: concrete and wood. To put this number in perspective, the whole waste management industry in the US is worth $70 billions (Waste Business Journal 2017); this number includes waste from every single industry. This thesis shows that two materials from one industry, on their own, are on the order of 5% compared to this national number.

This is a realistic achievable target based on South Korean waste processing statistics, which state that the concrete recycling rate in Korea is about 100 percent, and the wood recycling rate is about 95% (SKME and Korea Environment Corporation, 2017). In fact, diverting these two C&D materials alone (concrete and wood) from US landfills can save around 15% of MSW by weight. That is exactly what the author discussed earlier when attempting to identify a limited number of leverage points that could solve a considerable portion of the problem, in accordance with the Pareto principle also termed the 80-20 rule.

It is important to note that these estimated values are only based on diverting a very limited number of C&D waste material types from landfills and do not include resource efficiency improvement. The author used an average sale value for different uses of the material to provide a conservative estimate. This value may be greatly enhanced if resource efficiency improvements are considered.

CHAPTER 8

DISCUSSION BASED ON A CASE STUDY ON DEMOLITION WASTE

After quantitatively estimating the magnitude and potential value or recovering C&D wasted materials, the author conducted a brief case study of one of the largest demolition contractors in the State of Arizona to qualify some of the findings and investigate how some of the C&D materials are being handled. The contractor organization recycles and reuses materials on most of their jobs. They usually separate C&D waste on site because it is cheaper, save on transportation costs, make the whole process leaner than separating off-site. They also save landfill tipping fees, which vary depending on the material but would range between $30 and $85.

The company leadership stated that the nature of the waste materials helps determine if the company will recycle them or not. For interior demolitions, they recycle most metals, but other interior materials such as drywalls, architectural wood, glass, and plastics are usually considered as trash. Carpet is sometimes recycled, and wood is generally taken as trash except for the main frames and large logs in columns or joists. Inert materials, such as hollow masonry units, concrete, and bricks, are crushed and used as fill materials for the project itself or for other projects. Concrete waste can be sent to recycling yards where it can be disposed with lower fees because of its resale value. Bricks are sometimes crushed separately and reused in decorative landscape concrete floors and walls. Structural steel is always recycled or reused. The resale of reclaimed structural steel allows demolition contractors to provide project owners with more competitive bids. Steel prices fluctuate greatly depending on the market. At the time of this writing, steel is at low market price and reclaimed steel is sold at around $100/ton compared to around $280/ton in previous years.

The case study confirmed the findings from the quantitative analysis of this research. It also provided an overview of which materials are easier to reuse or recycle, along with typical practices for these materials.

CHAPTER 9

CONCLUSION

As the population grows globally, so is the built environment housing it, and in turn the demand for raw materials. These trends motivate the architecture, engineering, and construction industry to investigate alternatives to the current linear consumption model and complement it with a more circular model that can provide a stable supply of materials while ensuring the continuity of material flows to the next generations. Applying CE to the built environment can help sustain the industry's material supply while providing monetary benefits in the process.

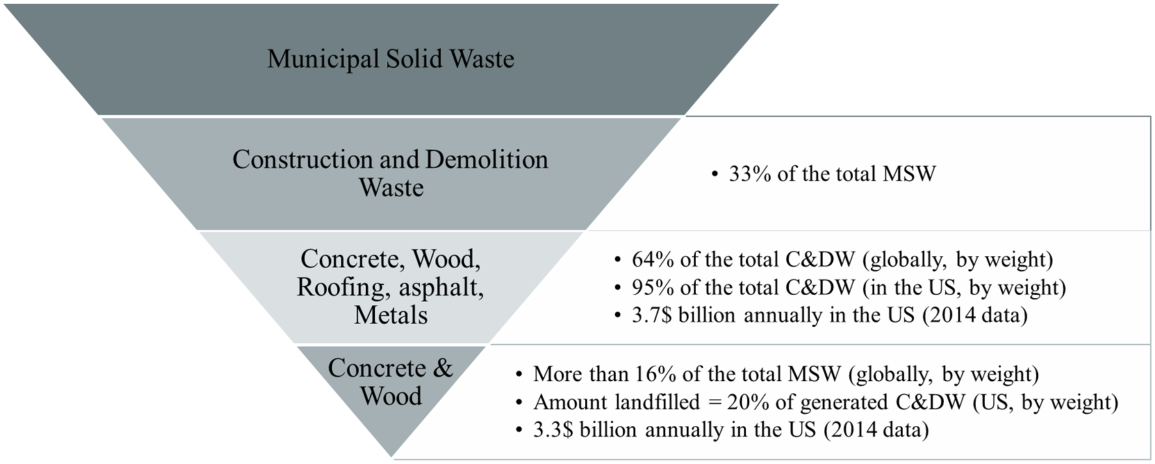


Fig. 10. Waste Impact Pyramid

This thesis assessed the benefits of applying CE to the built environment's C&D waste. As can be seen in Figure 10, C&D waste constitutes 33% of the total MSW although the construction industry does not represent more than 7% - 9% of any country's Gross Domestic Product (GDP). Concrete and wood are the top two materials. Roofing, metals and asphalt round out the top five list. These landfilled materials are considered as a high potential value, and their potential financial cost/value is estimated by considering data on collecting, transporting, processing and resale activities, in addition to tipping fee savings. The estimate is about $3.7 billion yearly in the US alone.

Concrete and wood waste is responsible for $3.35 billion of the wasted potential. This presents another case of the Pareto principle where only two materials are responsible for the biggest amount of waste. These two materials are the two major leverage points that can be used as an incentive to the built environment stakeholders to advance the CE implementation in the built environment. These leverage points and their financial value such as the ones before were not previously found in the literature on the cost-benefit of C&D waste management. In the case of asphalt and metals, these two materials' recovery rate is around 98%. These two materials' waste would generate more benefits if they are reused instead of recycled. The estimate only takes into account the financial benefit of diverting from the landfill, without taking into account the improvements that can be made to reuse some of the currently recycled materials. This is not the only economic gain that can result from applying CE in the built environment. This thesis only focused on a small portion of the CE possibilities.

The author found that four U.S. regions, specifically the States of Washington and Massachusetts and the cities of Portland, OR, and San Francisco, CA, have exceptionally high recycling and reuse rates compared to other regions. This superior material recovery performance is strongly supported by two distinct strategies: (1) regulatory strategies such as governmental regulations determining the minimum diversion percentages, waste disposal ban on specific type of waste and local funding to recycling and waste management programs; and (2) economic strategies such as increased landfill tipping fees and having well-developed and growing recycling industry with many recycling facilities.

This finding shows that the right policies can make a significant impact on the circularity of C&D waste. Such guidance can come from the federal level, such as the USEPA (2007) construction waste management specifications, but as found in this thesis, appropriate guidance at the state and city level also makes a significant impact while considering key regional differences.

Research Limitations

The data used in this research for C&D waste was collected from different literature and statistics. These literature and statistics were inconsistent in the way they reported the amount and composition of C&D waste. Some data sets excluded the infrastructure and transportation waste, mainly asphalt, and some data sets included dredging waste in the total C&D waste amount, such as the case of the UK where it resulted in a higher percentage of C&D waste compared to the total MSW. In the case of Spain, ceramic waste constituted 44.6% of the total C&D waste composition, which was considered in this thesis as an outlier because no other region reported ceramic to be a significant C&D waste material. Some data sets would put all concrete, brick, masonry as one waste item titled rubble while other data sets would go into the details of breaking down the different product waste of concrete.

Another challenge is the geographical factor affecting the C&D waste composition. C&D waste data was found and collected for different locations. Every location is expected to have a unique C&D waste composition depending on the regionally predominant design and construction practices, and most importantly the materials readily available and used in the specific region. For instance, it makes sense that wood be responsible for a large fraction of C&D waste in Canada and the northeast of the US. Thus, averaging the values from different regions is not the most optimal solution but was only considered to give an indication of the top waste materials. However, such waste patterns indicate that when considering the best C&D waste management practices, while some practices may apply globally, other practices may need to be tailored to specific regions based on their C&D waste composition.

Material reuse and recycling practices can produce very different end products with different resale values. Examples include wood waste, which can be used as pulp wood with a value of $35/ton (Carter 2013), or it can be worth $1700/ton when structural wood is deconstructed prior to demolition, recovered, treated, and reused as flooring boards (Falk 2002). The estimate made in this research was conservative, and the final financial value can be much higher than estimated.

Finally, a dollar value for the environmental impact of reusing and recycling the large amounts of C&D waste was not considered in this thesis. There will be a great reduction in the carbon footprint as a result of the recovered waste. For example, the amount of concrete waste landfilled in the US in 2014 was 86,307,966 tons (Table 10). Using a dollar value for this large amount of waste would increase the feasibility of recovering the concrete waste.

Future Work

Future work can focus on the application of CE in all stages of the built environment to achieve a complete circular life cycle, as well as developing circular processes for specific components and building systems. This may include deconstruction in lieu of demolition, designing for deconstruction, and leasing services in lieu of buying equipment (such as lighting services and furniture services following the examples of Philips lighting, Interface carpets, and Davies furniture).

Future work can focus on increasing the efficiency of recovering the C&D waste materials because reaching a circular economy requires maximizing the efficiency of the materials by optimizing resource yield. For examples, 98% of the asphalt and steel waste is being recovered. However, not all of it is being utilized at its highest efficiency. Asphalt waste can be downcycled as aggregates with a value of $9/ton (C&E Excavating 2018) or it can be utilized in the production of new asphalt with a value of $36/ton (Hansen and Copeland 2015).

Future work on the subject of C&D waste management should focus more on the waste supply chain management. This is important because a continuous flow of high-quality materials to construction sites is needed to increase the use of recovered C&D waste materials and vice versa, there should be an established system of how to reclaim the C&D waste from construction sites. An unpredictable supply chain and low-quality C&D waste materials are barriers to the implementation of CE in the built environment.

CE is still in its infancy and may be able to provide a harmonized circular business model that changes traditional business models in the long term. Futuristic materials and building techniques can be an area where CE in the built environment can be expanded. Prefabricated building components fixed with clamp connections rather than mechanical fixing would be a low waste option for the future. Integrating this with futuristic building materials such as green concrete, which uses less cement than regular concrete, green tiles or low-carbon bricks would result in a built environment that is more sustainable and more circular. The built environment may be a launching pad for CE’s widespread adoption and impact and the lessons learned can be applied to other industries.

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