UNIVERSITÉ DU QUÉBEC À MONTRÉAL

A CASE STUDY ON DESIGN FOR DISASSEMBLY, ITS APPLICATION IN BUILDING DESIGN AND POTENTIAL FOR COMPONENT REUSE AND MATERIAL RECYCLING TO MITIGATE CONSTRUCTION WASTE

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SUSAN SADRAEE

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SUSAN SADRAEE

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DEDICATION

To my grandfather, who taught me that education is the most valuable wealth in the world. I am deeply grateful for your words of wisdom and wish you could have seen the end of the journey.

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RÉSUMÉ

Cette recherche examine l'application de l'approche *Design for disassembly* (DfD) dans la conception des bâtiments. Différents aspects de cette approche seront étudiés afin d'explorer les possibilités qu'elle offre pour conserver les matériaux et composantes d'un bâtiment, faciliter leur réutilisation et recyclage, et diminuer la quantité de déchets de construction. Cette étude analyse les méthodes actuelles de gestion des déchets dans l'industrie de la construction, identifie les écarts existants, et propose des mesures que les designers peuvent intégrer dans la conception de leurs projets.

Afin de faciliter la réutilisation et le recyclage des matériaux et composantes d'un bâtiment, *design for disassembly* offre des stratégies pour éviter la démolition. Nous aborderons comment DfD peut éviter la démolition, conserver les matériaux et diminuer la quantité de déchets en intégrant des mesures de flexibilité et d'adaptabilité dans la configuration des systèmes.

Actuellement, les méthodes de conception conventionnelles, le manque de motivations économiques pour la réutilisation et le recyclage des matériaux, ainsi que l'absence de cadre standard pour DfD constituent les obstacles à la mise en œuvre de cette approche comme méthode dans la conception des bâtiments. Malgré de nombreuses barrières, les designers peuvent identifier les limitations à la réutilisation et au recyclage des matériaux issus des activités de construction, de rénovation ainsi que de démolition, et les prendre en considération dans la conception de leurs projets afin de contribuer ainsi à la transition vers une économie circulaire dans l'industrie de construction.
La revue de littérature de gestion des déchets de construction au Québec, une revue d'une série d'exemples, et une étude de cas nous permettront d'identifier le potentiel pour l'intervention des designers afin de mettre en œuvre l'approche *design for disassembly*, d'optimiser l'utilisation des ressources et de réduire la quantité des déchets dans l'industrie de construction.

Mots clés : Design de l'environnement, *Design for assembly*, *Design for disassembly*, construction, fin de vie, adaptabilité, réutilisation, recyclage, réduction de déchets

ABSTRACT

This research project examines the application of the design for disassembly (DfD) approach in building design. Different aspects of DfD are studied to explore possibilities to preserve materials and mitigate construction waste by facilitating component reuse and material recycling. This study reviews current waste management methods in the construction industry to identify existing gaps and determine the potential for designers to consider material efficiency in the planning phase of projects.

To facilitate the reuse and recycling of materials and components, design for disassembly suggests strategies to prevent demolition. This study will discuss how DfD can prevent demolition, preserve materials and reduce the amount of waste through flexibility and adaptability of systems during a building's life span and at the end of its life.

Currently, anchored traditional methodologies in building design, lack of economic incentives for reuse and recycling, and lack of a standard framework for DfD are obstacles to the implementation of DfD as a method. Despite these obstacles, designers can identify gaps and limitations in the waste management sector and design to address these gaps and contribute to move towards a circular economy in the construction industry. Through a review of literature on construction waste management in Quebec, a review of a set of examples and a specific case study, this project presents potential interventions for designers to implement DfD principals to reduce construction waste.

Keywords: Environmental design, Design for assembly, Design for disassembly, Building construction, End-of-life scenario, adaptability, flexibility, Reuse, Recycling, waste reduction

INTRODUCTION
INFLUENCE OF MODERN ARCHITECTURE ON CONSTRUCTION WASTE, FROM DESIGN FOR ASSEMBLY TO DESIGN FOR DISASSEMBLY

This research project focuses on the concept of design for disassembly (DfD) in the building industry. DfD aims to mitigate the negative environmental impacts of buildings by facilitating the recovery, reuse and recycling of their materials and components. The recovery, reuse and recycling of materials and components keep them in use cycles and preserve their physical and economic value and their embodied energy.

The starting point for this project is the author's previous research undertaken as part of the one-year graduate program, *Diplôme d'Études supérieures Spécilisées* (*DESS*) *en Architecture Moderne et Patrimoine*, offered by the School of Design at the Université du Québec à Montréal. The *DESS en Architecture Moderne et Patrimoine* program's framework follows the Docomomo international's[1] goals to document, preserve and enhance buildings designed and constructed during the Modern movement in the twentieth century. This program covers the history of Modern architecture and studies the cultural and social contexts of the early twentieth century which led to the evolution in construction technologies. These evolutions consist of the innovative construction methods, modular design, prefabrication and standardization of building components, on-site assembly of factory-made components, and the use of new industrialized materials. These technologies, developed from industrialization, were basically solutions to the early twentieth century and post-war housing crisis.

[1]Docomomo, the abbreviated acronym for The International Working Party for Documentation and Conservation of Buildings, Sites and Neighborhoods of the Modern Movement, is "an international organization established in 1988 out of concern for the increasing demolition of buildings not deemed 'historic' by age" (Carroon, 2010, p. 364).

They contributed to optimize time and cost of construction and were integrated in the framework of the approach design for assembly in building design. Today, these technologies can be discussed in the framework of the emerging appraoch of design for disassembly to address the issues related to material consumption and construction waste. " Given the vast inventory of twentieth-century buildings, the challenges and importance of reuse or preservation for both cultural and environmental reasons is immense" (Carroon, 2010, p. 364). Construction, renovation and demolition activities are some of the largest contributors to environmental degradation as they consume large amounts of raw materials and produce large amounts of waste. The choice between demolishing and conserving buildings and their systems is sometimes related to the construction methods used in the original buildings. In most cases, conservation processes are costly and laborious because construction techniques do not favour the adaptation and maintenance of buildings and systems, or replacing or repairing of their parts (Gorgolewski, 2017). Design for disassembly, developed form design for assembly, suggests strategies and construction techniques to facilitate the adaptation and maintenance of buildings and systems during their operation life and the recovery of their materials and components at the end of their operation life. This approach contributes to preserve materials for reuse or recycling to reduce the quantity of construction waste and harvest fewer raw materials. In this project we examine how the innovations of Modern architecture integrated into the DfD's framework can contribute to the preservation of building materials and components through subsequent reuse, repair and recycling. We also discuss how extending buildings' life spans through resilience, flexibility and adaptability can reduce the negative environmental impacts of buildings.

BACKGROUND AND PROBLEM STATEMENT

Population growth, economic developments and technological evolution lead to constant urbanization and change in the built environment (Lehmann & Crocker, 2012). Rapid evolution in the built environment through the increasingly large numbers of construction, renovation and demolition activities causes severe stresses on the environment. After food production, the construction industry is the largest consumer of raw materials and the biggest producer of waste worldwide (Berge, 2009). In the U.S., "no other sector of the industry uses more materials, produces more waste and contributes less to recycling than the construction sector" (US EPA, 2009 as cited in Lehmann & Crocker, 2012, p. 324). Based on estimates from multiple sources, the construction industry uses approximately 40% of the total raw materials in North America and 50% of European resource extraction (Carroon, 2010; Ruuska & Häkkinen, 2014; Gorgolewski, 2017; USGBC, 2019). Moreover, in developed countries, 25-30% of the total amount of waste produced in all industries is from construction, renovation and demolition projects (Gorgolewski, 2017). This amount rises to 35% in Quebec and 47% in Canada (Morneau, 2009; Giroux, 2014).

The overconsumption of raw materials and the generation of large amounts of waste in the construction industry is the result of the current linear model of material flow (ARUP, 2016; Gorgolewski, 2017). A linear model in the construction industry consists of extraction, transport, production, construction, demolition and disposal of residual materials in landfills. The constant extraction of raw materials and the landfilling of products with high embodied energy present three issues with important negative impacts on the natural environment; 1) the depletion of natural resource reserves, 2) the emission of significant amount of greenhouse gases (GHG), and 3) the pollution of waters and soils (Lehmann & Crocker, 2012; Kibert, 2013; ARUP, 2016; Gorgolewski, 2017; USGBC, 2019).

The first issue caused by a linear model of material flow is the depletion and scarcity of natural resources. Resource scarcity is highlighted by a global consensus that the consumption of natural resources is growing at an alarming rate (Lehmann & Crocker, 2012; Kibert, 2013; Gorgolewski, 2017). Worldwide metal and mineral use has increased by 66%, from 19 billion tons in 1980, to 31.5 billion tons in 2010 and it is estimated that this amount will grow to 53.7 billion tons by 2030 (Friends of the Earth Europe, n.d. as cite in Gorgolewski, 2017; Mckinsey & Partners, 2015 as cited in Gorgolewski, 2017). "The Worldwatch Institute[2] has estimated that by the year 2030, the world will have run out of many raw building materials "(Brown, 1990 as cited in Gorgolewski, 2017, p.10). It is believed that we have already consumed most of the easily accessible material supplies and in the near future, material markets will compete with energy markets for resources (Gorgolewski, 2017; Lehmann & Crocker, 2012). Ruuska & Häkkinen (2014) emphasize that materials such as coal, oil, and metallic minerals have more limited reserves, and some materials like oil are approaching their production peaks while others have already passed their peak. Lehmann & Crocker (2012) point out that iron ore, lithium and copper are already much rarer than oil.

Unlike the global consensus on the rate of resource depletion, the condition of material reserves used in the construction industry remains undefined (Lehmann & Crocker, 2012; Ruuska & Häkkinen, 2014; Gorgolewski, 2017). There are still large reserves of the most common building materials such as aggregates, clay lime, stone, gypsum and quartz (Ruuska & Häkkinen, 2014). However, there are doubts about the production

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[2] The Worldwatch Institute works to accelerate the transition to a sustainable world that meets human needs through research and outreach that inspire action (Worldwatch Institute, 2019).

capacity of oil, which is needed for manufacturing polymer-based building materials (Ruuska & Häkkinen, 2014). There is also a continuous decrease in ore grades which are the sources of some other common building materials such as metals and ceramics (Ruuska & Häkkinen, 2014).

Resource scarcity is not only linked to the physical exhaustion of supplies, but also to their availability which can be limited by the financial resources needed to extract, process or transport materials (Gorgolewski, 2017). There are materials that are still abundant in nature but are considered scarce as economically and environmentally they are becoming less accessible (Gorgolewski, 2017).

Two other issues related to the linear model of consumption in the construction industry are gaseous emissions and soil and water pollution. The extraction, manufacturing, processing, transportation, construction, demolition and disposal are energy-intensive activities that emit a high amount of greenhouse gases (Kibert, 2013). In addition to gaseous emissions, waste disposal in landfills and waters causes soil contamination and water pollution, which present serious problems for future generations (Jackson, 1996; Carroon, 2010). Large cities generate huge amounts of waste and nearby landfill sites have already reached or are reaching their capacity (Melnyk, 2016). Since 1978, three-quarters of North America's landfill sites have been filled to capacity and are now closed (Carroon, 2010; Melnyk, 2016). The U.S. is rapidly running out of landfill space (McCarthy, 2018). Due to the decrease in landfill capacity, areas are expanding near cities and consequently, the nearby environment is becoming contaminated (WRAP, 2009).

The awareness of the negative impacts of the linear model of material flow in the construction industry has led to constant evolution in waste management perspectives. Over the past few decades, new strategies, methods and policies have been implemented to protect the environment and the population from the negative impacts of waste disposal (Thormark, 2001; Durmisevic, 2006). Governments and policymakers have been implementing regulations to divert materials from landfills. One of the most effective measures that have been implemented are tax increases for material disposal in landfills and for incineration to reduce the number of residues in elimination facilities (Gorgolewski, 2008; Jeffrey, 2011).

Ruuska & Häkkinen (2014) highlight that there are many potential ways for the building industry to reduce waste. The reuse and recycling of residuals from construction, renovation and demolition activities are the most significant practices developed and implemented in the construction industry to reduce waste (Gorgolewski, 2008; Zelechowski, 2012). These two practices help to divert materials from landfills and convert a linear model of material flow to a closed-loop material flow (Thormark, 2001). Reuse and recycling of materials are more effective if building materials and components are recovered without damage and contamination. Deconstruction is an alternative to demolition that prevents the damage of materials and contributes to reuse and recycling. During the last 15 years, the U.S. Environmental Protection Agency (US EPA) has initiated a series of deconstruction pilot projects and created several deconstruction manuals. It conducted and documented a residential DfD pilot project in 2006 to examine the impact of the approach on reducing construction waste (US EPA, 2018). The results show that disassembly potentials integrated into different parts of the house would favour the recovery and reuse of several parts, such as interior walls, that may considerably reduce the amount of waste (EPA, 2010).

Deconstruction and disassembly of buildings or their systems for reuse show a growing recognition of the benefits that deconstruction and material reuse provide (Zelechowski, 2012). In some places in the world, reuse is an evolving industry in the building sector with social and economic benefits (Zelechowski, 2012).

Despite a significant evolution in waste management, reuse and recycling, studies show that the conventional methods in building design provide limited possibilities for the deconstruction of buildings, and the reuse and recycling of their components and materials (Durmisevic, 2006). The chemical complexity of composite and engineered products that are increasingly used in the building industry makes recycling and reuse difficult as it is energy-intensive to break down composite components into their constituent parts (Guy & Ciarimboli, 2007). Currently, most buildings are demolished with little or no attempt to recover their materials for reuse or recycling.

Durmisevic & Yeang (2009) relate demolition and the lack of material reuse to current building design scenarios that are based only on easy assembly but not disassembly. Conventional building design scenarios do not consider changes during the life cycle of a building or the end of its life span in the planning phase. Although assembly methods evolved and improved to optimize efficiencies in the construction phase, there have been limited attempts for the deconstruction phase. As such, components and materials are designed and prefabricated in a way to be assembled rapidly on-site, but not designed to be separated easily for reuse.

Recently, the issue of solid waste from construction activities has become an area of interest for developing methods and strategies to relate building design to waste management. To make the connection, designers and architects suggest approaches that plan the management of residual materials at the end of a building's life.

Design for disassembly is an approach that considers waste mitigation with a focus on the architecture of components, methods of connection between components and material selection (Rios, Chong, & Grau, 2015; Durmisevic & Yeang, 2009; Guy & Ciarimboli, 2007). One of the DfD's goals is to make the components and parts of a building accessible and flexible. Flexibility and accessibility allow for spaces to be adapted to the needs of a building's occupants, prevent demolition and contribute to preserve materials and reduce waste.

Through a review of the literature and a series of examples and case studies, this research study investigates the following questions to explore the impact of design for disassembly to mitigate waste in the construction industry.

First, this review will investigate *how policies and regulations contribute to diverting residual materials from landfills and to promoting reuse and recycling?* and *what are the existing gaps in the reuse and recycling practices that can be addressed by design for disassembly to reduce construction waste?* Second, a discussion of design for disassembly and its different aspects will explore *how design for disassembly considers the waste mitigation in the planning stages of a project?* Third, a series of examples will look at *what aspects of design for disassembly promote the reuse and recycling of components and materials?*

Following a series of examples, an in-depth analysis of the interior partition assembly system of a local building is presented to assess the literature and identify the limitations of current design practices for material recovery and reuse. It will also discuss how the implementation of DfD in the same system could allow for the reuse of a large number of materials.

CHAPTER I
WASTE MANAGEMENT IN THE CONSTRUCTION, RENOVATION AND DEMOLITION INDUSTRY

In the construction industry, waste comes from three major activities; new construction, renovation, or demolition and is associated with two sectors; civil engineering and building (Boisvert, Bosniak, & Dallaire, 2014). It is known as C&D waste (construction and demolition) or CRD waste (construction, renovation, demolition) (Jeffrey, 2011). CRD waste is essentially composed of asphalt, concrete, cement, stone, brick, ferrous and non-ferrous metals, wood, plasterboard, asphalt shingles, paper, plastic and cardboard packaging (Jeffrey, 2011; Boisvert et al., 2014). This chapter reviews the material flow and waste management strategies in the building sector.

The amount and type of waste from buildings differs depending on the context (residential, industrial, commercial, institutional) and the type of activities (construction, renovation, demolition) (Boisvert et al., 2014). Table 1.1 shows the characteristics of CRD waste generated in different types of activities in the building sector.

Table 1.1. This table shows the characteristics of waste form CRD activities in the building sector (Boisvert et al., 2014).

Type of activity	Quantity of residues	Type of residues	Sorting, reuse & recycling potentials
New construction	Low to moderate	Mostly surplus, offcuts & packaging	High potential
Renovation	Moderate	Combination of old materials & surplus of new materials	Moderate potential
Demolition	High	A mix of old, damaged & contaminated materials (crushed concrete, drywall, bricks, wood scraps, doors & windows, sanitary equipment, etc.)	Low potential

In general, a significant amount of CRD waste is generated from renovation and demolition activities. Environment Canada (2014) estimated that in Canada, 89% (about 3,562,100 tons) of the total waste generated in the CRD sector came from renovation and demolition activities in 2010. A demolition project produces 20 to 30 times more waste than a new construction or renovation project. However, since renovation projects outnumber demolition projects, the renovation sector is considered more wasteful (Boisvert et al., 2014). According to a study by Environment Canada (2014), the amount of waste from the renovation sector was two times higher than the waste from the demolition sector in 2010. In the U.S., the Rebuilding Exchange, a Chicago company that recovers building materials for reuse announced that its major source of supply, about 80%, is from renovations (Zelechowski, 2012). This is due to the far larger number of renovations compared with full deconstructions or demolitions.

There have been various attempts to address the large volume of waste generated from the construction industry. The current management strategy for CRD waste is based on the 4R-D principle. 4R-D stands for 'reduce, reuse, recycle, recovery for energy, and disposal.' This waste management hierarchy, generally illustrated in the form of a pyramid, indicates the order of priority for processes first to reduce waste production, and then to divert waste. Landfill disposal is the last option in the pyramid for materials that cannot be reused, recycled or used for energy recovery (Figure 1.1).

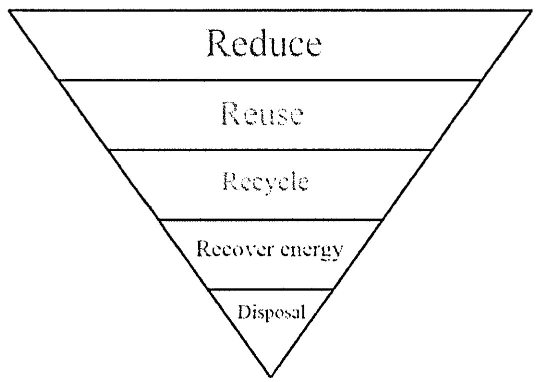

Figure 1.1. This pyramid shows the order of priority in waste management. Created by S. Sadraee.

4R-D remains a complex strategy in the waste management sector associated with social, economic, organizational and technical challenges (Boisvert et al., 2014). These challenges make waste disposal in landfills more economically beneficial than recovery practices (Boisvert et al., 2014). However, there is a growing interest in directing waste management from elimination to recovery.

Design for disassembly can be implemented as a part of the 4R-D strategy as both, DfD and 4R-D, emphasize the reduction of resource use and waste generation. Introducing the DfD approach to the 4R-D process can address gaps resulting from inefficiencies in the 'reduce' process and present opportunities for a design approach to reduce the amount of construction waste. In the following section, current waste management policies and practices in the CRD sector in Quebec will be reviewed.

1.1 CRD waste management in Quebec

This section covers three topics related to the CRD waste stream in Quebec; 1) the types and amounts of residual materials, 2) the legal framework for waste management, and 3) the current methods and facilities that sort, recover, recycle or eliminate residual materials.

1.1.1 Type and amount of residual materials

The construction, renovation and demolition industry generates approximately a third of the total waste produced in Quebec (Morneau, 2009; RECYC-QUÉBEC, 2016; RECYC-QUÉBEC, 2018). In 2008, this industry produced 4.57 million tons of residual materials in both the civil engineering and building sectors in the province (RECYC-QUÉBEC, 2018). In 2008, 3.22 million tons (74%) of CRD debris were recovered and revalued (Morneau, 2009; RECYC-QUÉBEC, 2018). The high recovery rate for CRD debris in Quebec is widely related to the increased recovery of aggregates notably concrete, asphalt, brick and stone and to a lesser extent, the recovery of wood (Boisvert et al., 2014). Aggregates, mostly from the civil engineering sector, represent 2.72 million tons of the total CRD debris that were recovered and revalued (RECYC-QUÉBEC, 2018). The high recovery rate of aggregates is due to the implementation of a standard by the *Bureau de normalization du Québec* (BNQ)[3] in 2002 for the development of markets for recycled concrete (Vachon, Beaulne-Bélisle, Rosset, Gariépy, & McGrath, 2009). In Quebec, concrete is recovered from renovation or demolition sites and is recycled and used as road base, and if free of contamination, it is used as dry aggregate to produce new concrete (Gagné, 2008). Apart from aggregates, various types of other materials such as wood, metals, shingles and gypsum, representing 500,000 tons, were recovered and revalued in the CRD industry in 2008 (Morneau, 2009; RECYC-QUÉBEC, 2018).

There is a lack of precise information regarding the composition of the total CRD debris generated in Quebec as there is not a system that tracks materials from CRD sites to

[3] This standard classifies and characterizes recycled materials, a mixture of concrete, bituminous coated and brick in order to control and encourage their use to replace new granular materials (Bureau de normalisation du Quebec (BNQ), n.d.)

management facilities (Vachon et al., 2009). The most relevant data that is available is from an exhaustive study of the Quebec waste management sector in 2009 carried out by Vachon et al. (2009). This study presents an estimation of the composition of CRD waste by the *Regroupement des récupérateurs et des Recycleurs de Matériaux de Construction et de démolition du Québec* (3R MCDQ). This data has been referenced in several research projects and is presented in Table 1.2.

Table 1.2. This table, designed by Vachon et al. (2009, p. 7) and based on the 3R MCDQ's estimations and data from the *Institut de la statistique du Québec*. It shows the approximate proportion of different types of construction and demolition debris generated in Quebec.

Type of waste	Approximate composition (after 3R MCDQ)	Equivalent quantity (metric ton)
Stone, brick, concrete & asphalt	40 to 60%	1,75M to 2,63M
Wood (treated or untreated)	10 to 20%	0,44M to 1,1M
Metals	3 to 15%	0,1M to 0,7M
Paper & cardboard	3 to 10%	0,1M to 0,44M
Soil	2 to 10%	0,09M to 0,44M
Others (plastics, asphalt shingles, gypsum)	10 to 20%	0,44M to 0,88M
Total	100 %	4380 141 mt

1.1.2 Legal framework for waste management

In 1989, the *Ministère de l'Environnement du Québec* adopted the *Politique de gestion intégrée des déchets solides*. This policy set a target for a 50% reduction in the disposal of residual materials by the year 2000 (Ménard, 2008). In 1995, the *Bureau d'audiences publiques sur l'environnement* (BAPE) established a committee and a public consultation on waste management at the request of the *Ministère de l'Environnement et de la Faune* (BAPE, 1997). In 1997, the committee presented a report entitled *Déchets d'hier, Ressource de demain* in which it analyzed the opinions of more than one hundred stakeholders. Following this report and based on the results of the consultation, the Quebec government created the *Plan d'action québécois sur la gestion des matières résiduelles 1998-2008* (BAPE, 1997). In 2000, the Quebec National Assembly adopted the action plan and introduced it as the *Politique québécoise de gestion des matières résiduelles 1998-2008* (Millette, 2010). Within the context of the policy's principles, the Quebec government aims to implement measures to reduce waste at source and create a zero-waste society. It seeks to maximize added value through sound waste management and to make end-waste the only residual material sent for disposal (Q-2, r. 19, 2005; Q-2, r.43, 2006). The policy outlines and discusses the following 11 principles:

- 4R-D,
- Social equity and solidarity,
- Environmental protection,
- Economic efficiency,
- Participation and commitment,
- Access to knowledge
- Subsidiarity,
- Prevention,
- Responsible production and consumption,

- Polluter pays, and
- Internalization of costs (Légis Québec, 2019).

The *Politique québécoise de gestion des matières résiduelles* is accompanied by a plan that describes initiatives, sets intermediate goals, and establishes deadlines for a period of five years. RECYC-QUÉBEC is the association for the recovery and recycling of residual materials that sets a series of activities to achieve the intermediate goals of each action plan and to ensure that a maximum quantity of residual materials is recovered and revalued. The performance of each action plan is reviewed and assessed during its operation, and the Minister may readjust the acts and make recommendations for a future action plan (Légis Québec, 2019). For example, the 1998-2008 Action Plan set the goal to divert 60% of CRD residual materials from landfills (Millette, 2010). In the 2011-2015 Action Plan, the goal has been increased to recycle or reclaim 80% of concrete, brick, and asphalt residuals (addressing mostly the civil engineering sector); and to sort at source or send 70% of CRD residuals from the building sector to sorting facilities (Ministère du Développement durable, de l'Environnement et des Parcs (MDDEP), 2011).

Included in the policy, the Quebec Environment Quality Act calls for a *Plan de gestion de matières résiduelles* (PGMR) for each regional municipality (Vachon et al., 2009). Each regional plan benefits from governmental financial aid and includes directives for the management of all domestic, industrial, commercial, institutional or CRD residual materials produced on the concerned territory (RECYC-QUÉBEC, 2018). Act 32 of the 2011-2015 Action Plan requires that each PGMR controls the sorting of residual materials from the building sector on site or in recovery sorting facilities. This can be demanded when delivering CRD permits to contractors with projects that generate significant quantities of debris in the building sector (MDDEP, 2011). In addition to regional municipalities, industries, businesses; institutions and CRD companies are responsible for materials they generate on the territory covered by the related PGMR.

This responsibility consists of paying the costs of their management and fulfilling the goals as determined by the PGMR (MDDEP, 2011).

The execution of two important regulations in Quebec contributed to the goal set by the *Politique québécoise de gestion des matières résiduelles*. First, since 2006, the *Règlement sur les redevances pour l'élimination de matières résiduelles* has aimed to reduce the amount of residual material in landfills and incinerators (Légis Québec, 2019). This regulation demands that elimination facility owners pay for each metric ton of residual materials they eliminate. As of 2019, the cost of elimination for each metric ton of material is $12.48 (Légis Québec, 2019). Second, Act 13 of the 2011-2015 Action Plan has set the goal to progressively exclude all types of wood from elimination in landfills, beginning with virgin wood. As defined in the action plan, by the end of 2014, all types of wood should have been recovered for reuse, recycling and valorization (Boisvert et al., 2014).

In addition to each five-year action plan, RECYC-QUÉBEC has been developing plans each focusing on a specific measure with the aim of reducing the amount of waste disposed of in landfills. The 2016-2017 Action Plan exclusively addressed the reduction of waste at source. Regarding the CRD sector, RECYC-QUÉBEC presented the eco-management of CRD sites in the building sector as a necessary measure to implement. In 2016, the Quebec government called for proposals to fund a project to suggest a methodology for the eco-management of construction sites (RECYC-QUÉBEC, 2016). The selected project had to include one or several of the following measures in the proposition:

- Maintenance of buildings during their whole life cycle and a plan for waste management at the end of the life cycle of buildings,
- Promotion of sustainable interior design,
- Use of eco-materials,
- Improvement of markets for reclaimed materials,

- Reconversion and recycling buildings,
- Life cycle assessment, and
- Selective deconstruction (RECYC-QUÉBEC, 2016).

In contrast to conventional methods of waste elimination, in general, waste management policies in Quebec are evolving toward methods of recovery and reuse. The next section will cover suggestions for waste management at the municipal level.

1.1.2.1 Municipal programs

To fulfil Quebec's policy goal on waste reduction, regional municipalities support government regulations by setting specific requirements for construction, renovation or demolition permits. Since 2009, the City of Montreal requires the Gold LEED[4] certification for every new municipal building over 500 m^2 and the Silver LEED certification for all major renovations in municipal buildings (Boisvert et al., 2014). Since the application of this program, a police station, a soccer stadium and a library have been constructed based on Gold LEED criteria and the Montreal Planetarium has also received a Platinum LEED certification (Boisvert et al., 2014). According to *LEED Canada for New Construction and major renovations 2009*, The LEED Canada rating system offers points for the responsible use and management of materials in two of its seven categories. The first category is the 'Responsible materials and resources management' which offers a maximum of fourteen points. The second category is the 'Regional Priority' that includes criteria for a building's durability and requires the development and implementation of a Building Durability Plan in accordance with the principles in the Guideline on Durability in Buildings -CSA S478-95 (R2007)- (Canada

[44] Leadership in Energy and Environmental Design (LEED) was created in 2000 by the US Green Building Council (USGBC), for rating design and construction practices that would define a green building (Vierra, 2016). There are four levels of LEED certification; Certified, Silver, Gold, and Platinum, which are given based on the credits that buildings can obtain in seven categories as defined by LEED.

Green Building Council (CaGBC), 2010). One of the directives is to consider and predict the service life of components and assemblies to adapt the predicted service life to the designed service life of a building (CaGBC, 2010). The points that a building obtains in the 'Responsible materials and resources management' and 'Regional Priority' categories along with other points contribute to a building being awarded Gold or Platinum LEED certification (CaGBC, 2010). It is assumed that buildings which are Gold or Platinum LEED-certified have managed their residual waste responsibly and have used their resources efficiently.

Some municipal programs also encourage contractors and architects to use reclaimed materials in their projects. As an example, the City of Montreal has accelerated construction permit procurement for projects which integrate the application of a certain quantity of reclaimed materials (Boisvert et al., 2014). Two programs in the City of Gatineau offer grants or additional discounts for the construction of housing that has obtained LEED certification. The first program offers an additional grant of $2500 per house for a LEED-certified project. The second program offers a 75% discount on the municipal taxes for a period of two years for a LEED-certified construction (Boisvert et al., 2014).

1.1.2.2 Non-governmental guidelines

Besides the governmental framework for the management of CRD materials, few non-governmental organizations are actively improving the performance of the 4R-D approach in Quebec. The most significant of these organizations is the *Regroupement des récupérateurs et des recycleurs de matériaux de construction et de démolition du Québec* (3R MCDQ). 3R MCDQ is an association that represents companies and stakeholders from all regions of Quebec and has 150 active members who share activities such as collecting, transporting, sorting, reclaiming, recycling and reusing CRD materials throughout Quebec (3R MCDQ), 2019). 3R MCDQ is engaged in offering solutions to promote the recovery, recycling and reclaiming of non-putrescible products and materials (3R MCDQ, 2019).

Residual materials from construction, renovation and demolition sites are sent to different types of facilities, and through different methods, sorted materials will be reused, recycled, repurposed, used for energy recovery or disposed of in landfills.

1.1.3 Waste management methods and facilities

In Quebec, waste management in the CRD sector is based on the 4R-D approach, which is the first principle of the *Politique québécoise de gestion des matières résiduelles* and presents two major methods of waste disposal; elimination and recovery. CRD residues are either recovered for reuse, recycling, energy recovery or eliminated in landfills.

1.1.3.1 Elimination

Disposal or elimination of waste is the final stage of the 4R-D process. Elimination generally concerns all residues from recycling or repurposing processes that cannot be reused for any purpose or includes products or materials for which there is no market. The end waste is generally eliminated either in incinerators or in landfills. According to Boisvert et al. (2014) and Vachon et al. (2009), there are two types of landfills for CRD residual materials in Quebec:

1) *Lieu d'enfouissement de débris de construction et de démolition* (LEDCD) (construction and demolition disposal sites), previously called *Dépôts de matériaux secs* (dry materials disposal sites), are the most common facilities used for burying CRD debris. They have different capacities in rural and urban regions. Because of the beneficial rates they offer for non-putrescible materials, these facilities are the major obstacle to the recovery of CRD debris in Quebec

(Vachon et al., 2009). In 2016, 12 LEDCDs were identified by RECYC-QUÉBEC (RECYC-QUÉBEC, 2018).

2) *Lieux d'enfouissement technique* (LET) (engineered landfills) have the highest capacity of disposal and are designed to conform to the requirements of the *Règlement sur l'enfouissement et l'incinération de matières résiduelles* (REIMR) (Vachon et al., 2009). These requirements consist of using waterproof landfilling units, controlling liquid and gaseous emissions from landfilled materials, and testing soil for eventual contamination by biogas (RiDR, 2016).

1.1.3.2 Material recovery

The 13 million tons of waste produced in Quebec annually presents great potential for reuse, recycling and recovery for energy (Légis Québec, 2019). A survey showed that, in 2006, 2.5 million tons of residual materials such as metals, plastic, cardboard, paper and glass were recovered in Quebec (Légis Québec, 2019). These materials represented a value of 550 million dollars and their management provided about 10,000 job opportunities (Légis Québec, 2019). Three major organizations responsible for the recovery and repurposing of CRD waste in Quebec were identified; eco-centers, CRD waste sorting facilities and CRD retail companies. The high recovery rate of CRD debris is partly attributable to 260 eco-centers and 48 CRD waste sorting facilities, and partly to 18 CRD retail companies (Vachon et al., 2009).

A. Eco-centers

Eco-centers or eco-parks are open areas with containers that accept non-putrescible voluminous residual materials of all types that are not collected during the regular waste collection (Ville de Montréal, 2019). These centers normally receive household waste (hazardous waste, home appliances), electronic devices, recyclable materials (paper, cardboard, glass, plastic, metal), worn-out tires and small loads of CRD debris

(Ville de Montréal, 2019). Eco-centers provide containers to small contractors or citizens with construction, renovation or demolition projects who do not have space for a container on the construction site (Vachon et al., 2009). In 2015, RECYC-QUÉBEC identified 260 eco-centers in Quebec. Of these centers, 75% belong to municipalities, regional municipalities or the inter-municipal administrations and some private companies, non-profitable organisms or mixed (public-private) organizations manage the other 25% of eco-centers (Vachon et al., 2009). Each eco-center has a method to manage the debris it receives. Most of the eco-centers require that contractors and citizens manually sort their debris by category (wood, aggregates, shingles, gypsum) before leaving them in containers (RECYC-QUÉBEC, 2018). Eco-centers refuse voluminous products that are larger than the containers (Ville de Montréal, 2019).

There is no data available that shows the total amount of residual materials that all eco-centers receive. However, according to the RECYC-QUÉBEC survey for the revaluation of the 2011-2015 Action Plan, 185 eco-centers that serve 75% of the Quebec population, accepted 405,000 tons of residual materials from all sectors in 2015. 66% of this amount came from the CRD sector. According to Vachon et al. (2009), wood, aggregates (concrete, brick, stone) and metal are the most common CRD materials that eco-centers receive. Due to lack of market, eco-centers do not revalue asphalt shingles, gypsum and treated wood and they are generally sent for disposal (Vachon et al., 2009).

B. CRD waste sorting facilities

In the 2011-2015 Action Plan, the Quebec government intended to allocate 3 million dollars for making recycling more efficient. The government has planned to modernize the processing and sorting plants for CRD residual materials and to develop markets for reclaimed materials (MDDEP, 2011).

CRD waste sorting facilities, also called material recovery centers, receive several types of materials. Sorted materials are sent for valorization or elimination. Most of the sorting facilities have limited capacity and receive less than 20,000 tons of materials annually (RECYC-QUÉBEC, 2018). Sorting centers are categorized based on the equipment they use for sorting and the mechanization level (Vachon et al., 2009). Although they share several similarities, none of these centers are identical. Each of them has its own sorting method, physical characteristics, equipment and market (Vachon et al., 2009).

In general, there are three types of sorting facilities; 1) centers where materials are sorted manually without using any equipment, 2) centers where basic equipment is used to sort materials, and 3) centers where technologically advanced equipment are used to sort materials (Vachon et al., 2009). RECYC-QUÉBEC identified and addressed 48 sorting facilities for the revaluation of the action plan in 2015. 37 sorting facilities participated in the survey and announced to have received 1.63 million tons of CRD residual materials and sent out 1,49 million tons of sorted materials.
This quantity of materials had three major destinations; 1) 53% (794,000 tons) were sent for recycling and energy recovery, 2) 24% were sent to landfill sites to be used as alternative landfill liner and cover materials, and 3) 23% (343,000 tons) were rejected and sent for disposal in landfills (RECYC-QUÉBEC, 2018) (Figure 1.2).

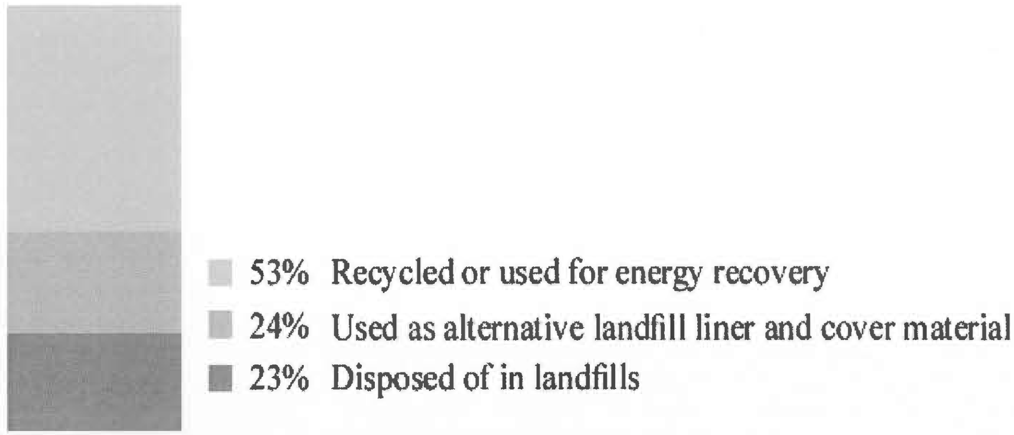

Figure 1.2. This figure shows the destination of CRD debris sorted in sorting facilities. This figure comes from a report prepared by RECYC-QUÉBEC in 2018.

Sorting facility operators have confirmed that these centers generally reject treated wood, fiberglass, insulating materials, carpets, window glass, porcelain, vinyl base materials (tubes or PVC outdoor coatings), composite products (wood-aluminum window frames) and send them to elimination facilities. Generally, these materials are not accepted because there is no market for them (RECYC-QUÉBEC, 2018). Figure 1.3 shows that wood and aggregates constitute high proportions of all sorted materials that enter the recycling stream or energy recovery facilities. This confirms the effectiveness of regulations that prohibit landfilling of all types of wood and encourage the recovery and recycling of aggregates. However, as shown in Figure 1.3, a greater proportion of wood is used for energy recovery and cannot be reused. The lack of interest for the valorization of wood is due to several factors; critical

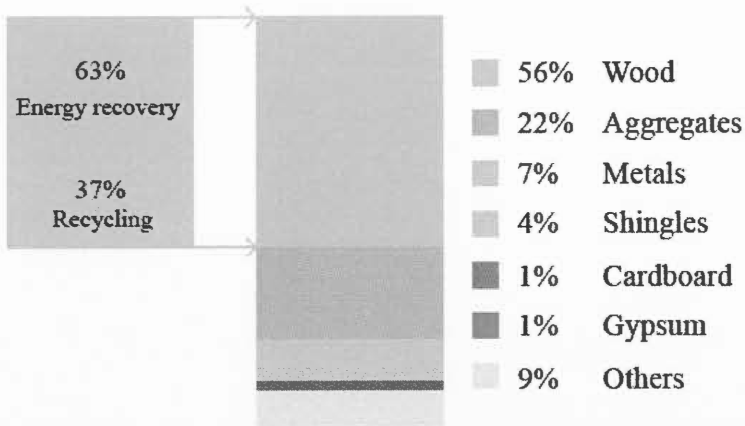

Figure 1.3. This figure shows the proportion of materials sent for recycling or energy recovery, and the proportion of two types of wood valorization. This figure is presented in a report prepared by RECYC-QUÉBEC in 2018.

transport of materials to appropriate recycling and valorization installations, low capacity of sorting, recycling and valorization installations for wood, lack of appropriate method of sorting for different types of wood debris, and the lack of markets for the revalued residues (Boisvert et al., 2014)

The results from the survey of 37 sorting centers helped RECYC-QUÉBEC estimate the total amount of sorted residue from all the 48 existing sorting facilities in Quebec to be 1.85 million tons. Based on this estimation and considering the amount of eliminated residues from all sources of the construction industry (building sector and civil engineering sector), RECYC-QUÉBEC estimates that 71.5% of the total CRD residuals were diverted from elimination facilities through sorting, reusing and recycling in 2015. The provincial goal that set the recovery rate at 70% in the 2011-2015 Action Plan was slightly surpassed according to the RECYC-QUÉBEC estimation.

C. CRD retail companies

CRD retail companies acquire used building materials through demolition and selective deconstruction contracts or buy them from contractors, individuals or receive them as charity donations (Vachon et al., 2009). There are three categories of businesses that have retail stores that offer reclaimed materials in Quebec; 1) demolition contractors who also specialize in reselling materials, 2) social economy enterprises that recover and resell building materials and have the mission of reintegration, hiring and training workers, and 3) family-owned business that buy and sell used construction materials (Vachon et al., 2009).

In Montreal, Restore and Éco-Réno are two well-known retail companies which recover and sell reclaimed materials with a high capacity of storage and high turnover (Habitat pour l'humanité, 2019; ÉcoRéno, n.d.). However, companies located in urban areas offer limited varieties of compact reclaimed materials. This is due to the limited space they have for storage (Vachon et al., 2009). Stores located in cities mostly offer products like doors, windows, bathtubs, sinks, plumbing, lighting or electrical tools from residential renovations or demolitions (Vachon et al., 2009). Retail companies located outside of urban zones offer beams, roofing, floors, windows, doors, steel structures and other outdoor materials in addition to the previously mentioned products (Vachon et al., 2009). Most retail companies offer demolition and deconstruction services, as they need to guarantee the quality of the materials they offer for sale (Zelechowski, 2012). By offering selective deconstruction, these companies can recover large amounts of woodwork as a whole, doors with their frames, and do less damage to components and materials (Zelechowski, 2012).

A connection between retail companies and contractors who have CRD projects is needed to set the practice of reusing of reclaimed materials. In that regard, Éco-Réno has developed a pilot project in collaboration with the Rosemont-La Petite-Patrie borough in Montreal. The borough provides a list of local applicants of construction, renovation and demolition permits to Éco-Réno, so that the company can offer its services to numerous contractors and can recover some quality materials from buildings under construction (Vachon et al., 2009).

In addition to retail companies, a few online platforms have been developed to connect buyers and sellers of CRD reclaimed materials. Voirvert, a platform for sustainable building in Quebec, has a section entitled Carrefour 3RV that is dedicated to buyers and sellers of reclaimed materials. *La Bourse des résidus industriels du Québec* (BRIQ), an exchange platform established in 2005 and taken down in 2016, was a collaboration between the *Centre de Transfert Technologique en Écologie Industrielle* (CTTEI) and RECYC-QUÉBEC that offered free access to 3R MCDQ members to a service to find markets for CRD sector materials ((RECYC-QUÉBEC, 2018). Since 2016, CTTEI adopted other initiatives to connect supply and demand in the sector.

The literature review on the waste management in the CRD sector in Quebec shows that policies, regulations, and municipal initiatives along with programs implemented by non-governmental organizations have led waste management toward recovery, reuse and recycling approaches to divert more materials from landfills. Among others, two regulations have increased the recovery rate of CRD debris; the implementation of the *Règlement sur l'enfouissement et l'incinération de matières résiduelles* (REIMR), and the *Règlement sur les redevances exigibles pour l'élimination de matières résiduelles.* These regulations have resulted in the closure of several landfills and the establishment of taxes for disposal of residual materials in elimination facilities (Légis Québec, 2019; Légis Québec, 2019).

In addition to the aforementioned regulations, the implementation of a standard for the recovery of aggregates by the *Bureau de normalization du Québec* (BNQ) and the Act, banning wood from disposal in landfills, has contributed to the increase in the recovery rate of residual materials in the CRD sector in Quebec. In general regulations and standards have provided significant incentives for the establishment and development of recovery facilities. RECYC-QUÉBEC's report on waste management in the CRD sector in 2018, shows an increase in the number of eco-centers, sorting facilities and local retail businesses for reclaimed materials during the past decade.

Despite the evolution in the waste management sector toward more recovery, reuse and recycling, several sources confirm that there is an inadequate application of the 4R-D approach and several barriers still exist in Quebec. Time and cost are two determinant factors in managing residual materials. Demolition is still a common practice as it is cost-effective and less labor-intensive than deconstruction. Recovery facilities and valorization installations require considerable investment to equip (Boisvert et al., 2014). Space constraints are another barrier to the recovery of materials, particularly in dense urban areas (Boisvert et al., 2014). Building materials need large amounts of space for sorting and storage. In most cases, there is not enough space on site for containers to sort debris. Therefore, materials and components should be transported to sorting facilities or storage areas which is costly for contractors (Mamfredis, 2017). Moreover, the high cost of transportation influence material prices. It has been mentioned that there is also a lack of inventory of available reclaimed materials and a system to link supply and demand (Mamfredis, 2017). Accordingly, there is still not a stable market for materials reclaimed by eco-centers or sorting facilities (Boisvert et al., 2014). Drywall, metals, asphalt shingles, carpet, insulation and cardboard too often end up in disposal sites due to the lack of a market for these materials (Boisvert et al., 2014).

As of 2009, in Quebec, there were many rural areas or small towns that lack eco-centers or sorting facilities (Vachon et al., 2009). During this project, no new studies were found, and therefore, no new information on the number of rural eco-centers is available.

Another barrier to the recovery of materials for repurposing, reusing, or recycling is conventional building design. The recovery of materials from buildings designed within conventional methods is costly, laborious and results, in many cases, in material or component damage. These methods do not include measures for the preservation of materials and components during the operation life of a building, and for their easy recovery at the end of life of the building.

A discussion of design for disassembly and its different aspects will explore how DfD as a method of radical change to conventional building design plan to preserve materials for reuse and recycling and reduce the amount of waste generated. In the next chapter, the literature review will explore how waste management can be connected to design for disassembly.

CHAPTER II
LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

The amount of landfilled waste can be reduced by keeping materials in use in continuous life cycles. This requires that materials are physically well-maintained so they can be reused or recycled in a closed-loop system. In the construction industry, a closed-loop system demands reform in the design of buildings (Gorgolewski, 2008; Keeler & Burke, 2009; Smith, 2010; Lehmann & Crocker, 2012; Kibert, 2013). It has been highlighted that conventional design scenarios are generally based on a linear flow of materials. Recovering materials from buildings built within conventional design scenarios only reduces the amount of waste to a limited extent (Lehmann & Crocker, 2012). According to Gorgolewski (2017), by adapting our design approach, we can change our treatment of waste. Designers can account for, model, and predict the deconstruction of buildings and their systems early in the design process to increase the recovery rate of components and materials for reuse and recycling (Lehmann & Crocker, 2012).

The idea of designing to eliminate waste through the constant reuse of materials in a closed-loop was extensively argued by William McDonough and Michael Braungart in the theory of *Cradle to Cradle* in 2002. This theory argues for a change in the way we make things. McDonough and Braungart's argument can be summarized by the expression, "waste equals food" (McDonough & Braungart, 2002, p. 102). In this theory, they assert that that in an industrial ecology, all the debris and refuse from production and construction processes should one day return to the use stream for new production and construction (McDonough & Braungart, 2002; Smith, 2010). In the cradle-to-cradle concept, buildings are considered part of an industrial metabolism and their components and materials are presented as industrial or technical nutrients. To shift to a closed-loop flow, buildings should be recognized as raw material storage facilities to be harvested for the reuse of their materials and components (Gorgolewski, 2008; Lehmann & Crocker, 2012).

Lending support to the concept of buildings as a collection of nutrients, Smith (2010) highlights that designing buildings for assembly and disassembly is a strategy for the ultimate cradle-to-cradle cycle. In this strategy, the factory-made components assembled on-site may be disassembled, reused and recycled at the end of their useful life for rebuilding elsewhere (Brand, 1994; Guy & Ciarimboli, 2007; Smith, 2010). In this vision, "buildings become organisms of growth, change, decay, and re-growth"; designed with components that can be reused (Smith, 2010, p. 223). Unlike conventional building design strategies, design for disassembly (DfD) consists of designing for the whole life cycle of a building. As DfD considers the value of materials, it suggests strategies for maintaining components during occupancy and strategies for reuse that continue post-occupancy. Reusing components and materials that extend their useful life saves their embodied energy, reduces the need for raw materials to manufacture the same products, and reduces waste (Durmisevic & Yeang, 2009).

2.1 Design for disassembly; towards changeable systems and waste mitigation

Several aspects of design for disassembly are rooted in Modernity. "The Modernist expression emphasized materials and forms without decorative embellishment, and Modern architecture often expressed a structure's assembly through materials and methods of connection" (Guy & Ciarimboli, 2007, p.4-5). Using connections such as bolts and what Guy & Ciarimboli (2007) call 'pure materials'[5] are key ingredients of Modern architecture. These features were further defined as principles of design for

[5] Guy & Ciarimboli (2007) refer to pure materials as metal, glass, stone and concrete.

disassembly to increase reuse and recycling possibilities, which lead to reducing the amount of waste from buildings (Guy & Ciarimboli, 2007). DfD was developed based on design for assembly, a building strategy developed during the course of the Modern movement, which aimed to reduce the time of construction. Design for assembly in architecture consists of fabricating modular and standardized components in factory to assemble them on the construction site. On-site assembly of prefabricated components reduces the amount of waste during construction.

Design for disassembly was first discussed in industrial design, specifically in the computer and automobile industries in the 1970s (Fikkert & Otheguy, 2013). In product design, DfD emerged from concerns about energy use, transportation, packaging, waste and disposal (Bogue, 2007). DfD-based research started in the 1980s, and since then, it has become an integrated practice in product design (Thormark, 2007). In industrial design, DfD proposes the separation of different parts of a product at the end of its life cycle to reuse them in future projects. It is believed that DfD can be applied to buildings in the same way that it is applied to other assembled products as buildings are "manufactured artifacts" that are made through a combination of pre-assembled parts and the on-site assembly of materials and components (Guy & Ciarimboli, 2007, p. 2). In building design, DfD encourages on-site separation of building components and materials in renovation, re-planning, and demolition projects to contribute to component reuse, material recycling, and to reduce the amount of construction waste (Guy & Ciarimboli, 2007).

Architect Jean Prouvé applied some DfD principles early on in Tropical House (Lehmann & Crocker, 2012). Tropical House, designed in 1949, was a prefabricated metal structure and a prototype for inexpensive, readily assembled housing that could be easily transported to France's African colonies (Arcspace, 2012). In 1951, this structure was erected in the town of Brazzaville, Congo, and was disassembled after nearly 50 years in 1999 and shipped to France for restoration (Arcspace, 2012). The disassembly potentials integrated into the design of Tropical House allowed for its relocation for restoration. Later, DfD principles were seen in the context of temporary architecture. The IBM Traveling Pavilion, designed by Renzo Piano in 1983, was assembled, exhibited for a month, disassembled, and then reassembled in 20 European destinations (RPBW, 2019).

Today, in building design, DfD is considered to be a concept that links design methodologies, waste management and sustainability in the built environment (Durmisevic, 2006). It aims to reduce the amount of waste by preserving materials and components of a building and reusing them in continuous life cycles. If DfD is adopted as a common design method to favor reuse of materials and to reduce waste, buildings, systems and their components should be considered as valuable long-term assets and stock to serve as a primary material sources for new construction where their preservation is essential.

One of the ways to preserve building materials is to prevent demolition. DfD can prevent demolition in two ways; 1) it provides flexibility and adaptability in systems and parts during the service life of a building, and 2) it suggests a process of dismantling of systems and parts of a building at the end of their life spans (Guy & Ciarimboli, 2007). Flexibility and adaptability provided by the disassembly of systems and parts allow the user to upgrade and adapt their living and working spaces to their changing needs. Adapting buildings and spaces avoids functional obsolescence and building vacancy, which are two major causes of demolition (Remøy, 2010). Dismantling systems and parts provides for the possibility of reusing components and recycling materials to diminish the amount of waste created during the operational life of a building while renovating and at the end of its life span. In the next section, the benefits of DfD during the life cycle of a building and at the end of its service life span are examined.

2.1.1 Benefits of DfD during the service life of a building

Observations show that throughout the last three decades, space occupancy scenarios have been changing quickly due to economic instability and the evolution of work and lifestyles in buildings (Durmisevic, 2006; Remøy, 2010). A high rate of dynamism in space occupancy requires adaptations and leads to physical changes in buildings. If there is no economic justification or technical solutions for the adaptation of a building to new requirements, functional obsolescence may occur. Functional obsolescence results in building vacancy, which means that the building has reached the end of its service life, and it may be demolished (Guy & Ciarimboli, 2007).

In the commercial context, space occupancy is based on shorter use scenarios (Durmisevic, 2006; Remøy, 2010). Therefore, if a commercial building cannot be adapted to the new users' needs, there is a higher risk of functional obsolescence, building vacancy and demolition.

In the residential context, use scenarios are generally longer. However, according to the report *Recycle: Lifecycle - How to renovate for change* by the Canada Mortgage and Housing Corporation (CMHC) (2003), most Canadians live in houses which are not new, nor designed to their specific needs. Inhabitants have more incentives to renovate than to build new constructions as renovation has a more stable market (CMHC, 2012). Studies show that there has been an increase in renovation activities since the 1970s in Canada (CMHC, 2012). Most renovation projects are undertaken for the maintenance of systems and services or for space adaptation to evolving occupants' requirements (CMHC, 2012).

Adapting buildings to user requirements increases renovation and demolition activities in different contexts. Therefore, design strategies are needed to deliver flexible structures and spaces for constant adaptations. Flexibility makes renovations less wasteful, decreases the demolition rate, and diminishes the amount of waste (Durmisevic, 2006). Within a DfD method, the designer plans to provide resilience and flexibility in a building by examining the frequency of changes during the service life of a building (Durmisevic, 2006). They integrate a systemized methodology in the process of design for the disassembly of components and parts when change and adaptation are needed (Lehmann & Crocker, 2012; Ordonez & Rahe, 2013).

To anticipate functional and physical changes in a building life cycle, Durmisevic (2006) suggests that designers must understand the service life of a building. The service life of a building is composed of two distinct cycles; the technical life cycle and the functional life cycle (Durmisevic, 2006). The technical life cycle of a building is the life span that physical parts of the building have independent of any consideration for use or obsolescence cycles, and the functional life span is the occupancy period of the building (Durmisevic, 2006; Guy & Ciarimboli, 2007). Durmisevic (2006) refers to the technical life cycle as supply, and the functional life cycle, demand. If a building is physically flexible and adaptable to the requirements of its users, the balance between the supply and the demand can be achieved (Durmisevic, 2006).

Commonly, buildings designed and constructed with conventional methods have a technical life cycle between 50-100 years (Brand, 1994; Durmisevic, 2006). Within this period, a building may be used for different functions and scenarios. Different use scenarios in a building have different spatial and technical requirements. Normally, the functional life cycle controls the technical life cycle and determines the service life of a building (Guy & Ciarimboli, 2007). An assessment of the physical quality of systems, services and materials can indicate if a building can be adapted to new requirements. If it is not physically possible to alter the building and there is no economic justification for adapting the systems and structures to new requirements, the building may be functionally obsolete leading to demolition while it is still in a good physical condition (Durmisevic, 2006; Remøy, 2010). Design for disassembly suggests scenarios to create a balance between supply and demand by making building systems flexible and adaptable for the changing needs of building occupants (Smith, 2010). It balances functional and technical life cycles by; 1) separating short and long scenarios, and longer and shorter-lived components and materials, and by 2) setting conditions for transformations early in the design process (Durmisevic, 2006).

2.1.2 Flexibility and adaptability in building design

Le Corbusier, one of the pioneers of the Modern movement, developed and published five principles for Modern architecture in the 1920s. One of the five principles is an open and free plan that emphasized the absence of load-bearing walls for flexible use of the living space. Later, in the 1960s, ideas related to flexibility and adaptability in spatial organization were discussed and elaborated on by John Habraken and the SAR[6] in the theoretical framework of Open Building. The general idea of Open Building is that "the built environment is the product of an ongoing, never ending design, in constant transformation," and therefore, change, adaptability and flexibility should be recognized in the design phase (Kendall, 2015).

Open Building developed a method to give a new construction the capacity for long-term change (Kendall, 1999). It demands reform in design and promotes a flexible design that allows for variation in housing types and adaptable dwellings. This design approach is based on occupant participation and consists of "an accompanying procedure and a decision-making framework for every level of scale to accommodate building change" (Bosma, Hoogstraten, & Voos, 2000, p. 334).

The Open Building theory aims to give the user control over their dwelling, so they can make changes and adapt their dwelling to their changing needs over time (Habraken, Boekholt, & Thijssen, 1976). Open Building is principally discussed as a theory of two

[6]The SAR (Stichting Architecten Research) is a foundation for architectural research in Eindhoven, the Netherlands and was founded in 1965 to 'stimulate industrialization in housing'. More generally, it sought to study issues surrounding the relationship between the architecture profession and the housing industry, and to chart new directions for architects in housing design (Kendall, 2015).

distinct levels of decision or distinct levels of intervention in architecture and urban design (Kendall, 1999). These two levels are 'support' or 'base building,' and 'infill' or 'fit-out' or 'detachable units' (Habraken et al., 1976; Kendall, 2015). According to Habraken et al., (1976), different factors determine which part of a building provides support and which part is a detachable unit. However, based on the SAR approach, non-load bearing walls and partitions are always considered detachable units. Basically, the SAR's experiments and theoretical developments focused on a method and a series of agreements that allowed support and infill to remain distinct while their needs were connected (Bosma et al., 2000). The independence of support and infill meant that a "support project had no standard floor plan," and freedom in a floor-plan organization provides control over the dwelling (Bosma et al., 2000, p. 334). The designer and the architect have control over support, and the user can modify the infill configuration according to their needs. Detachable units are designed to be flexible and adaptable and allow the user to participate in the decision-making process. Developments in base building technologies and the variety of infill systems that exist on the market offer users the chance to design their own interiors (Kendall, 1999). The user's control over partitions and walls allows them to modify their interiors through the time of occupation without needing to demolish and reconstruct their interior to have a suitable dwelling adapted to their requirements.

In Open Building, a multi-unit building is designed for a variety of occupant preferences, and the design has no extra cost for the developer compared with a building in which all units are designed in the same way (Kendall, 1999). NEXT 21 in Osaka, Japan, is designed based on the concept of support and infill that demonstrates several new construction methods for urban multifamily housing. The 18-unit housing project, conceived by the Osaka Gas Company and the NEXT 21 Construction Committee, is highly flexible in terms of architectural systems (Kendall, 1999). Different parts of the building such as the frame or skeleton, the exterior cladding, the interior finishes and the mechanical systems are separate subsystems, each with a different life cycle allowing each system to be repaired or replaced at a different time (Kendall, 1999). The units were designed after the building frame was conceived, and the design continued during the construction of the frame (Kendall, 1999). The unit plans were designed, places for integrated mechanical systems were spotted, and then the mechanical systems and services for units were installed later as one project by a different contractor. The building was designed as one system with various separate subsystems that can be adjusted autonomously in the future (Kendall, 1999).

Although Open Building provides a high level of flexibility and adaptability, Habraken et al. (1976) note that designers cannot predict when and for what reasons houses might be altered in the years after the construction. They believe that it is not possible to predict the future, the lifestyles of future generations or the incentives that lead people to make changes in their homes (Habraken et al., 1976).

Later in the 1990s, this gap was addressed in the theory of shearing layers of change, developed by Frank Duffy. Duffy argues that a building consists of several independent time-related layers where every layer has its own life span (Brand, 1994; Thormark, 2007). This theory supports design scenarios for present requirements and future changes. It discusses the systematization of changing levels within a building and studies the change frequency during the building's whole life cycle (Durmisevic, 2006).

2.1.2.1 Flexible and adaptable buildings: the importance of time-related layers

A design methodology that considers a building as a set of independent time-related layers facilitates the accommodation of technological and organizational changes and makes the building and its systems flexible and adaptable (Brand, 1994; Durmisevic, 2006). Frank Duffy, known for his work on the flexible use of space in the office context, argues that there is not such a thing as 'a building', and that, "a building, properly conceived is several layers of longevity of built components" (Duffy, n.d. as cited in Brand, 1994, p.12). Based on this idea, Duffy developed the 4S's concept that represents a building as a composition of four layers, referred to as the 'Shell,' 'Services,' 'Scenery' and 'Set.' In Duffy's theory, 'Shell' is the structure with a lifespan of fifty years in Britain and nearly thirty-five years in North America. 'Services' define cabling, plumbing, air conditioning and elevators, which need maintenance every fifteen years or so. 'Scenery' is the layout of the partitions, such as dropped ceilings, which may require changes every five to seven years. 'Set' is the furniture configuration, which can be reorganized within months or weeks (Brand, 1994). Duffy's theory of shearing layers was later expanded by Stewart Brand in 1994 and presented as the 6S's theory. According to Brand, the six separate and independent layers of a building are; 'Site,' 'Structure,' 'Skin,' 'Services,' 'Space plan' and 'Stuff', each with a different life span (Figure 2.1).

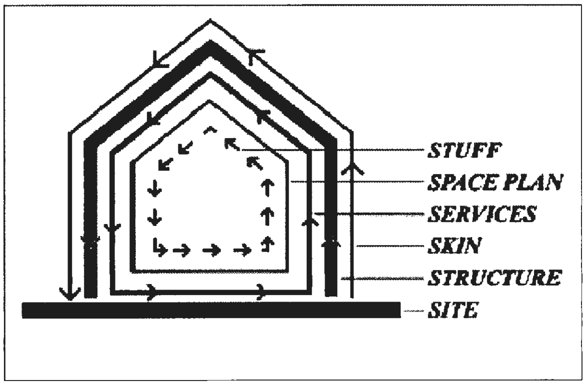

Figure 2.1. This figure shows the Shearing layers of change and is presented by Brand in his book *How Buildings Learn: What Happens After They're Built* (Brand, 1994).

Brand has estimated that services require changes every 5 to 10 years, the space plan every 10 years, the enclosure or skin every 20 years while the frame or structure can last for 50 to 75 years (Brand, 1994; Durmisevic, 2006; Guy & Ciarimboli, 2007). Based on this theory, a building with a 50-year technical life cycle and 5-year-use scenarios may be subject to transformations 10 times during its life cycle. Considering this frequency of change, designing independent layers can make the building and its systems adaptable and flexible. Flexibility allows for easy maintenance and repair at the service level within several timescales during the functional life of a building (Durmisevic, 2006). In a building constituted of separate layers each containing several subsystems, if maintenance is needed, wiring or piping embedded in the walls are accessible in the surface of the wall independent from the wall system. This approach is considered sustainable as the design is based on the long-term performance of systems and parts where each level can be removed and replaced independently (Durmisevic, 2006).

Duffy and Brand acknowledge that a conflict may occur in a building when the faster changing layers are controlled by the slower changing layers. For example, there is a risk of functional obsolescence or demolition if the space plan with faster change frequency is dependent on the structure which has longer change frequency as making changes to the space plan may require structural modifications (Guy & Ciarimboli, 2007). It has been asserted by Duffy and Brand that the faster-changing layers like the services and space plan (scenery) can be more flexible if they are accessible independently from the slower changing layers like the structure. Technical flexibility of these layers provides spatial flexibility, essential to coping with the shorter life cycles of these layers (Durmisevic, 2006; Guy & Ciarimboli, 2007). In designing for disassembly, designers should focus on the points of connection between separate systems that have the most disparate service lives (Guy & Ciarimboli, 2007). This approach has environmental benefits such as reducing the amount of waste, in addition to the flexibility that it provides for spatial reconfigurations and adaptations (Kendall, 1999).

2.1.3 How can DfD connect the concepts of flexibility, adaptability and shearing layers to waste mitigation?

The idea of a building as a composition of distinct levels of intervention or time-related layers, developed respectively in Open Building and the theory of shearing layers, establishes the foundation of DfD. This section reviews how flexibility and adaptability can be linked to waste mitigation in the DfD framework.

With the aim of reducing construction waste, DfD favors flexibility and adaptability to changing needs by suggesting three types of scenarios during the life cycle of a building. The first type should allow for moderate interior transformations related to layers with shorter life spans, the second type of scenario addresses major structural modifications related to layers with longer life spans, and the third type is for the end-of-life management of a building, its components and materials (Durmisevic, 2006). The three types of scenarios are based on the disassembly potentials of different parts related to different layers. To explore how the components of different layers can be dismantle-able for the three scenarios, we suggest a holistic conceptual and practical framework for DfD, based on the remapping of the concepts of Open Building, the shearing layers, and Durmisevic (2006, 2009) and Guy & Ciarimboli's (2007) arguments. Figure 2.2 illustrates this framework. The conceptual support for the development of the framework and how it is related to waste mitigation through some technical requirements is presented in sequential order in the diagram. The direction of the arrows shows how each concept is connected to the previous concept.

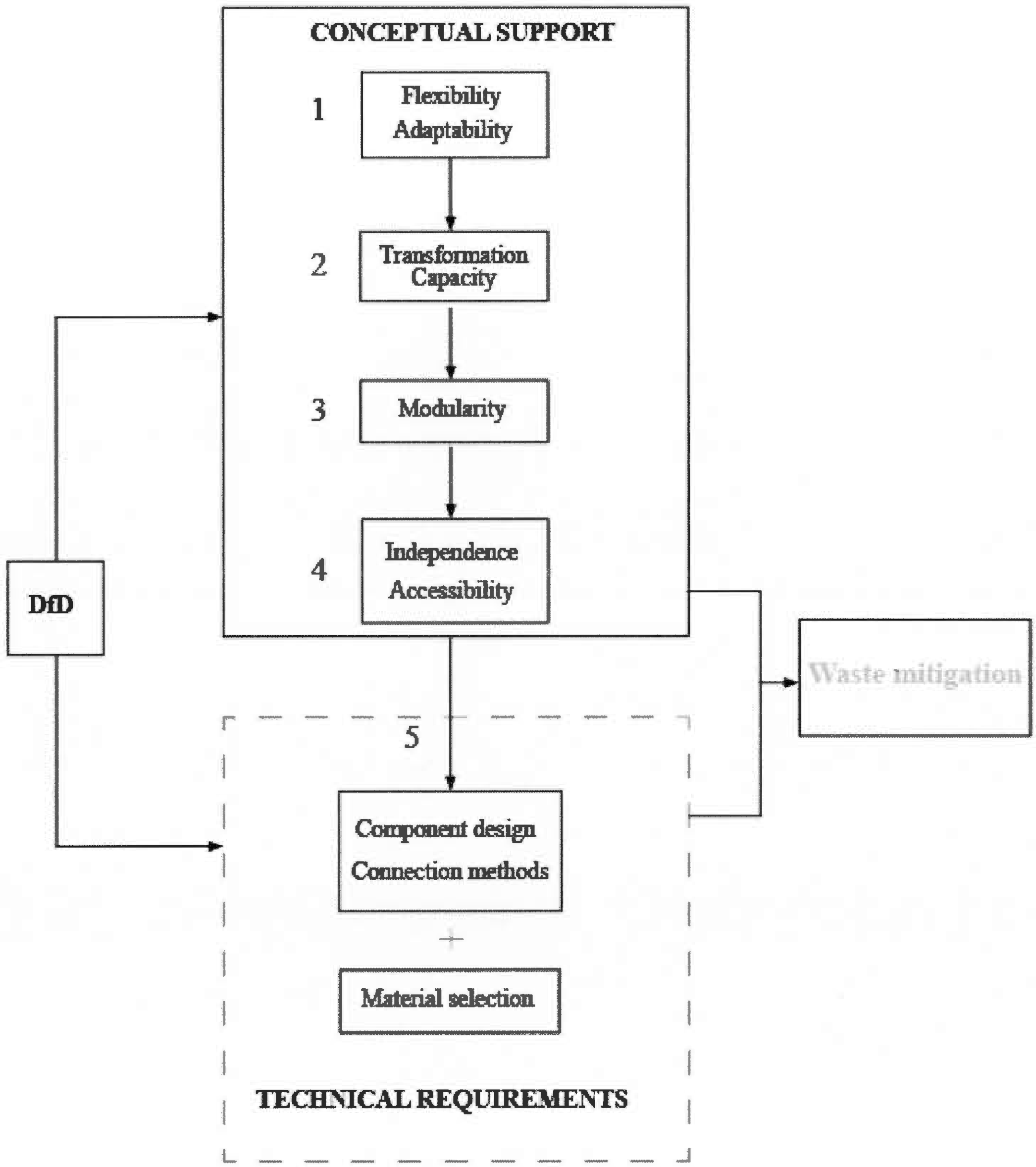

Figure 2.2. This diagram shows how DfD connects the conceptual framework of flexibility and adaptability to waste mitigation. Created by S. Sadraee.

2.1.3.1 Transformation Capacity

We mentioned earlier that flexibility and adaptability are two concepts that can prevent functional obsolescence, building vacancy and demolition. According to Durmisevic (2006), flexibility and adaptability depend on the physical capacity of different building layers for transformation. Durmisevic presents the term Transformation Capacity (TC) and asserts that the TC is the indicator of a building's or system's flexibility. A high degree of TC results in high flexibility. High TC can facilitate space reconfiguration and the adaptation of a building to new requirements and allows for replacing and reusing components and extends the lifespan of a building (Durmisevic, 2006). In her argument, Durmisevic concludes that a TC that relies on the high disassembly potential of structures also results in high sustainability and environmental efficiency.

As shown in Figure 2.2, the modularity of assemblies, their independence and accessibility are the factors that determine the TC of a building (Durmisevic, 2006). Durmisevic (2006) explains that a flexible system with a high TC is achieved when a building is designed as a set of independent assemblies and subassemblies composed of modular components which are accessible independently. She calls such a system a 'dynamic configuration'. In a dynamic configuration, in addition to the modularity, independence and accessibility of components, the assembly sequence is important. Generally, dynamic configurations are recognized by a parallel assembly sequence of components (Durmisevic, 2006; Kieran & Timberlake, 2011). A parallel assembly sequence provides high TC where assemblies and subassemblies can be demounted, replaced, displaced, reconfigured, and their components can be reused or recycled (Durmisevic, 2006; Kieran & Timberlake, 2011).

Compared with dynamic configurations, in conventional building methods there are imposing and static configurations with parts that are not modular, independent or accessible. Moreover, components of systems and subsystems are assembled in a physically dependent way (Durmisevic, 2006). A building or a system with imposing and static configurations has low Transformation Capacity and the assembly sequence in the static configuration is hierarchical. A hierarchical organization between assemblies and subassemblies makes them dependent (Durmisevic, 2006; Kieran & Timberlake, 2011). In a hierarchical organization, the faster-changing layers are controlled by the slower changing layers. Entangling several assemblies and subassemblies in a building's infrastructure is hierarchical organization. This may create a conflict among technical systems and various parts controlling the subsystems (Kendall, 1999). An example of a hierarchical organization which causes a static configuration is burying pipes, conduits and cables inside concrete walls and floors or hiding them deeply within wall and floor cavities (Kendall, 1999). In such an organization, as services, which are systems with shorter life cycles, are controlled by the structure with a longer life cycle, changes to services cause change or damage to the structure (Kendall, 1999; Guy & Ciarimboli, 2007). Assigning several functions to a single solid closed structure, in which different sets of technical systems and materials are integrated, creates additional material destruction when one component needs to be repaired or maintained. As such, DfD scenarios assign each set of assemblies to a separate function, creating a parallel relationship (Durmisevic, 2006; Kieran & Timberlake, 2011). In a parallel relationship, each set of assemblies is associated with a function and is physically independent of other sets. Each set with a different life cycle can be transformed, repaired or removed without disturbing other sets.

In addition to the accessibility, independence and modularity of assemblies and subassemblies to increase the Transformation Capacity of systems and subsystems, within its framework, DfD accentuates three factors that increase the potential for component reuse and material recycling. These three factors include the shape of the components, their constituent materials and the methods applied to connect them together or to other systems (Bogue, 2007; Guy & Ciarimboli, 2007). In the literature, these factors are usually known as the principles of DfD. To dismantle a system and to recover and reuse its components and materials, DfD suggests 1) selecting mechanical and reversible joints, connectors and fasteners and using them in an accessible manner, 2) improving the component design and the product architecture, and 3) selecting and using materials that can be integrated into a local reuse or recycling stream (Durmisevic & Yeang, 2009; Bogue, 2007; Guy & Ciarimboli, 2007). The first factor makes systems demountable, and the second and the third factors helps to reuse or recycle the dismantled components and materials.

The type of joints, connectors and fasteners and their physical, visual and ergonomic accessibility are the most important factors for the disassembly of systems and components. Static configurations that cannot be disassembled are recognized by elements interconnected within dependent assembly sequences, with chemical connections and fixation methods that are not reversible and are often incorporated into other systems (Durmisevic, 2006; Guy & Ciarimboli, 2007). Brick is a standardized and modular component, and blocks of brick can be easily assembled and are accessible after assembly. However, as they are connected with mortar, the separation and recovery processes are laborious and costly with a high risk of component damage. Connecting standardized and modular components with wet connection methods does not necessarily lead to the reuse of components.

To create dynamic and changeable configurations, DfD suggests reducing or eliminating chemical and wet connectors such as mortar, sealants, adhesives or welding, and replacing them by reversible mechanical fasteners (Durmisevic, 2006, Bogue, 2007, Guy & Ciarimboli, 2007; Durmisevic & Yeang, 2009). It also proposes simplifying connections, using standard and limited palettes of connectors such as bolts, screws and nails (Guy & Ciarimboli, 2007).

The second important principle of DfD is the geometry and the architecture of components which define the interaction between them. In this principle, the less components physically interact in ways that cause the penetration of one material by another, the fewer physical changes occur. Fewer physical changes lead to easier disassembly and reuse of components. This aspect is analyzed and illustrated in detail through case studies presented in Chapter 3.

The selection of materials is the third important principle of DfD. Durmisevic (2006), Guy & Ciarimboli (2007), Bogue (2007) and Kibert (2013) suggest minimizing the component count, reducing the use of composite materials and components, eliminating the use of finishing, optimizing the component standardization, minimizing product variants, using recyclable materials and eliminating toxic or hazardous materials. In the construction industry, there are materials such as timber and steel that can be easily reused and some materials such as engineered wood or gypsum panels, that cannot be easily reused and recycled due to their material composition or contamination (Lehmann & Crocker, 2012). The resin or binder used to combine wood chips, or layers in engineered wood and the finishing paint layer applied on plasterboards in a drywall system are factors that make the recycling processes of these materials complex (Mamfredis, 2017).

The example of a drywall system can illustrate that design for disassembly can effectively reduce waste through reuse and recycling if all the factors discussed in its framework are implemented. A report on the waste management of a residential renovation project carried out in 2005 in Montreal shows that almost 30% (17.12 tons) of the total waste generated during the renovation activities was plaster from drywall (Mamfredis, 2006). According to this report, the entire amount was sent to landfills, and no proportion was reused or recycled. Below, the analysis of the design and the assembly method of a drywall system can explain how this type of situation can occur.

Drywall is an infill system widely used for interior partitioning. A drywall system can be installed independent of the structure of a building. The independence of this system from the structure provides flexibility and adaptability and allows the user to configure and reconfigure their space layout according to their needs. Moreover, the system is composed of modular components; metal or wooden studs and gypsum panels, that can be easily assembled by the user without any special skill. The assembly consists of fixing the stud to the ceiling and floor and fastening the gypsum boards to the stud using mechanical fasteners such as nails or screws.

Despite the modularity of its components, the use of mechanical fasteners and the flexibility and adaptability that a drywall system provides, it is considered to be a static configuration with a low Transformation Capacity which can result in a conflict between the different systems. There are two main issues originating with the installation of a drywall system; 1) a drywall system incorporates technical systems and services, making them dependent and inaccessible. As technical systems, such as sockets, wiring and plumbing are incorporated into drywalls, gypsum panels are generally broken for service repair or maintenance, 2) joint compound and a layer of paint applied to gypsum panels as finishing contaminate the gypsum panels and make them inseparable. In the design of drywall system, despite the easy assembly of the components, no consideration has been given to the disassembly of the constituent parts of the system. Service maintenance, repair of technical systems, and spatial reconfigurations result in breaking and damaging gypsum panels. Although recycling damaged gypsum panels is becoming more common, it is a complex task which is not cost-effective. It is complicated to recover gypsum from panels contaminated with paint and joint sealants. Moreover, raw gypsum exists in abundant supply and is inexpensive. Therefore, there is a demand for raw gypsum. Disposing of gypsum in landfill sites has negative consequences such as biological and chemical reactions from the generation of hydrogen sulfide gas which can cause odors and even human death (Saotome, 2007).

A drywall system or similar systems can favor transformations of services within the system without damaging its parts if the assembly method is reversible. A reversible assembly method allows the reuse of the components and materials, reduces the amount of waste and the demand for new materials.

To reduce construction waste through design for disassembly, architects and designers should fundamentally change their approach to designing buildings and systems with reversible connections and with materials that can be returned to local reuse and recycling streams (Lehmann & Crocker, 2012; Gorgolewski, 2017). McDonough and Braungart (2002) postulate that demolition and waste generation should be considered design flaws to be corrected in the planning phase of each project. For example, the standard installation method of a drywall system is a design flaw because gypsum panels are standard, modular components connected with nails or screws that cannot be recovered intact to be reused.

2.2 Barriers to DfD application

DfD is not yet an accepted method of design for buildings. Several barriers to its implementation still exist. Designing for disassembly contributes to reduce the amount of waste if several stakeholders in the construction industry collaborate and coordinate. It should engage the waste management sector, designers, builders, operators, contractors, material producers, and other potential professions during the entire life span of a building; from the planning, construction, operation and maintenance, to end-of-life, deconstruction, recovery and repurposing stages. Designers who intend to reduce construction waste through DfD need information about the recovery, reuse and recycling potentials in local waste management sectors before selecting materials in their projects. There is still not enough connection between designers and the waste management sector. Moreover, operators, contractors and disassemblers need disassembly instructions so they can replace materials and components during the service life of a system or recover them for reuse at the end of the service life of systems. Documentation such as 3D models, drawings and specifications should explain how materials, components and connections should be put together during construction, maintained during the operation, and disassembled at the end of the service life of buildings (Guy & Ciarimboli, 2007). There is still no standard framework for DfD in which these documents are available to the stakeholders. Lack of standards or regulations for DfD as a design method complicate the collaboration between stakeholders.

Other barriers to the DfD implementation include organizational deficiencies related to the ownership, management and maintenance of building components and materials after they are disassembled (Mamfredis, 2017). The final owner of the building should accept responsibility for materials after the disassembly of a building. Recovered materials and components should be transported to specific locations, repurposed, stored and maintained. The transport, repurposing, storage and maintenance are all costly processes, and generally, contractors are not open to accepting these costs (Mamfredis, 2017).

Economic issues are other barriers to the implementation of DfD as a method because conventional construction methods are still more cost-efficient. For example, using wet connection methods and chemical fasteners and finishes is cheaper in the short term (Durmisevic, 2006).

Although there are obstacles to the implementation of DfD, research and prototypes in some countries, like the Netherlands, are determining evolving practices for DfD.

2.3 DfD in Canada

In 2004, the Canadian Standards Association (CSA) established a committee on sustainable construction practices to develop standards leading to changes in design and deconstruction practices in support of sustainable development initiatives (Kyle, Foo, & Torrey, 2012). This committee was engaged to develop national standards to promote the design, construction and maintenance of buildings in a sustainable manner by drafting guidelines on design for disassembly and adaptability (DfD/A) in the built environment (Canadian Standards Association (CSA), 2004; Kyle, Foo, & Torrey, 2012). The first edition entitled, 'Guideline for design for disassembly and adaptability, CSA-Z782-06' was published in November of 2006 (Kyle, Foo, & Torrey, 2012). This guideline defines a framework for DfD/A principles and concepts and promotes reducing building construction waste through the consideration of DfD/A principles at the design phase (Kyle, Foo, & Torrey, 2012). This guideline also "reviews quantifiable metrics for each DfD/A principle that subject to further development, can be assembled into a matrix or checklist to guide users in the direction of disassembly criteria design" (Kyle, Foo, & Torrey, 2012, p. 2). This document is a plan to apply a life-cycle assessment methodology to point out the overall benefits of DfD/A. The goal of the guideline is to provide designers with more information on design for disassembly and to develop a tool to assess different building layers or components intended to be reused (Gorgolewski, 2008).

The CSA Z782 outlines and discusses the following 14 DfD/A principles.

- Versatility
- Convertibility
- Expandability
- Accessibility
- Documentation of disassembly information
- Durability
- Exposed and reversible connections
- Independence
- Inherent finishes
- Recyclability
- Refurbish-ability
- Re-manufacturability
- Reusability

- Simplicity (Kyle, Foo, & Torrey, 2012, p.3)

Based on information gained from interviews with architects and some references in the City of Montreal, the construction and building industry in Quebec is not open to apply DfD as a design and construction method. Except for a few deconstruction projects carried out as pilot projects, there is no documentation on deconstruction or intentions for future practices in the industry. Lack of building code standards and credits for design for disassembly in certification systems such as LEED are important factors for the marginal acceptance of DfD in Quebec (Wood, 2018). However, we can observe some DfD principles applied at system level such as in partitioning in few buildings in Quebec.

In the next chapter, four cases demonstrating design for disassembly in different contexts will be reviewed and compared with the Mountain Equipment Co-op's (MEC) Montreal store. The company claims to integrate approaches such as DfD into the design of its stores to address its environmental engagements. The case study will illustrate how DfD was integrated into the project and if it contributed to waste mitigation.

CHAPTER III
METHODOLOGY AND CASE STUDIES

3.1 Introduction

As discussed in the literature review, design for disassembly is well theorized but marginally accepted and practiced in the construction industry as a method. The gap between the theory of DfD and its implementation is related in part to the lack of standards and collaboration among the actors in the building industry, and to the wide application of conventional construction techniques. Implementing DfD as a method requires a standard design framework and reform of current design strategies.

This chapter illustrates the gap between the theory of DfD and its implementation through a series of case studies. In this regard, the three principles of DfD, discussed in Chapter 2, are reviewed in three experimental projects in three different contexts and an infill system in which DfD is effectively implemented. The goal is to compare the results of the cases with an analysis of a local case where some principles of DfD are implemented. This comparison allows for the identification of the limitations of the current design for the recovery and reuse of materials and components in the local case selected. It also presents the potential for designers to develop their assembly methods and adapt the selection of components and materials to increase the recovery, reuse and recycling of materials in the Quebec context.

3.2 Methodology: case studies

A case study method has been selected for this project. As Eisenhardt (1989) stated, case studies are well suited to new research areas (Eisenhardt, 1989, as cited in Rowley, 2002). Moreover, case study analysis is an empirical method that investigates a contemporary phenomenon (a case) in-depth and within its real-world context and can reveal gaps in a specific area of research (Yin, 2017).

In this project, the case studies allowed for the examination of the validity and reliability of the theories and concepts previously discussed in real-world projects. Yin[7] believes that one of the best ways to develop or to test theory is to study cases in the real world, and that conversely, case studies should be based in theory (Groat & Wang, 2013). A multiple-case study is designed to examine if all the cases support the same theory. According to Rowley (2002), if two or more cases support the same theory, replication can be claimed. The replication logic will further allow for the generalization of the results of this study. "The power of generalizability comes from the concept of replication, rather than the concept of sampling" (Groat & Wang, 2013, p. 432).

3.3 Limits of the study

Two factors are the principal limits of this research project; case selection, and available data.

The three major constraints of case selection are:

1) As mentioned previously, design for disassembly has been mostly applied in temporary architecture such as the exhibition's structures, pavilions, or temporary shelters (Guy & Ciarimboli, 2007). It is an emerging concept for designing buildings with a longer life span and is not still accepted as a common methodology. Limited examples of buildings are designed and built with

[7] Robert K. Yin, an American social scientist is known for his work on case study research as well as on qualitative research. Over the years, his work on case study research has been frequently cited (Marshall & Rossman, 2010).

disassembly potentials implemented in their design. The limited number of buildings designed for disassembly offered the researcher few options for the case selection. In Quebec, there is no building built based on DfD that can be entirely disassembled at the end of its operational life. The disassembly possibility can be observed partially within certain systems such as interior partitions but not in the design of the buildings.

2) As DfD is an emerging practice, minimal data on waste management after a disassembly operation is available. Analyzing buildings that are still in operation and contain some DfD principles does not provide accurate results on waste management at the end of the life span of buildings.

3) The accessibility of data and documents was another challenge in the selection of cases. Technical drawings and documents were not easily accessible, especially for non-local cases. Data collection for selected cases outside Canada introduced limitations to the analysis of the cases. Therefore, secondary sources were used. Moreover, in some cases, data sources refused to provide resource documents, and this limited the options of case selection to the most documentable cases which are often part of existing studies and literature.

Regarding the type of data available for the case study section, part of collected data for the case analysis are secondary sources mostly published on the internet as advertising documents. Using these documents caused limitations for a critical and objective analysis of the projects and in some cases led to commercial presentations of the projects. As for Mountain Equipment Co-op, the company refused to provide information and documentation to this research project. Few primary sources were collected through the architect of the project. Collecting data from one source caused a degree of subjectivity in the analysis.

3.4 Analytical grid for case studies

In order to compare cases from different contexts, they are all analyzed according to the same criteria in the analytical grid. The analytical grid aims to study the context, the design approach and the architecture of each case to examine the potentials that these factors provide for the disassembly, recovery, reuse and recycling of their materials. The analysis of each case is presented separately in a text format.

3.4.1 Theoretical background for the analytical grid

The analytical grid is designed based on the theories reviewed in the literature and is illustrated in the diagram below (Figure 3.1). The analysis of each case follows the sequence presented in Figure 3.1.

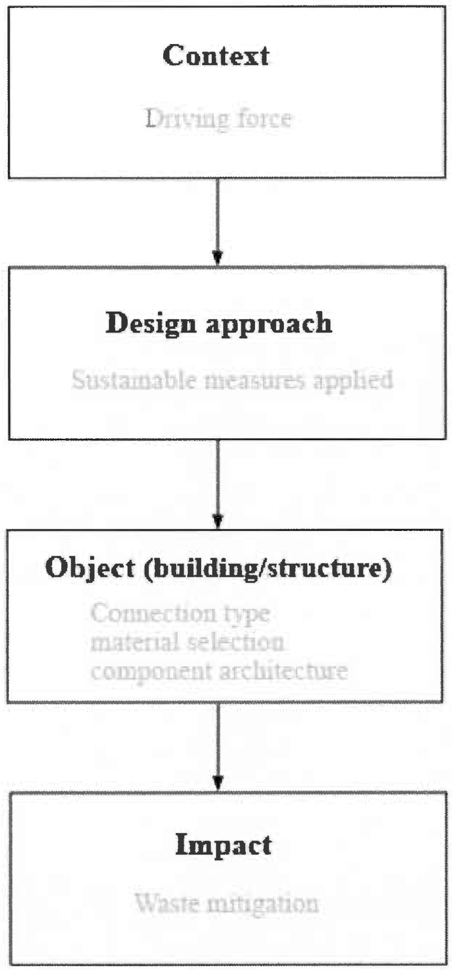

Figure 3.1. This diagram presents the analytical grid framework for the case studies. Created by S. Sadraee

Context is the first criterium in the grid. Through a review of the cases, it was concluded that context is a driving force for the implementation of DfD as a methodology. In experimental projects, buildings are prototypes to present solutions to problems specific to their contexts.

The second criterium is the design approach applied for each case. The third criterium is the observation of the implementation of three major principles of DfD (connection methods, component architecture, material selection) in each case. The fourth and final element of the analysis is the potentials for waste mitigation provided by the design approach. The result of the analysis helped provide answers to the previously raised question: *Which aspects of design for disassembly increase the potential for the reuse and recycling of components and materials in each case?*

Below, the text format of the grid and different criteria analyzed in each stage are presented.

ANALYTICAL GRID

1. Context analysis
    - Social
    - Organizational (approach)
2. Design approach
    - Sustainable measures applied
3. Object analysis
    - Architectural characteristics
    - Assembly methods
    - Material selection

4. Potentials of the design approach for waste reduction

    - Potentials provided by assembly methods, component architecture and selected materials for reuse and recycling and waste mitigation.

3.5. Selection of cases

The cases include three buildings and two interior partition systems. The first category of cases presents three experimental projects, in three different contexts and designed for different purposes. The cases are, Office Building XX in Delft, the Netherlands, ICEhouse in Davos, Switzerland, and Cellophane House in New York, United States.

Building XX is an office building, ICEhouse is a temporary structure for annual events, and Cellophane House was a prototype for a contemporary urban dwelling assembled during an exhibition at the Museum of Modern Art (MoMA) in New York and disassembled at the end of the exhibition in 2008. These three cases are complemented by an analysis of the DIRTT (Do It Right This Time) company. DIRTT is a North American manufacturer of prefabricated interior partitions, designing its products for on-site assembly and disassembly. Finally, the study focuses in greater detail on the analysis of the interior partition system of the Mountain Equipment Co-op (MEC) store in Montreal.

Based on their life span, the selected cases can be classified into two categories. The first category includes the three experimental buildings which were designed with a specified life span. The second group includes the partition systems for which no specified life span was considered in their design (Table 3.1).

Table 3.1. This table shows two categories of cases based on the life span of the projects.

Experimental projects – life span	Local cases – unspecified life span
Office Building XX – 20 years	DIRTT
ICEhouse – 1 week	MEC
Cellophane House – 3 months	

The selection of cases with a specified life span offers the possibility of studying the entire life cycle of the buildings. For example, ICEhouse and Cellophane House were designed as prototypes and were entirely disassembled after their first designated life span.

Office Building XX, in the first category is still in operation although it was designed with a 20-year life span in 1998 and the disassembly was planned for 2018. In a personal interview[8] in 2018, the architect of Office XX confirmed that the building is still in a good physical condition and the client intends to extend the tenancy for ten more years. Although the building was not disassembled, it is a relevant case to study as the disassembly of its composing parts and pieces was established as design criteria.

ICEhouse is selected because it shows how a structure can be entirely assembled and disassembled within a short time schedule, and it is a zero-waste project. This project

[8] The researcher conducted an interview on May 29, 2018 with Jouke Post, the architect of Office XX.

is remarkable in terms of innovative materials that have been used (William McDonough + Partners, 2019). The designers present the materials used in the ICEhouse structure as technical nutriments that can be reused endlessly in the same or other structures or in other industries (World Green Building Council, 2019). Cellophane House is selected as it presents a proposal for reforming design and construction methodologies (Kieran & Timberlake, 2011). This contemporary urban dwelling was entirely assembled and disassembled on site with no waste generation.

The accessibility of data and resources in the local context was the determinant for the selection of the MEC building in Montreal and the DIRTT systems for in-depth analysis. The selection of two local cases allowed for in-situ data collection from a variety of sources to design the in-depth analysis. According to Yin (2017), the ability to deal with a full variety of evidence is the case study's unique strength.

The MEC store in Montreal is a building that features disassembly potentials only at a system level in the interior partitions. However, the analysis of this case is important for three reasons. First, the building is one of the first green buildings built in Quebec in 2003. Second, in most of MEC's buildings, an integrated design approach is applied. This analysis intends to examine how the designers have considered material efficiency in their integrated design method. Third, technical drawings and specifications for the project were accessible, and in-situ observation and interview with the architect were possible.

In the case of DIRTT, disassembly is a strategy that the company applies to fulfil its environmental engagements. The method applied in the DIRTT's partition system favors the reuse and recycling of components and materials as they can be disassembled and recovered in good physical condition. It is important to study the design method of this company to compare it with the MEC building's partitioning system.

Data collection methods included document analysis, in-situ observations, and interviews with project designers and stakeholders. Office XX, ICEhouse and Cellophane House's data were collected through analyzing documents and materials available online or in print. In-situ observations were carried out for the two local cases, the MEC building and DIRTT company. In-person observations were conducted of the MEC store at Marché Central and of Gaz Métro's office completed by DIRTT in Montreal. The visits allowed for an in-situ analysis of the partition systems along with pictures of the systems.

The next section presents the review and analysis of the five cases.

3.5.1 Office Building

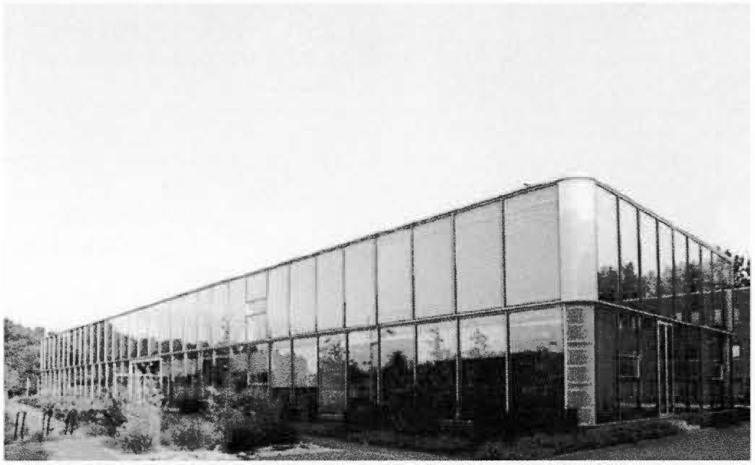

Figure 3.2. Office Building XX in Delftech Park, Delft, J. M. Post, XX Architecten.

Table 3.2. Table shows an overview of the Office Building XX project.

Architect	Jouke Post
Location, year	TU Delft Science Park, Delft, Netherlands, 1998
Project type, current situation	Experimental, building in operation
Project's goals	Technical & functional coordination
Design approach	Design for end-of-life, disassembly & reuse
Scale of the analysis	Building level

3.5.1.1 Context analysis

- Social: Oversupply of office spaces and high demolition rate caused by functional obsolescence and structural vacancy.

- Organizational (approach): Experimental project in the context of investigations of office buildings vacancy, designed with a short life span to create the balance between the technical and functional life cycles based on the average functional life cycle of an office building in the Dutch context.

In the Netherlands, more than 6 million square meters of Gross Leasable Area (GLA)[9] of office spaces were reported vacant in 2007 (Remøy, 2010). Space vacancy results in issues such as oversupply of office spaces on the market, structural vacancy, increase in demolition activities, and large amounts of waste from demolition (Remøy, 2010; Kibert, 2013). A mismatch between demand (occupancy) and supply (physical inventory) in the commercial context has increased the vacancy rate since the 1990s (Remøy, 2010). This number, which represents 13% of the total office spaces in the Netherlands, is above the upper limit of natural vacancy which is 8% in the Dutch context (Remøy, 2010).

Several research projects have been conducted since the 1990s on surplus of office space and structural vacancy in the Netherland (Remøy, 2010; Guequierre & Kristinsson, 1999; Durmisevic, 2006; Kibert, 2013). The Dutch government has also allocated considerable grants to investigations of office building vacancy (Guequierre & Kristinsson, 1999). In this context, Jouke Post designed Building XX as an experiment to study solutions to issues related to structural vacancy, demolition and the increasing amount of construction waste (Kibert, 2013).

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[9] Gross Leasable Area (GLA) is the amount of space in a commercial building that can be rented by a tenant (Commercial Real Estate Loans, 2018).

The building is located in Delftech Park in Delft, Netherlands. The Delftech Park or the TU Delft Science Park is a part of TU Delft, known to be one of the best climates for science innovation and a leading location for research and development in Europe (TU Delft, n.d.). It is the home to more than 200 national and international companies whose research institutes are linked to the scientific research at TU Delft (TU Delft, n.d.).

Office XX was designed with a 20-year life span by ‘XX architecten’ and built by Wereldhave, a Dutch real estate investment company in the Netherlands in 1998 (Durmisevic, 2006; Kibert, 2013). The XX architecten firm, a consortium of Post ter Avest and Brouwer Associates architectural firms, works in sustainable building design and uses the cradle-to-cradle concept in many of its projects.

Jouke Post, the architect of Office XX, studied several reasons for structural vacancy in office buildings and concluded that building vacancy in a commercial context is mostly related to functional obsolescence (Durmisevic & Yeang, 2009). Functional obsolescence happens when spaces and buildings cannot be adapted to users’ needs and frequent changes are required in commercial context due to several factors. According to Remøy (2010), functional obsolescence is the result of three major factors. The first factor is the changing work style and technology requirements in the commercial context (Remøy, 2010). During the past 50 years, there have been drastic changes in work style and office organizations (Remøy, 2010). “50 years ago, work was more formal, office hours more rigid, organizations were more hierarchical, and office building were monotonous in their spatial layout” (Remøy, 2010, p. 50). Today work is less formal, organizations are less hierarchical, office hours are flexible, and office buildings include informal work and meeting spaces (Remøy, 2010). The new workstyle requires different types of spaces which can be flexible and adaptable to rapid changes and new requirements (Durmisevic, 2006).

The second factor that results in functional obsolescence is visual obsolescence of spaces and buildings (Remøy, 2010). Visual aspects are important as they represent the value of companies. Buildings or spaces with poor visual qualities or any evidence of vandalism or decay that cannot be upgraded or repaired may be functionally obsolete (Remøy, 2010). The third factor is financial or economic obsolescence, and it occurs when the costs of maintenance, adaptations, reconfigurations or renovations exceed the benefits of occupation (Remøy, 2010). An assessment of the potential for reconfiguration and adaptation can determine if it is profitable to adapt existing structures and spaces to new functions.

There is a higher risk of obsolescence in buildings that are designed and built with conventional methods (Durmisevic, 2006; Remøy, 2010). As we mentioned earlier, this is because conventional methods deliver buildings with static configurations and inflexible technical elements that cannot be upgraded. Studies show that most office buildings built in the past 20 years are not technically adaptable to organizational changes (Remøy, 2010). Lack of structural flexibility and spatial adaptability leads to organizations and businesses relocating and causes building vacancy, demolition and high amounts of waste generation (Durmisevic, 2006).

The architect considered several factors in the design of Building XX to prevent functional obsolescence. These factors are reviewed in the following sections.

3.5.1.2 Design approach

Sustainable measures applied:

- Designed to create a balance between the technical and functional life cycles.
- Designed based on energy and material efficiency.
- Designed for disassembly and reuse.

Office XX is resource-efficient in terms of energy performance and material use (Kibert, 2013). It is energy efficient as the architect integrated the optimized use of natural light and high levels of insulation which both removed the need for supplementary mechanical heating and cooling systems (WRAP, n.d.; Kibert, 2013). Moreover, the disassembly of the building in the future and the reuse and recycling of its components and materials may save the embodied energy of materials and reduce the need to harvest raw materials (Kibert, 2013).

The designer considered material efficiency by designing the building with a specified life span to avoid building vacancy, demolition, generation of large amounts of waste and to save materials and components for reuse (Kibert, 2013). This project is an experiment in thinking about innovative assembly techniques to achieve flexibility and disassembly potentials of an entire building (Durmisevic, 2006). The main approach in this project is to create a balance between the functional life cycle and the technical life cycle, considering the functional life span of an office building in the Dutch context. The architect estimates that the functional life span of office buildings in the Netherlands is typically 20 years (Kibert, 2013). Therefore, he integrated disassembly potentials for a building with a 20-year-life span so the building could be dismantled in 2018. Post estimates that building for a specified life span which corresponds to the average life cycle of office buildings in the Dutch context strikes a balance between the office workstyle needs, the average life cycle of an office building and the future of materials (Durmisevic, 2006). The architect applied methods of assembly and integrated materials in a way that at the end of the building's service life, materials will either have perished or can be dismantled and reused as planned (Project XX, 2019). Durmisevic (2006) states that this experimental two-story construction explored a solution to the structural vacancy and the waste problem.

3.5.1.3 Object analysis

- Architectural characteristics: exposed structure, open plan with no interior partitions.
- Assembly methods: Prefabricated and standard-size frame, façade, floor and roof panels, assembled on-site with mechanical connection methods.
- Material selection: Local materials, pre-made and dry-assembled finishing.

Office XX is a 2,000 square meter (21,500 ft2), two-story building with a simple, open and unified rectangular floor plan (Kibert, 2013). The ground floor consists of a concrete slab with 20% recycled aggregate, and the framing system consists of exposed laminated veneer lumber beams connected to each other by steel rod chords and bolts (WRAP, n.d.; Kibert, 2013) (Figures 3.3 and 3.4). In addition to the floor and wall finishes, all materials and components were prefabricated and dry assembled so the entire building can be disassembled at the end of its operational life cycle (Durmisevic, 2006).

Figure 3.3. This figure shows the columns and beams during the construction, exposed and connected by stand-off steel rod lower chords and bolts. © J. M. Post, XX Architecten.

Figure 3.4. This figure shows the interior of the completed Office XX. © J. M. Post, XX Architecten.

The first important aspect of design implemented in the building is the structural and spatial flexibility and adaptability. According to Guequierre & Kristinsson (1999), the concept of 'support' and 'in-fill' is well integrated into this building which makes the structure flexible. As an example, the interior layout of the building has an open plan with no partitioning, and this provides spatial flexibility and allows the building to change from an office to an industrial building (WRAP, n.d.). The architect has considered independent levels that can be completely removed to create a space that is eight meters tall and convenient for industrial use (WRAP, n.d.). The structure is also held together in a way so that parts can be easily separated whenever disassembly is needed. Standard steel rod chords, pins and bolts connect columns and beams together (Kibert, 2013).

To maximize material recovery without damage during the disassembly of different levels, pre-made channels for electrical services and holes for pipework are inserted into a limited number of locations in the floor panels (Durmisevic, 2006). This aspect makes the maintenance and repair of services easier. Moreover, the carpeting inside the building is not glued (WRAP, n.d.).

The material and component selection is harmonized as much as possible with the 20-year life cycle of the building (Guequierre & Kristinsson, 1999). The architect considered several factors such as durability, strength, cost and future reuse and recycling in the local context to select the materials for the structure (Durmisevic, 2006). Wood was chosen for the structural frame after analyzing all alternatives such as steel, aluminum, concrete, stone, synthetic material and cardboard (Durmisevic, 2006; Kibert, 2013). There are also several considerations for the reuse and recycling of other materials and components in different parts of the building. The building envelop consists of floor-to-ceiling rectangular glass panels which are approximately 2 meters by 5 meters standard-sized, triple-paned glazed windows (Kibert, 2013). Using standard components increases the reuse potential of components when the building is disassembled. The glass panels are installed on wooden frames that are independent of the main structure but attached to it by brackets. This allows for easy separation of the envelope from the structure and the panels can be recovered and reclaimed (Durmisevic, 2006). The roof is made of fibrous concrete and recyclable bituminous roof covering so they can be recycled when the building reaches the end of its life cycle (Durmisevic, 2006; Kibert, 2013). Sandwiched panels of 600 cm by 500 cm filled with sand are used between levels to improve the acoustical separation (Kibert, 2013). These components can also be recycled after disassembly. All horizontal return air ductwork that runs along the perimeter of the building is composed of cardboard tubes which are highly recyclable (Durmisevic, 2006; Kibert, 2013).

3.5.1.4 Potentials of the design approach for waste reduction

Potentials provided by assembly methods and selected materials for reuse and recycling and waste mitigation:

- Designing independent levels assembled within a parallel relationship.
- Using standard-size modules increases the potential for reuse.
- Applying mechanical connections provides easy access and disassembly.
- Selected materials for the structure are highly reusable and recyclable.

In contrast to buildings designed with conventional methods where most components can be partially recycled on a material level, in Office XX, Post applied strategies so that materials and components can be reused as products after disassembly (Guequierre & Kristinsson, 1999). Three major strategies may decrease the amount of waste at the end of the life cycle of the building through high reuse and recycling of components and materials; 1) designing independent layers, 2) assembly methods, and 3) the selection of materials and components.

1) Designing independent levels and applying a parallel assembly sequence allow for the reconfiguration and adaptation of the interior space to other functions and prevents the demolition of parts and saves materials for reuse or recycling. The building's envelop is independent of the main structure, and this allows for the recovery of glass panels without damaging the structure and the panels. Independence is provided by installing a wooden frame that is used as a connector and intermediary between the glass panels and the main structure. Regarding the floor, thin foil separates the ground floor from thermal insulation so the floor can be easily replaced or recycled in the future (Durmisevic, 2006).

2) Connecting materials and components with reversible fasteners ease the separation process and make them reusable after disassembly (Guequierre &

Kristinsson, 1999). Different parts and components such as the roof, floor, columns and beams, facade and the carpeting are assembled with methods that are also considered for their disassembly. Components or materials that cannot be reused in their current state are designed to enter the local recycling streams (Kibert, 2013). Durmisevic (2006) has carried out an in-depth analysis of assembly methods which shows that the building is changeable at the component level, but not changeable at the system-level and partially changeable at the building level. The analysis shows that components in each system are modular, independent and accessible and are connected to each other with mechanical and reversible connections. However, she noted that there is a dependence between the facade, roofing and floor systems which makes the building non-changeable on system-level and will result in partial demolition (Durmisevic, 2006).

3) There was a special intention to select materials that can be reused or recycled in local material streams (Durmisevic, 2006; Kibert, 2013). Timber can be 100% reused or recycled. Sand, used in sandwich panels between each level, is a natural material that can be reused. Unpainted softwood for internal cladding panels can be recycled as well (Kibert, 2013). Reusing and recycling of Building XX components and materials may lead to waste reduction at the end of its service life.

In the Office Building XX project, the application of two principle aspects of DfD may promote the reuse and recycling of components and materials and waste reduction. Selecting timber for the structure and standardized glass panels, using mechanical connection methods applied and considering the independence of the layers of the building increase the reuse and recycling potentials. The cost of the disassembly process at the end of operation life of Building XX can be paid back in reducing the need for raw materials and the amount of waste to be managed.

3.5.2 ICEhouse

Figure 3.5. ICE house, Davos, 2016, Brady Johnson.

Table 3.3. This table shows an overview of the ICEhouse project.

Architect	William McDonough + Partners
Location, year	Davos, Switzerland, 2016
Project type, current situation	Experimental, structure in operation
Project's goals	Implementing cradle-to-cradle measures
Design approach	Design for end-of-life, disassembly & reuse
Scale of the analysis	Building level

3.5.2.1. Context Analysis

- Social: ICEhouse is the Chair of the World Economic Forum and the location for Innovations for Circular Economy, located at Hub Culture Pavilion in Davos.
- Organizational (approach): A place to present innovations for the Circular Economy.

ICEhouse (Innovation for the Circular Economy house) is a structure located at Hub Culture Pavilion in Davos, a mountain resort in Graubünden, in the eastern Alps region of Switzerland. It was designed by William McDonough + Partners. McDonough, a globally recognized leader in sustainable development, is currently serving on the World Economic Forum (WEF)[10]'s Global Future Council on the Future of Environment and Natural Resource Security (William McDonough + Partners, 2019). He designed ICEhouse for the 2016 World Economic Forum annual meeting. The same structure was reused during the 2017, 2018 and 2019 WEF meetings and today, as an official meeting space, ICEhouse is considered the seat for the World Economic Forum's annual meetings (William McDonough + Partners, 2019).

The WEF is a part of the activities held at Hub Culture Pavilion. Hub Culture Davos Pavilion is one of several Hub culture pavilions built in several key cities around the world. These pavilions promote sustainability, work efficiency, and community development by offering workplaces for influential urban professionals to discuss

[10]The World Economic Forum (WEF) is a Swiss non-profit organization, founded in 1971, based in Geneva, Switzerland and best known for the annual meeting in Davos held at the end of January. Top business leaders, international political leaders, civil society, economists and journalists gather for up to four days to consider and discuss major global management, economic and social issues of the day and to brainstorm on solutions to address these challenges. At WEF, innovations for the Circular Economy is at the core of the meetings (World Economic Forum, 2019).

innovative subjects and ideas and provide interaction opportunities for the networked individual and forward-thinking companies (Hub Culture, 2019).

McDonough mentions that ICEhouse demonstrates "the positive design framework described in the book *Cradle to Cradle: Remaking the Way We Make Things,* as well as the sustainable development goals of the United Nations and the reuse of resources implicit in the Circular Economy" (William McDonough + Partners, 2019). The project also demonstrates how design can eliminate the concept of waste and add to the 'resourcefulness' of a system. As McDonough mentions, the idea is, "putting the 're' back in 'resources' which is a foundation of the Circular Economy" (William McDonough + Partners, 2019).

3.5.2.2 Design approach

Sustainable measures applied:

- Adaptable to local cultures and individual aesthetics.
- Temporary but durable as it is designed for disassembly and reuse.
- Demonstration of the Cradle-to-Cradle framework.

The designers' initial purpose in the ICEhouse project was to create a structure that could fulfill urgent shelter needs by using a rapid-response-emergency structural system that could transform from temporary housing into permanent housing and dwellings of long-term value (William McDonough + Partners, 2019). ICEhouse can be relocated to different contexts; it is adaptable to various climates, local cultures and individual aesthetics as various types of materials are compatible with the structure (William McDonough + Partners, 2019). The main vision of the design team is to work on an approach to structures that could fulfill urgent shelter needs and to find replacements for wood and steel for the structure (William McDonough + Partners, 2019).

ICEhouse is a temporary but durable structure. It is temporary as it is assembled for the WEF's annuals meetings for a week and then is disassembled after the event. It is durable because the whole structure can be assembled, disassembled and reassembled for continuous life cycles. The whole structure can be used on the same site, or its components can be independently reused in other projects on different sites. McDonough mentions that selected materials in ICEhouse are technical nutrients that can be returned to the industry at the end of their use cycle and can be endlessly remanufactured into new products with no loss in material quality (World Green Building Council, 2019). In this project, the designers experiment with new materials which are either Cradle to Cradle Certified™ or in the process of becoming certified (William McDonough + Partners, 2019). The continuous disassembly and reassembly potential of ICEhouse is based on the limited number of components, the simplicity of the assembly method, and the accessibility of its connections (William McDonough + Partners, 2019).

3.5.2.3 Object analysis

- Architectural characteristics: The whole structure is built with 3 basic components.
- Assembly method: Assembly method is through using simple, reversible and mechanical connections.
- Material selection: Innovative materials are used; they are presented as industrial nutriments that can remain in use for several cycles.

ICEhouse has a simple metal aluminum frame, and the whole structure is comprised of three basic pieces that are connected and assembled using simple tools such as bolts (Figure 3.6 & 3.7). All the components can be packed in boxes that weigh 18kg and are designed for easy transport and local distribution (William McDonough + Partners, 2019).

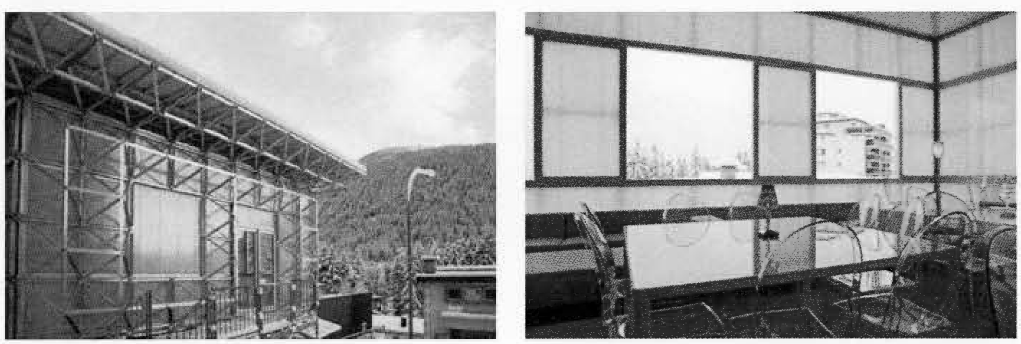

Figure 3.6. These pictures show the outside and inside view of ICEhouse, Davos, 2016, © William McDonough + Partners.

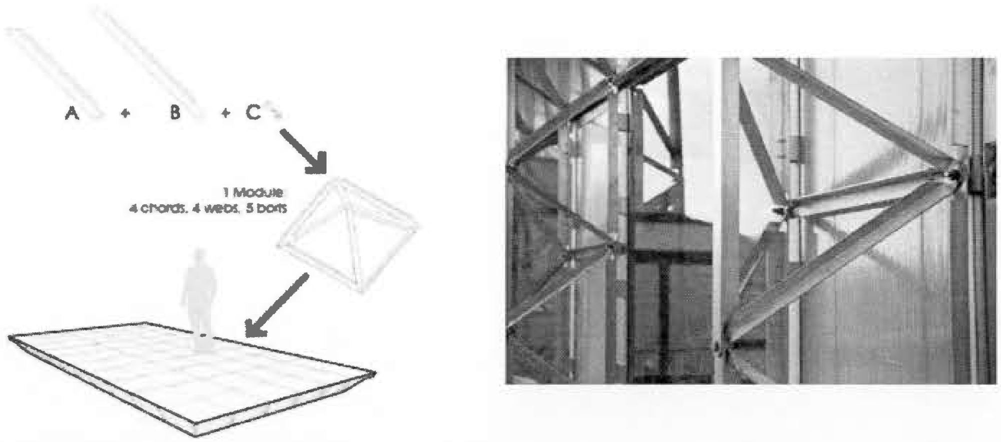

Figure 3.7. This figure shows the basic components of ICEhouse. © William McDonough + Partners, 2018.

The most considerable feature to analyze in ICEhouse are the materials that are selected for this structure. ICEhouse is primarily made of four materials;

- The structural frame, called WonderFrame™ is made of aluminum,
- The wall cladding, ceiling, windows and roofing are different configurations of polycarbonate sheets,
- Aerogel is used as insulation within the wall and ceiling system, and
- Nylon 6 carpet is used for the flooring.

ICEhouse offers the visitors of the WEF the occasion to discover the opportunities of WonderFrame™, the most important structural element of the project. It is a patent-pending, open-source frame system and the result of research and experiments for simple, flexible and inexpensive structural solutions (William McDonough + Partners, 2019). WonderFrame™ was originally designed as a temporary structure at the 2016 WEF Annual Meeting in Davos. Later, it was used as a permanent structure in other projects such as Universidad EAN in Bogota, Colombia (William McDonough, 2017). WonderFrame™ can be erected quickly and can be easily dismantled to be reused in different projects. A crew of four workers assembles the prefabricated components, walls and the roof structure of ICEhouse on-site, in nine days for annual meetings in Davos (William McDonough + Partners, 2019).

Figure. 3.8. ICEhouse can be assembled rapidly in different climate conditions, Davos, © William McDonough + Partners.

While the framing system for ICEhouse is made of aluminum, WonderFrame™ is an open system that can also be made of a variety of recovered materials such as thermoplastics from refuse streams or a locally available feedstock to make cost-effective components (William McDonough + Partners, 2019). Research is currently underway for using other feedstock such as plastics and bamboo (William McDonough + Partners, 2019).

The translucent wall cladding, the ceiling and windows are sheets made of polycarbonate, products of Sabic Company. The sheet is registered under the commercial name of LEXAN™ sheet. It is a robust multi-layer component filled with nanogel, a type of highly-thermal insulation (Sabic, 2016). LEXAN™ sheet is 250 times more impact resistant than glass, UV resistant, and virtually unbreakable. It is resistant to extreme weather changes from -40°C to +120°C, and in windstorms, snowstorms under ice formation conditions (Sabic, 2016). LEXAN™ sheets have also a climate control performance. Their multi-layer structure creates air pockets between the exterior and interior of the building (Sabic, 2016). Multi-wall sheets allow natural daylight to enter the building and offer considerable energy savings of up to 50% compared to single-pane glass panels (Sabic, 2016). McDonough highlights that LEXAN™ sheet is a technical nutrient that can be recovered and reused continuously in several use cycles (World Green Building Council, 2019).

3.5.2.4 Potentials of the design approach for waste reduction

Potentials provided by assembly methods and selected materials for reuse and recycling and waste mitigation:

- Disassembly increases the reuse and recycling potentials.
- Local materials can return to the local recycling system.
- Innovative materials selected are all recyclable.

ICEhouse is a demonstration of the cradle-to-cradle framework. ICEhouse has been assembled, disassembled and reassembled five times with no waste (World Green Building Council, 2019). Two factors make ICEhouse a zero-waste structure; the method of assembly for its components, and the selection of recyclable and innovative materials that are reusable and recyclable in the local waste stream. William McDonough + Partners conducted research to adapt the structure to a variety of materials, especially local materials from recycling streams. As mentioned previously, components and materials used in this structure can be reused and recycled endlessly in a closed-loop for the same structure or independently in other configurations elsewhere (World Green Building Council, 2019). For example, the aluminum used for the structure in the Davos version is an endlessly reusable and recyclable material. The innovative polycarbonate LEXAN™ sheet is also 100% recyclable. It is durable, light and versatile which is an excellent choice for buildings designed for disassembly and reuse, fulfilling the goal of circular economy.

In the ICEhouse project, two principal aspects of DfD made the building a zero waste project; use of recyclable materials, and mechanical connections which made the structure 100% demountable. We assume that the disassembly costs may be paid back in eliminating disposal costs and reducing the need for raw materials.

3.5.3 Cellophane House

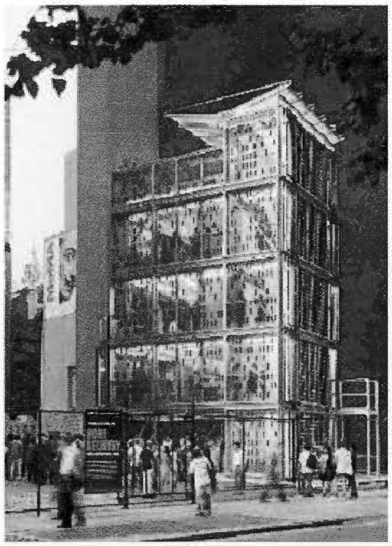

Figure 3.9. Cellophane House at MoMA, 2008, Peter Aaron/ OTTO.

Table 3.4. This table shows an overview of the Cellophane House project.

Architect	KieranTimberlake
Location, year	MoMA, New York, 2008
Project type, current situation	Prototype, disassembled
Project's goals	Demonstration of contemporary prefabrication
Design approach	Design for disassembly & reuse
Scale of the analysis	Building level

3.5.3.1 Context analysis

- Social: Exhibited at Home Delivery: Fabricating the Modern Dwelling at MoMA.
- Organizational (approach): A demonstration of potentials of prefabrication for the disassembly of a whole structure and the potential evolution of prefabrication in urban dwellings.

Cellophane House is a full-scale green urban-dwelling designed in 2007 by the firm KieranTimberlake. The project was a part of the *Home Delivery: Fabricating the modern dwelling* exhibition at the Museum of Modern Art (MoMA) in New York City in 2008. The exhibition is comprised of two parts. The first part was a selective survey of the evolution of prefabricated house, represented by timeline, from 1833 to 2008. The timeline demonstrated two hundred years of architectural history; a focus on outstanding architectural movements, innovations in serial production, prefabrication, introduction of new materials and computer technology's impact on design and architecture (MoMA, 2008). The second part exposed five full-scale buildings, located on the Museum's west vacant lot. The five projects, including the Cellophane House, were designed by five contemporary architectural firms and showcased a variety of approaches to prefabrication, the current state and the future potential of prefabricated architecture, and disassembly possibilities of an entire building (MoMA, 2008; Kieran & Timberlake, 2011). The five prototypes, built with prefabricated components, illustrated technological innovations in prefabrication, parametric design and digital fabrication with cost efficiency and speed (MoMA, 2008). The goal of the exhibition of these five prototypes was to show how a prefabricated house is an important factor in the discourse around sustainability, architectural inventions, new materials and formal research (MoMA, 2008)

3.5.3.2 Design approach

- Sustainable measures applied: using parametric design, 3D digital modelling of potential methods for assembly and disassembly.

Kieran & Timberlake's major approach to architecture is to evolve what they learn from their experiences (Kieran & Timberlake, 2011). Cellophane House was an experiment and a concretization of the architects' theories, previously discussed and developed in their book *refabricating Architecture* (Kieran & Timberlake, 2011). Six months prior to the design of Cellophane House, the firm completed Loblolly House, an off-site fabricated home on the Chesapeake Bay in the U.S. (Kieran & Timberlake, 2011). Loblolly project was an opportunity for the architects to confirm some theoretical positions drawn in *refabricating Architecture* (2003) by incorporating 3D digital modelling and integrated component assemblies. In this project, all the elements of the house were assembled off-site in a factory, and the house was assembled on-site in six weeks (Kieran & Timberlake, 2011). As the architects highlight, Loblolly House was a reference for the design and fabrication of Cellophane House which continued to provide architects with valuable feedback after its completion (Kieran & Timberlake, 2011). In Cellophane House, the architects wanted to benefit from the customizable nature of assembly and apply the same methodology in a different context, for a five-story urban dwelling (Kieran & Timberlake, 2011). Kieran & Timberlake mentioned that they intended to design a provocative prototype. Therefore, they selected the height and provided a variety of program and product options that were not available until that time to introduce a new type of house to the marketplace (Kieran & Timberlake, 2011). Loblolly House and Cellophane House challenged the perception of off-site fabricated architecture as there is a belief that prefabricated architecture may not fit well into different contexts and cannot be used for tall, large-scale structures (Kieran & Timberlake, 2011).

Another goal was to explore the speed of on-site assembly, design for disassembly, and a holistic approach to the life cycles of materials for a contemporary urban dwelling (Kieran & Timberlake, 2011). The whole process, from selection to planning and delivery took eleven months (MoMA, 2008).

The designers' approach to material management was using information technology and planning disassembly at the beginning of the project. Cellophane House was designed as a three-dimensional parametric model using Building Information Modeling (BIM) software (Kieran & Timberlake, 2011). Disassembly was presented as one of several potential areas for prefabrication. The simulation of disassembly through digital tools makes the interaction of building elements visible and closes the inherent gaps in two-dimensional representation (Kieran & Timberlake, 2011). According to the architects, the parametric model was applied to bridge the gaps created by conventional methods of designing as it contains all the information necessary for the development, fabrication, and assembly of a building (Kieran & Timberlake, 2011). Designing with technologies like BIM allows designers to virtually reconcile dimensional discrepancies in the model rather than during construction (Kieran & Timberlake, 2011). According to Kieran & Timberlake (2011), in conventional methods, even if many drawings and specifications are presented, there are still critical connections that are not understood until the moment of construction (Kieran & Timberlake, 2011). "BIM yields more efficient structural and mechanical coordination, greater management of parts and schedules for procurement, a clearer approach to assembly sequencing, and a greater measure of control over fabrication and construction" (Kieran & Timberlake, 2011, p. 16). In the construction stage, BIM provided a shared working model in which architects, engineers, planners, fabricators and assemblers could work in a more fully integrated environment (Kieran & Timberlake, 2011). In the disassembly stage, BIM performed a virtual disassembly down to the removal of individual bolts (Kieran & Timberlake, 2011). By using BIM, the architects could test two different disassembly scenarios to calculate the cost of labor, materials, transportation, and storage. The architects used BIM to design and describe the building to fabricators and assemblers through isometric models and sequence drawings (Kieran & Timberlake, 2011). It also allowed them to order the correct quantities of required materials and suppliers could plan cuts well in advance of assembly (Kieran and Timberlake, 2011).

3.5.3.3 Object analysis

- Architectural characteristics: the building was a completely demountable five-story structure.
- Assembly methods: the on-site assembly of prefabricated parts was through exposed connections.
- Material selection: innovative materials were used for the MoMA version; an envelope equipped with photovoltaic cells made the structure off-the-grid and energy-efficient, and a wide variety of materials is suggested for different contexts.

Cellophane House is a five-story, 1,800 square-foot building with an aluminum frame carrying all the structural load and anchored to the site on a grade beam of cast-in-place concrete (Kieran & Timberlake, 2011). Through simple modifications, any kind of foundation could work for the building (Kieran & Timberlake, 2011).

The architects call Cellophane House "a scaffold, an armature of parts that can be configured to meet specific needs or desires" and also "a matrix for the connection of materials" (Kieran & Timberlake, 2011, p. 32). The designers offer various materials options so the house can accommodate the needs, tastes, and budgets of a range of occupants (Kieran & Timberlake, 2011). A wide range of material options provides a high level of adaptability to different contexts. Simple modifications can adapt the building to a different site and climatic conditions, solar orientations, slopes, and adjacencies without changing the nature of the building (Kieran & Timberlake, 2011). In total, 32,245 pounds of off-the-shelf aluminum was used for the structural frame of Cellophane House, all of which were reclaimed through the disassembly strategy.

The transparency of the building's skin references cellophane, a material which is based on cellulose. The word cellophane is the combination of 'Cello,' a contraction of cellulose, and 'pane,' which refers to diaphanous, or lightness, delicacy, and translucency (Kieran & Timberlake, 2011, p. 137). Kieran & Timberlake chose a transparent material, to offer possibilities to envision what it might be like to live transparently. As mentioned above, a wide range of materials can be used instead of the transparent wrapper used in the prototype at MoMA. The designers also offered opaque panel materials to give solid and dense aspect to the building instead of having a light and ephemeral aspect (Kieran & Timberlake, 2011).

The transparent panel used for the building's skin is an innovative material, called SmartWrap™. SmartWrap™ is primarily made of polyethylene terephthalate (PET). It is 3 millimeters thick, lightweight, energy gathering, mass customizable, and a recyclable building envelope system. It can cover a larger surface area with a minimal volume of material relative to glass curtain wall assemblies and can be erected in less time than is time needed for a conventional building, using less labor and smaller machinery (Kieran & Timberlake, 2011).

SmartWrap™ made Cellophane House off-the-grid (Kieran & Timberlake, 2011). Prior to Cellophane House, SmartWrap™ was unveiled as a prototype at the Cooper-Hewitt, National Design Museum in 2003 (Kieran & Timberlake, 2011). It was an experiment on organic photovoltaics (OPV) and organic light-emitting diodes (OLED) deposition printed onto thin plastic film, creating a system of functional building layers on a single substrate (Kieran & Timberlake, 2011). In the Cellophane House™ project, the designers experimented with printed OPV and OLED technologies to explore how the material can be developed for a large-scale application (Kieran & Timberlake, 2011).

The interior floors, ceilings, and wall partitions are made of structural plastic, eliminating the need for additional structural framing. The translucent roof is made from modular polycarbonate panels that feature a standing seam connection method that snaps in place and requires no sealant or adhesives.

In analyzing the assembly method of Cellophane House, we should consider two important factors; the type of connections and the component architecture, especially the framing system. Cellophane House is assembled by a reversible connection method that offers easy and fast on-site assembly and disassembly. As illustrated in Figure 3.10, this is notably thanks to the off-the-shelf aluminum structural frame, engineered and manufactured by Bosch Rexroth, that provides the means to connect and disconnect the individual components (Kieran & Timberlake, 2011). Figure 3.10 shows how parts of the framing structure can be stacked and unstacked and how they are attached and detached by bolts.

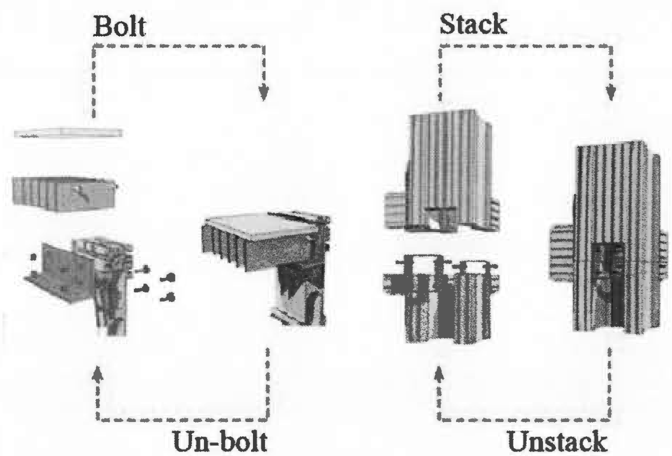

Figure 3.10. This figure shows how the aluminum framing provides the means to fasten materials together with reversible connections (Kieran & Timberlake, 2011, p. 25).

Figure 3.11 shows how the architecture of components has an impact on their assembly and disassembly. The T-shaped slot on each side of the framing strut serves as the negative receptor for a variety of friction connections. This method of component assembly avoids using chemical connections and allows for components and materials to be reclaimed through their disassembly.

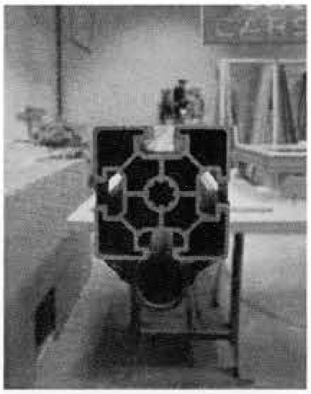

Figure 3.11. This figure shows the section of aluminum framing, featuring a T-shaped slot on each side (Kieran & Timberlake, 2011, p. 23).

Beams, columns, and accessories are fastened together with gussets and T-bolts which are compatible with the T-shaped slot on the aluminum channel, rather than welds or adhesives (Kieran & Timberlake, 201) (Figure 3.12).

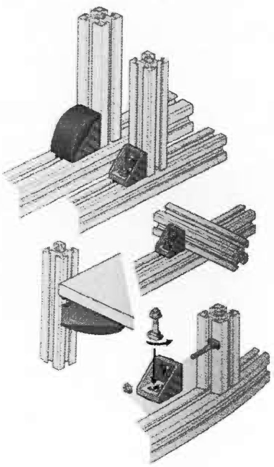

Figure 3.12. Aluminum members are connected with gussets and T-bolts (Kieran & Timberlake, 2011, p. 28).

In addition to serving structural connections, the T-shaped slot is used as a channel for covering wiring and for the operation of the sliding doors within the house and the SmartWrap™ panels (Kieran & Timberlake, 2011). Figure 3.13 shows how panels slide into the slot on the extruded channels.

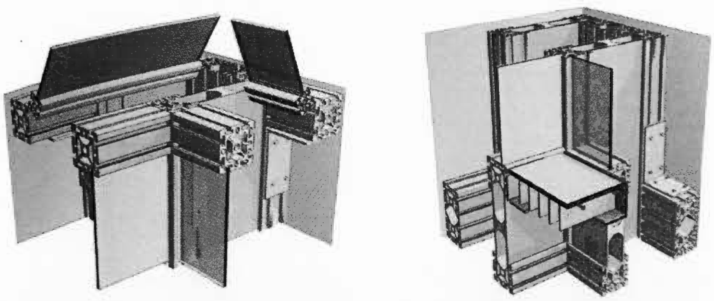

Figure 3.13. This figure shows the connection detail at upper and lower corners bolts (Kieran & Timberlake, 2011, p. 55).

The interior wall partitions and floor panels are attached to the frame with 3M VHB (Very High Bond) frame tape, a proven alternative to screws, rivets, welds and other forms of mechanical fasteners (Kieran & Timberlake, 2011) (Figure 3.14). It is simple to apply the tape, and it securely fastens the polycarbonate panels and lights to the aluminum frame. The tape cross-bonds structurally and gets stronger with time. During the disassembly process, the polycarbonate panels were pulled off, and the tape was easily removed (Kieran and Timberlake, 2011).

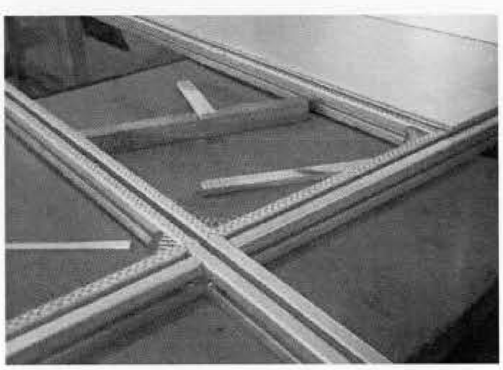

Figure 3.14. Wall partition and floor panels are taped to the aluminum frame (Kieran & Timberlake, 2011, p. 26).

3.5.3.4 Potentials of the design approach for waste reduction

Potentials provided by assembly methods, component architecture and selected materials for reuse and recycling and waste mitigation:

- The advanced disassembly simulation through 3D modelling reduced the possibility of materials becoming damaged at the end of life of the building.
- The architecture of the selected components allows for easy assembly and disassembly and prevents damage to the components.
- Mechanical connections allowed for the recovery and reuse of materials.
- Designers selected materials that could return to the recycling streams.

Designing for disassembly and selecting lightweight materials that were all part of existing recycling streams were implemented to minimize the amount of waste in this project. The study of the assembly and disassembly of Cellophane House shows that the three major principles of DfD, previously discussed, were considered in its design. The 3D modelling of the entire structure before construction through BIM was the most efficient factor in a successful disassembly of Cellophane House. Thanks to BIM, the assembly and disassembly processes were documented and accessible to the assemblers. Accessible documentation increased labor efficiency in terms of time, cost, storage and transportation (Kieran & Timberlake, 2011).

In terms of assembly methods, reversible connection methods, as applied in this project, yield a high level of flexibility and accessibility for separation, exchanging, reusing and recycling of materials and components (Kieran & Timberlake, 2011). The design and architecture of components, especially the structural framing components, based on sliding and stacking, avoided the use of adhesives, welding and gluing to connect the parts together.

Moreover, the material selection for Cellophane House reveals that special attention was paid to reuse and recycling. Aluminum has a high level of embodied energy; however, it is lightweight, durable and does not rust or break down from exposure, needs no painting or finishing and is completely recyclable. All 32,245 pounds of aluminum in the frame was reclaimed through the disassembly strategy (Kieran & Timberlake, 2011). Glass and SmartWrap™ are both recyclable materials and so the SmartWrap™ were easily disassembled, and at the end of its useful life, can be fed into a recycling stream (Kieran & Timberlake, 2011).

According to Kieran and Timberlake (2011), there was a significant investment on the Cellophane House project. We assume that a part of this investment may include the costs related to the end of life of the building; the disassembly, transport, and the storage of the components as they had to be dismantled, recovered, transported and stored with caution so they could be reassembled on other sites. These cost were partly paid back as the project was a zero waste project and there was no cost related to the waste management and disposal.

3.5.4 DIRTT

Figure 3.15. DIRTT partitions in an interior in Salk Lake City, Utah, DIRTT

Table 3.5. This table shows an overview of DIRTT manufacturing company.

Designer/ Company	DIRTT
Location, year	Calgary, Alberta, Canada, since 2005
Products	Prefabricated interior system
Design approach	Design for disassembly & reuse
Scale of the analysis	System level

3.5.4.1 Context analysis

Organizational (approach):

- Designer and manufacturer of standard prefabricated interiors adaptable to other standard systems and designs
- The company offers a verified Life Cycle Assessment and Environmental Product Declarations for its prefabricated modular walls

DIRTT (Doing It Right This Time), founded in 2005 by Mogen Smed (entrepreneur), Barrie Loberg (technology genius) and Geoff Gosling (designer), is a company that designs and manufactures prefabricated interior partition systems. The company's headquarters are situated in Calgary, Alberta, and the company has four manufacturing facilities; two in Canada (Calgary and Kelowna), and two in the U.S. (Phoenix and Savannah) (DIRTT, 2018). Several Green Learning Centers allocated to research and experimentations are strategically located throughout North America and the UK (DIRTT, 2018).

The company's idea is to design smarter and more flexible interiors that can be built faster with less waste than conventional methods. Through an unconventional design approach, DIRTT conserves materials with its special manufacturing techniques. DIRTT is a leader in manufacturing standard custom interior installations using fewer resources than typical manufactures (DIRTT, 2018). DIRTT's suite of solutions includes walls, millwork, power, networks, ceilings, doors and flooring. They are manufactured based on custom designs adapted to various tastes and aesthetics and can be used for any type of industry from healthcare facilities, kindergarten schools to commercial offices in different contexts (DIRTT, 2018).

DIRTT is known as "the first in interior prefab industry to standardize and complete Environmental Product Declarations (EPD)"[11] (DIRTT, 2018). The company has set the official international standard with the completion of a verified Life Cycle Assessment (LCA) and 15 EPDs for prefabricated modular walls (DIRTT, 2018). To prepare EPDs, that are similar to the nutrition labels on food, a life cycle assessment on environmental impacts of the products is required. Climate Earth is a third-party environmental data and software company responsible for creating LCAs on DIRTT's products (DIRTT, 2018). The assessment is performed across all stages from gathering raw materials to manufacturing, transporting, installing, disassembling, recycling, and landfilling (DIRTT, 2018). In the context of the extended producer responsibility (EPR) strategy, which requires that prefabricated products' producers remain responsible for their materials and products in the secondary market, DIRTT has an alternative lease option for its products (Smith, 2010). This option helps to reduce costs to a great extent especially for the secondary market and demands material and component stewardship during the lease time.

DIRTT is the winner of numerous national and international awards for innovation in design approach. The company won the 2015 Green Building Product Award offered by Canada Green Building Council's (CaGBC) for one of its interior wall system entitled 'Enzo.' For this product, DIRTT completed an LCA, created a global Product Category Rule (PCR) and had a third-party verified Environmental Product Declaration (EPD) completed (CaGBC, 2015).

[11]An Environmental Product Declaration (EPD) is an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products (Environdec, 2019).

3.5.4.2 Design approach

Sustainable measures applied:

- Design for disassembly and reuse based on the 'Support' and 'in-fill' concept.
- 3D modelling before manufacturing through company's exclusive ICE© software.
- Offering an alternative lease option for the products.

DIRTT's design approach is based on easy on-site assembly and disassembly of prefabricated components (Figure 3.16). It promotes assembly rather than construction and disassembly rather than demolition to optimize cost, time and the use of materials and diminish the quantity of waste.

Figure 3.16. This figure shows the DIRTT prefabricated modules ready to be assembled on-site in the Gaz Métro office in Montreal in 2017. Photo by S. Sadraee

The company designs for material optimization through three-dimensional coordination exercises. One of these exercises is 3D modelling through their exclusive software, ICE©, that presents the client's interior designed with DIRTT products prior to the fabrication of products. Space 3D modelling is a thoughtful way to eliminate dimensional conflicts that lead to extensive on-site waste, especially of off-cuts. Before manufacturing in a factory, ICE© calculates required materials based on 3D models. All the materials and components that arrive on-site are custom manufactured for that specific site based on ICE©'s calculations. In addition to material optimization, ICE© allows clients to visualize their remodeled interiors through a video game before making their orders. In terms of waste reduction, ICE© is a useful tool in the design and manufacturing processes. However, there are challenges in reusing and adapting custom designed partitions in different sites after disassembly. This issue will be discussed below in section 3.5.4.4.

DIRTT delivers prefabricated systems that are ready to be assembled and installed on-site. There is no need to apply a finish or to use chemical substances for the installation of its systems. Single coat finishes are applied in the manufacturing areas before shipping to the project site. This saves the time painters need on-site in conventional methods.

The company provides shop drawings to assemblers for on-site assembly. The assembly sequence is described in the documents. Components are marked with codes that correspond to a location in the shop drawings and on the site. DIRTT's products are standard and are compatible with other companies' products. For example, they can be used with Knoll's furniture and Joel Berman's glass products[12].

[12] The researcher collected this information during an in-situ observation at the Gaz Métro office in Montreal in April 2017.

3.5.4.3 Object analysis

- Architectural characteristics: the in-fill systems can be installed independent of buildings' structures.
- Assembly methods: reversible connection methods, no use of chemical fasteners thanks to the components' architecture, all the parts can be disassembled onsite without producing waste.
- Material selection: use of highly recyclable framing structure and finishing.

The DIRTT partition system, referred to as 'wall solutions' by the company, represents an in-fill system designed to be installed independently of the structure. The DIRTT partition system consists of a metal frame made of aluminum, solid wall tiles made of glass, medium-density fiberboard (MDF) or fabric tiles, and insulation made of cotton denim (Figures 3.17 & 3.18).

Figure 3.17. This figure shows the basic components of the DIRTT partition system, Burovision, Montreal, 2017. Photos by S. Sadraee

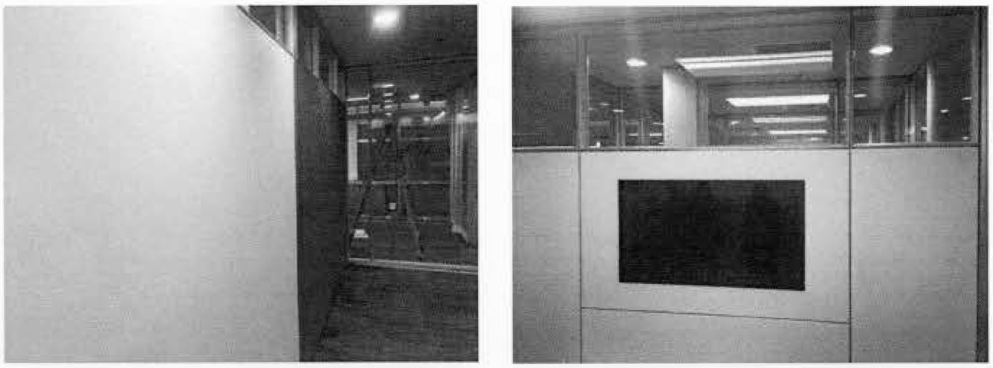

Figure 3.18. These pictures show fabric tiles, opaque and shiny MDF tiles, and glass panels installed on the metal framing in the Montreal Gaz Métro office, 2017. Photos by S. Sadraee

The glass panels slide into the metal frame, and the MDF or fabric tiles clip onto the framing structure. DIRTT's wall solutions incorporate electrical and plumbing systems (Figure 3.19).

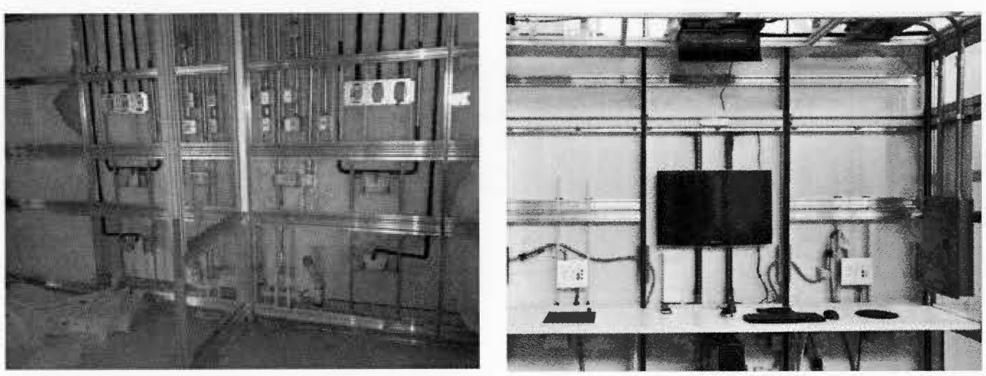

Figure 3.19. These pictures show that wiring, cabling and plumbing are incorporated in the partition system, © DIRTT

The attachment method of the DIRTT partition system to the structure is significant. Two metal studs, one on the ceiling and one on the floor, hold the prefabricated aluminum framing in place. As shown in Figure 3.20, a stud is horizontally perforated below the dropped ceiling and receives the sliding prefabricated aluminum frame.

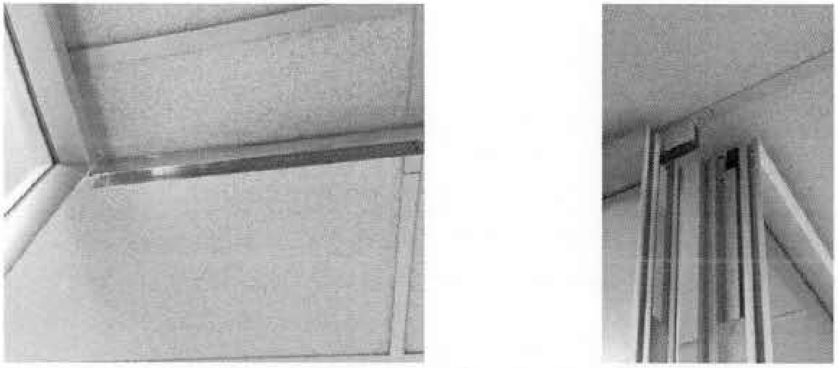

Figure 3.20. This figure shows how aluminum frame slide into a stud attached to the dropped ceiling, Burovision, Montreal, 2017. Photos by S. Sadraee

DIRTT uses a compression technique for the installation of the aluminum frame on the floor. A base plate on the floor holds and fixes the aluminum frame via screw jacks. The compression technique avoids perforating the floor or using chemical fasteners for the frame installation (Figure 3.21). This technique is especially advantageous for rental spaces if landlords require the space be maintained in the original condition. According to a personal interview[13] conducted by DIRTT, there is a definite cost reduction associated with vacating a building if DIRTT wall solutions are installed.

[13] This information was provided to the researcher by DIRTT in 2017.

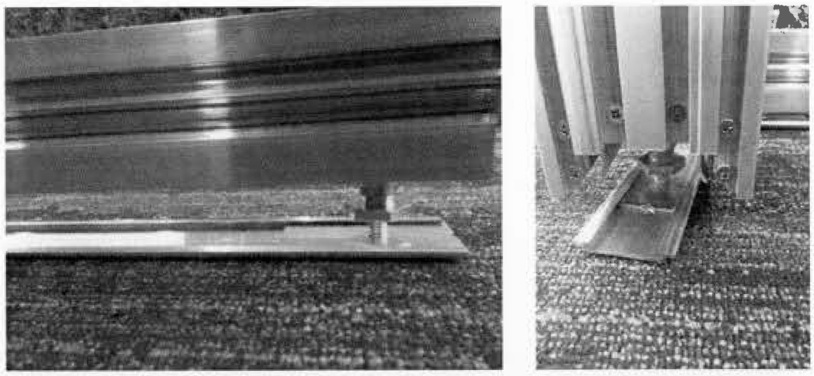

Figure 3.21. This figure shows how a screw jack fixes the aluminum frame on a horizontal stud on the floor, Gaz Métro, Montreal, 2017. Photos by S. Sadraee

Within the system, components are connected by mechanical fasteners. The frame is assembled using bolts and connectors shown in Figure 3.22. Separating panels slide or clip into the metal frame and can be easily removed and replaced. Figure 3.23 shows how prefabricated transparent laths are delivered to the site to be assembled on the metal channels.

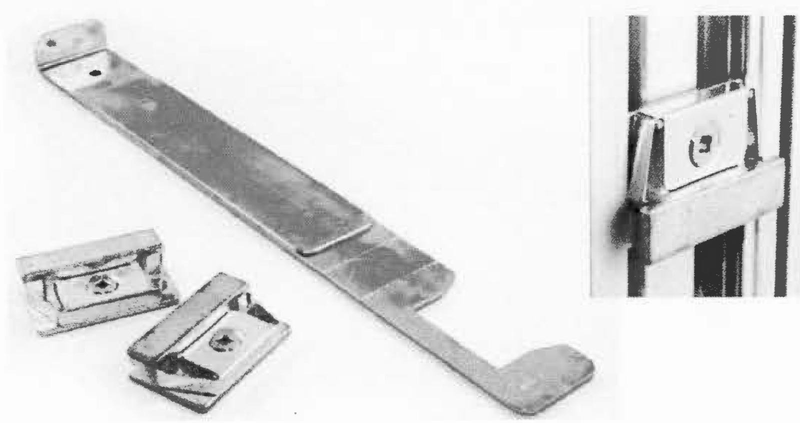

Figure 3.22. This Connector attaches the parts of the aluminum frame. © DIRTT

Figure 3.23. This figure shows the prefabricated and preassembled transparent laths, Gaz Métro, Montreal, 2017. Photos by S. Sadraee

All the materials that DIRTT specifies for its assemblies meet rigorous structural and environmental criteria to ensure human health and well-being (DIRTT, 2018). The company has several Green Learning Centers allocated to research and experimentations where they constantly explore and source new innovations for more environmentally conscious materials.

MDF tiles are offered in classical finishing or with a fabric or Willow Glass finishing. The finishing applied on the aluminum extrusions of the structure, and the MDF panels is a topcoat called Chromacoat which is a fine quality, water-based and thinly-sliced veneer (DIRTT, 2018). A zero volatile-organic-compound (VOC) adhesive is used to adhere the veneer to the aluminum frame (DIRTT, 2018). At the end of life of the system the veneer can be easily removed from materials, the aluminum frame and the glass can be recycled, and the MDF tiles can be reused if they are adaptable to other projects. DIRTT's glass-and-aluminum wall is SCS Indoor Advantage® Gold certified. SCS Indoor Advantage® is a certification for interior products in terms of VOC emissions. Advantage® Gold is recognized by EPA and qualifies for many building rating systems including LEED v4 and BREEAM (SCS global Services, 2019).

DIRTT claims to provide FSC-certified veneers and MDF. As an option in its material palette, DIRTT offers no-added-formaldehyde (NAF) MDF for wall tiles and millwork to clients concerned with VOC content (DIRTT, 2018). The DIRTT Wall with NAF MDF and standard Chromacoat conforms to several standard certifications.

3.5.4.4 Potentials of the design approach for waste reduction

Potentials provided by assembly methods, component architecture and selected materials for reuse and recycling and waste mitigation:

- Using ICE© software reduces offcuts during the assembly process.
- The geometry of the components and the connection methods allow for the disassembly, recovery and reuse of components.

DIRTT integrates strategies in planning, production and delivery of its products to mitigate the number of residual materials. Applying these strategies eliminates waste from the construction, operation and deconstruction phases and reduces waste in the manufacturing phase in the factory. In the production phase, DIRTT applies two efficient methods to reduce offcuts during the assembly process; it calculates the quantity and the dimensions of required materials through computer 3D modelling before manufacturing in the factory, and it supplies prefabricated and preassembled components ready to be installed onsite. These two methods make the construction phase a zero-waste process as there are no off-cuts or finishing residuals. During the operation phase and the end of life phase, the disassembly potential of the partition systems provides flexibility for spatial reconfigurations or deconstruction of the system. The disassembly of the partition system into its components allows for the reuse and recycling of the components and materials. Among the major aspects of DfD, the method for installing the prefabricated parts to the structure and the connection methods used to assemble components increase the potential for reuse and recycling. Using screw jacks to install the aluminum frame to the structure keeps the system independent of the structure. The partitions can be detached from the structure without causing damage or producing waste. Components can be recovered in their original state due to mechanical connections and can be reused in other projects. This extends the life cycle of components, makes systems more durable, decrease the amount of waste and fewer materials are needed to fabricate the same components for other projects. DIRTT has studied the recovery, reclamation and reuse of its products previously installed in its office in Calgary. According to Andree Iffrig[14] in a personal interview, during the renovation of its Calgary office, DIRTT recovered the interior partitions and donated them to Two Wheel View (TWV), a charity in Calgary that provides youth development and leadership programs. The entire system was disassembled in DIRTT's office and reassembled in the TWV space. As the entire partition system in the DIRTT's office was recovered and reassembled in another space, there was no cost related to waste management and the embodied energy of the materials was saved. This saving can recompense the high cost of the disassembly process.

Although DIRTT has implemented several measures to approach a zero-waste strategy, some existing challenges make some of the processes wasteful during the life cycle of its products. Fabricating partitions based on custom design is critical if their components are to be reused after disassembly in different spaces with different dimensions. Dimensional adjustments create offcuts. Offcuts of some materials like MDF cannot be recycled. MDF is an engineered wood that contains resins which cannot be separated from wood particles and makes recycling impossible. This challenge exists, especially in spaces that are not rectangular and have acute or obtuse angles. Using custom panels for these spaces make reusing them problematic.

During an interview in 2017, Iffrig confirmed that in terms of material selection, the company is searching for a recyclable material to replace MDF. The company is going through more recycled content each year (DIRTT, 2018). For example, the Savannah

[14] An interview was conducted with Andree Iffrig, DIRTT LEED AP in 2017.

factory is able to obtain the right quality of post- and pre-consumer recycled aluminum from suppliers in close proximity.

3.5.5 Mountain Equipment Co-op – Montreal store

Figure 3.24. Mountain Equipment store, Montreal, www.mec.ca

Table 3.6. This table shows an overview of the MEC store in Montreal.

Architect	Studio MMA, DFS Inc. Architecture, Lyse M. Tremblay Architect
Location, year	Montreal, Quebec, 2003
Project type, current situation	Retail store, Building in operation
Design approach	Energy & material efficiency
Scale of the analysis	System level

3.5.5.1 Context analysis

- Social: MEC is Canada's largest supplier of quality outdoor equipment, known for its environmental commitments in terms of products suppling, management and operation of its stores.
- Organizational (approach): The company is known for applying an integrated design approach in the design and operation of its buildings.

A. Mountain Equipment Co-op (MEC)

Mountain Equipment Co-op (MEC), founded in 1971 in Vancouver, British Columbia, is a Canadian consumer co-operative that sells outdoor recreation gear and clothing. The company has expanded and now operates stores in 22 cities across Canada (MEC, 2014). MEC is known as Canada's largest supplier of quality outdoor equipment and is known for its environmental commitments both in supplying its products, also in managing and operating its stores (MEC, 2019). MEC has applied adaptive reuse, which is reusing an existing structure on its original site, for some of the buildings it owns and leases (Gorgolewski, 2008). For example, the Victoria store is a former heritage hotel, and one of the Vancouver stores is a renovated former auto dealership (MEC, 2019).

MEC had the first and second retail stores in Canada (Winnipeg and Ottawa) to comply with the Natural Resources Canada C2000 Green Building Standard[15] (Ecohome,

[15]The C2000 Program for Advanced Commercial Buildings was a small demonstration program for high-performance buildings, developed and sponsored by the CANMET Energy Technology Center (CETC) of Natural Resources Canada. The emphasis of the program was on energy performance and water conservation. The program was launched in 1993 and its experience showed that the design process is the most important contributor to the realization of high-performance buildings. The knowledge and expertise resulting from this green building demonstration program are now serving to prepare Integrated Design Process (IDP) guidelines and energy performance assessment tools (Hydes, 2005).

2013). In 2010, the company launched the MEC Green Buildings System initiative through which it has been 'greening' its buildings and has become a leader in green buildings (MEC, 2019). MEC buildings are often known for their use of eco-friendly design features. Energy and material efficiency and minimum environmental impacts are highly considered in the design of its stores (MEC, 2007). Eight of the company's buildings in Winnipeg, Longueil, Burlington, North Vancouver and the Montreal office are designed to LEED Gold standards and the Head Office, located in Vancouver, is designed to a LEED platinum level (MEC, 2019). The Ottawa store is an early example where the architects applied DfD approach (Catalli & Williams, 2001).

MEC is a strong believer in reusing materials in the construction of its stores. According to a study by Gorgolewski, Starka, Edmonds and Sergio (2006), reclaimed steel components are seen in several recent MEC stores, including those in Toronto, Ottawa, Montreal and Winnipeg. For the Ottawa store, the company acquired the site with a 40-year-old two-story grocery store. By deconstructing the old building, the company recovered 75% of the materials and components, including the steel structure, and incorporated them into a new store (Gorgolewski et al., 2006).

In general, the company criteria for material selection are material durability, recycled content, energy efficiency, life cycle costs, low embodied energy and their potential of reuse (MEC, 2007). Other eco-friendly features, found in recently constructed MEC buildings, are green roofs, composting toilets, daylighting systems, recycled or reused materials, radiant flooring, efficient heating and cooling techniques and other energy-saving measures (MEC, 2019).

B. Montreal store

The Montreal store, which is the company's first store in Quebec, was opened in 2003 in Marché Central, an outdoor complex situated in the Ahuntsic-Cartierville borough of Montreal. The building was designed in 2002 by Studio MMA, an architectural firm founded in 1999 by Vouli Mamfredis and Rob Miners (Studio MMA, 2019). They also designed two other MEC stores in Longueuil and in Barrie, Ontario. The firm is a member of the Canadian Green Building Council and is committed to quality and sustainable design. The architects are both LEED Accredited Professionals, and their design philosophy supports the principles of sustainable development (Studio MMA, 2019). In their design, they encourage choices that favour durability, energy and water efficiency, effective use of site, responsible resource use and effective waste management (Studio MMA, 2019). In the 2000s, the Montreal store was among the few buildings with a green building label in Quebec and was the first commercial building in Quebec to conform to the National Research Council's C2000 Program for Advanced Commercial Buildings (Fortier, 2011; Studio MMA, 2019).

The Montreal store has distinctive characteristics due to the materials and energy-efficient technologies that have been used in its design. Reclaimed materials can be observed inside the building, while at the time the architects were designing the building ecological materials were rare in the market (Fortier, 2011). Moreover, many of the energy-efficient technologies used in the Montreal store were just emerging (Fortier, 2011). In an interview, Mamfredis mentioned that for the waste management of the Montreal store, the team had to go against the common practices in the building sector (Fortier, 2011).

3.5.5.2 Design approach

Sustainable measures applied:

- Designers applied an 'integrated approach' to optimize the use of daylighting and energy-saving methods.
- Recycled or reclaimed materials were used in the structure and interior partitions of the building.

The Montreal store is a high-performance building in terms of energy efficiency (MEC, 2019). Some of these measures optimize the natural lighting and ventilation and form an energy-efficient building envelope (Studio MMA, 2019).

The building has an open plan. The interior space is designed by a partition system that is entirely independent of the structure, and this provides flexibility for the interior layout. In different parts of the store reclaimed materials are used, especially in the partition system.

3.5.5.3 Object analysis

- Architectural characteristics: The open floor plan is designed with an in-fill system independent from the concrete structure.
- Assembly methods: The assembly method and the connection types allow for the disassembly of the interior systems.
- Material selection: 50% of materials used in the building contain recycled content, and reclaimed materials can be observed in many parts inside the building (MEC, 2019) .

The MEC Montreal store is a two-story building with a total surface area of 45,000 square feet (4,200 square meters) and a concrete frame structure. 50% of the materials used in the building contain recycled content by weight (MEC, 2019). The concrete slabs contain 27% blast furnace slag which is a by-product of steel manufacturing (MEC, 2019). Walls are insulated with cellulose fibre from recycled newsprint to cut down on energy consumption and they provide about twice as much thermal insulation as conventional retail buildings from the same era (MEC, 2019).

In the interior systems, reclaimed materials and components are used with no finishing. Rust, stains or holes in some parts confirm the use of reclaimed materials. The architects used the raw and unprocessed characteristics of reclaimed materials to create an unconventional aesthetic inside the building (MEC, 2019). Salvaged wood is used in many interior parts; in the entrance canopy, railings, partition system, and for the wood deck inside the curved roof of the building (MEC, 2019).

The following section will focus the analysis on the interior partition systems of the building to study the architects' intention for recovery and reuse of materials and components. In addition, the disassembly potential is only observed in the partitioning.

3.5.5.3.1 Partition system

The interior of the building is designed by an in-fill system installed independently of the concrete structure. It is possible to reconfigure the interior layout for different purposes thanks to the independence of the interior partitions from the main structure. In addition to the independence from the structure, all the components of the partition system can be disassembled. The disassembly potential of the partition system makes the interior of the building highly flexible and adaptable. The interior parts are assembled by mechanical fasteners which are exposed, accessible, and which have no finishing cover on them.

The interior partition system of the building is composed of a metal structure and separating panels which are mostly plywood, and in few places, natural wood and metal sheets. The aluminum frame is a strut system that serves as a partition system and display stands for products and holds items varying in size from small accessories to voluminous outdoor equipment. Figure 3.25 shows the different types of materials used for separating panels in the partition system.

Figures 3.25. This figure shows different materials used as separating panels, MEC store, Montreal, 2018. Photos by S. Sadraee

The standard strut channel system, known under the manufacturer trade name Unistrut, is a framing system that eliminates welding and drilling and provides fast assembly.

Unistrut products have been in the market for over 94 years since 1924 (Unistrut, 2017). These products were extensively used in nuclear, industrial and commercial construction markets (Unistrut, 2017). The system is presented as "the most complete and flexible support system" and "is committed to be the 'best' in the metal framing industry" (Unistrut, 2017). Generally, a strut system is used in the construction and electrical industries for light structural support, often for supporting wiring, plumbing, or mechanical components such as air conditioning or ventilation systems (Unistrut, 2017). Over time, the system has evolved into a comprehensive engineered building and support system which can serve light systems of product displays to heavy structural systems of partitioning and separations (Unistrut, 2017). The brand features a line of channels, fittings, fasteners, hangers, pipe clamps, and accessories (Unistrut, 2017).

Unistrut products include standard components that are adjustable and completely reusable for infinite configurations. Strut channels provide many possibilities for customized designs and are appropriate for configurations that need to be disassembled. They are designed to provide easy separation and have several advantages. Their design provides many available options for easily and rapidly connecting channels together and other items to the channels. The assembly requires minimal tools and moderately trained labor and the installation is cost-effective (Unistrut, 2017). The Unistrut system consists of three parts; 1) framing members or channels, 2) nuts and bolts, and 3) fittings.

1) Unistrut channels are basically made of stainless steel or aluminum. They are cold-formed from strips, folded over into an open channel shape with inwards-curving lips to provide additional stiffness and as a location to mount interconnecting components (Unistrut, 2017). Struts usually have holes of some sort in the base, to facilitate interconnection or fastening the strut to underlying building structures (Unistrut, 2017). Channels are

available in different widths from $1^{3/16}$ inch (20.6 mm) to $1^{5/8}$ inch (41.3 mm), where each type corresponds to a certain type of load.

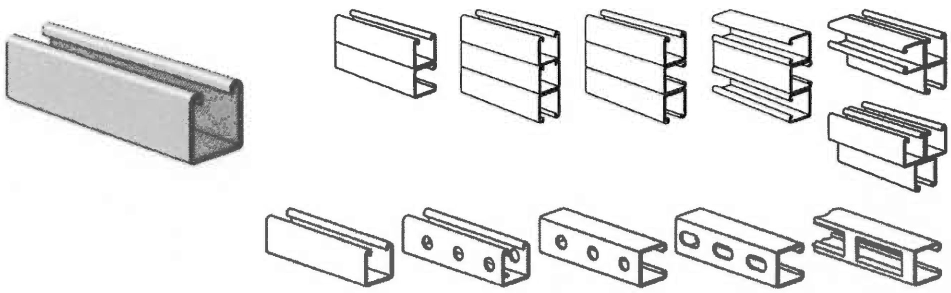

Figure 3.26. This figure shows different types and combination of strut channels, 2017 © Unistrut

2) Unistrut nuts are made from steel bars with a rectangular shape and ends shaped to permit a quarter turn clockwise in the channel after insertion through the slotted opening in the channel. Two toothed grooves on the top of the nut engage the interned edges of the channel. A bolt fixes the nut within the framing member and prevents any movement in the channel (Unistrut, 2017) (Figure 3.27).

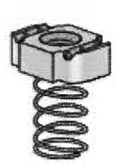

Figure 3.27. This figure shows the Unistrut nut (Unistrut, 2017).

3) Unistrut offers more than a hundred types of fittings. Fittings are used as connectors between channels for different configurations or to attach other objects to channels. Unistrut fittings are, in most cases, punch-press made

from hot-rolled, pickled and oiled steel plates, strip or coil, and conform to ASTM2 specifications (Unistrut, 2017).

The basic assembly concept is the connection of a simple spring nut and a fitting to a continuous channel. Figure 3.28 shows how three principal members of a strut system are connected.

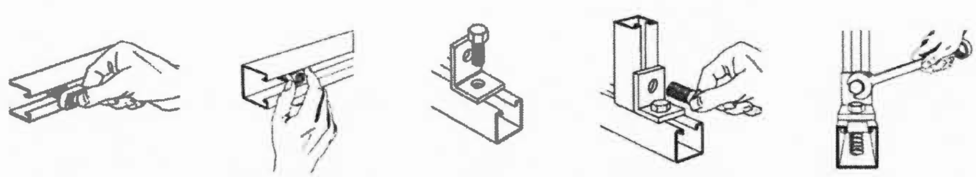

Figure 3.28. This figure shows how a Spring nut is fixed to a channel by a bolt (Unistrut, 2017).

3.5.5.3.1.1 Strut system in the MEC building

The channel series used in the partition system in Montreal store is the 1 $^{5/8}$-inch (41.3 mm) width series, a solid channel category appropriate to support heavy loads and for the widest variety of mechanical, electrical and general construction applications (Mountain Equipment Co-op). Each channel is $1^{5/8}$ inch by $1^{5/8}$ inch by 10 feet (Unistrut, 2017) (Figure 3.29).

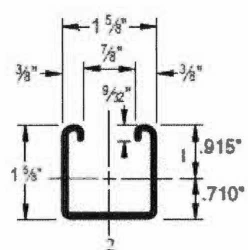

Figure 3.29. This figure shows the 1 $^{5/8}$-inch strut channel used in MEC partition system (Unistrut, 2017).

Few types of Unistrut fittings are used in the partitioning of the MEC store. In Figure 3.30, two types that were observed during the in-situ visit are shown.

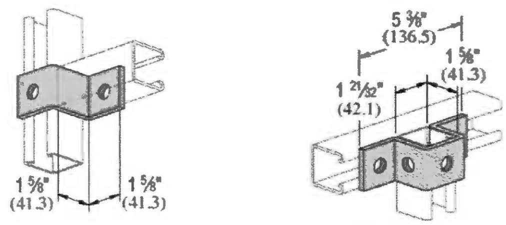

Figure 3.30. Two types of Unistrut fittings were observed in most parts of the partition system (Unistrut, 2017).

In addition to fixing the channels to the structure and connecting them together, fittings attach the separating panels (plywood sheets, reclaimed wood and metal) to the metal frame in the MEC building (Figure 3.31 & 3.32).

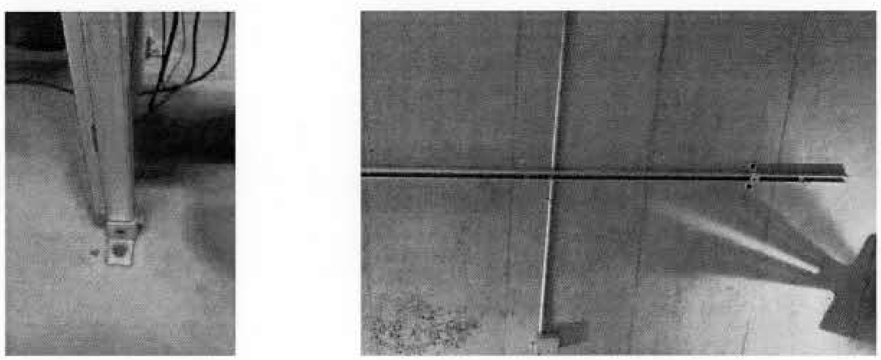

Figure 3.31. This figure shows how the strut system is fixed to the concrete slabs by bolts and fittings, MEC store, Montreal. Photos by S. Sadraee, 2018.

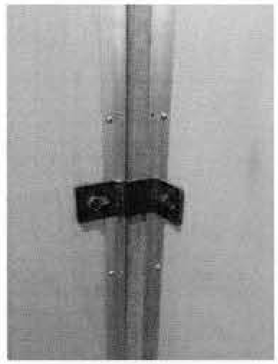

Figure 3.32. This figure shows how fittings attach the separating panels to the metal frame, MEC store, Montreal. Photo by S. Sadraee, 2018.

The interior partitioning of the MEC building presents several characteristics of DfD. The system is flexible because it is independent of the structure and is composed of independent modules. Modules are connected with reversible and mechanical fasteners that are exposed and accessible. This section shows the simulation of the partition system disassembly, and then, an in-depth analysis answers the following question: *What are the limitations of the connection method applied in the assembly of the partition system for reusing the components?*

The interaction between the components of the partition system shows some limitations of the assembly methods for reusing components. Figure 3.33 shows an exploded isometric view of the partition system in the MEC building. The partition system is composed of three basic components; 1) metal structure (strut channels), 2) separating panels (wood, metal sheets, etc.), and 3) connectors (fittings, bolts and nuts).

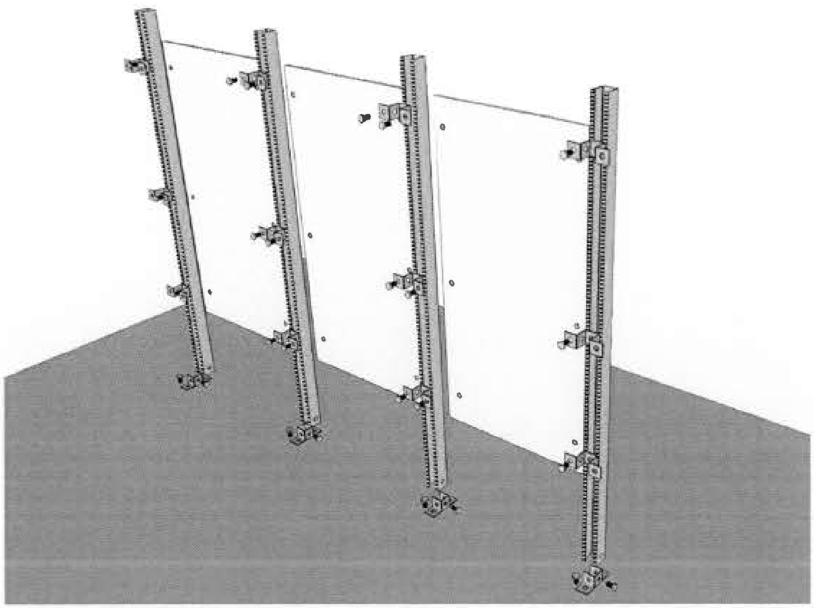

Figure 3.33. This figure presents the exploded isometric view of the MEC partition system. Schema created by S. Sadraee, 2019.

The following method allowed an in-depth analysis of the interaction between the components. Each system and component is identified with a number. The number one is given to the partition system, number two is given to the floor system, and number three is given to the ceiling. Each component of the partition system has the number of the system (partition: 1) and a letter. '1a' refers to the channels, '1b' to the fittings, and '1c' to the panels. Figure 3.34 shows the partition system in detail and presents the identification of each component.

1: Partition system

1a: Channels

1b: Fittings

1c: Panels

2: Floor

3: Ceiling

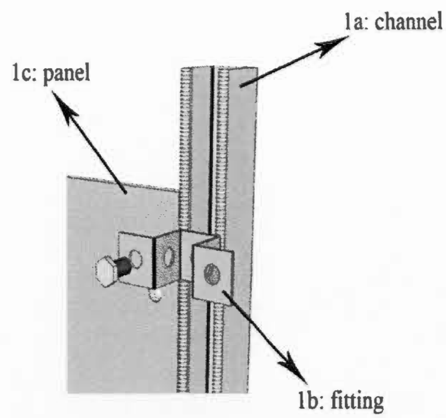

Figure 3.34. This figure presents the identification of components of the partition system. Schema created by S. Sadraee, 2019.

As shown in Figure 3.33, fittings and bolts attach channels to the concrete slabs and the components together. The technique used to connect channels to all kinds of surfaces is through drilling and anchoring to those surfaces. All the panels installed on the strut channels are perforated and attached by fittings and bolts.

Figure 3.35 shows the interaction between the partition system and the elements of the structure on which it is installed (Floor & ceiling), and Figure 3.36 shows the interaction between the components of the partition system.

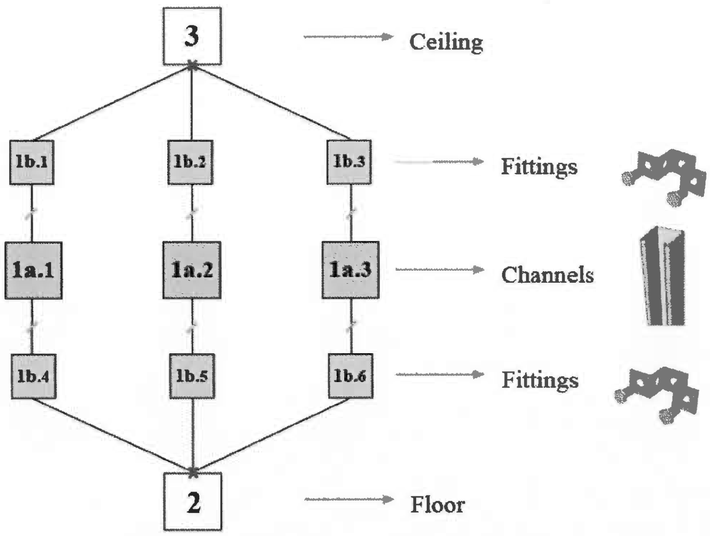

Figure 3.35. This figure presents the connection between channels and their connection to the ceiling and floor. The red 'Xs' represent physical damage of the concrete of the floor and ceiling after disassembly, and the green tick marks show that channels and fittings can be recovered intact. Schema created by S. Sadraee, 2019.

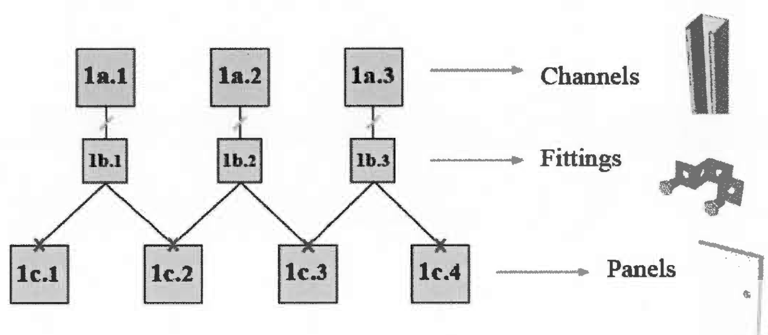

Figure 3.36. This figure illustrates the connection between metal structure and panels, the red 'Xs' present physical damage of panels after disassembly, and the green tick marks show that channels and fittings can be recovered intact, schema created by S. Sadraee,2019

In both figures, green tick marks show that the connection between the two elements can be split without affecting the physical properties of each component. This concerns the relationship between the metal studs and connectors or fittings. The strut system is designed in a way that connectors slide into the inwards-curving lips of channels; they can be replaced and adjusted anywhere on the channel. Red 'Xs' on both schemas show that the separation of two components affects the physical properties of at least one of the components. In Figure 3.35, red 'Xs' show that the connection method used to secure the metal frame to the concrete structure affects the physical property of one of the components; in this case the concrete. Wedge anchors which are irreversible connections attach strut channels to the concrete slab forming the floor and ceiling. Once they are inserted into a hole in the concrete, a nut within the anchor is turned clockwise and fixed permanently (Pistorino, 2011). Detaching the metal frame from the concrete may break and damage the concrete of the structure. In Figure 3.36, red 'Xs' show the physical impact of the connectors which perforate panels to attach them to the channels. Using fittings and bolts to fasten panels to the frame creates holes on them. Panels with holes may be considered damaged as they have a lower visual quality than the original material.

3.5.5.4 Potentials of the design approach for waste reduction

Potentials provided by assembly methods, component architecture and selected materials for reuse and recycling and waste mitigation.

- No interior finishes.
- Easy dismantling instead of demolishing thanks to a mechanical connection.
- Possibility of recovering materials.

The disassembly simulation shows that the connection method applied to the partition system of the MEC building damages the structure and creates some barriers to the reuse of components and materials. Reclaiming panels is possible through cutting and removing holes which creates offcuts and makes the process wasteful. Although two aspects of DfD-mechanical connections and type of materials- are applied in the design, there may be a high quantity of residual panels at the end of life of the partition system. This point will be expanded in the discussion section.

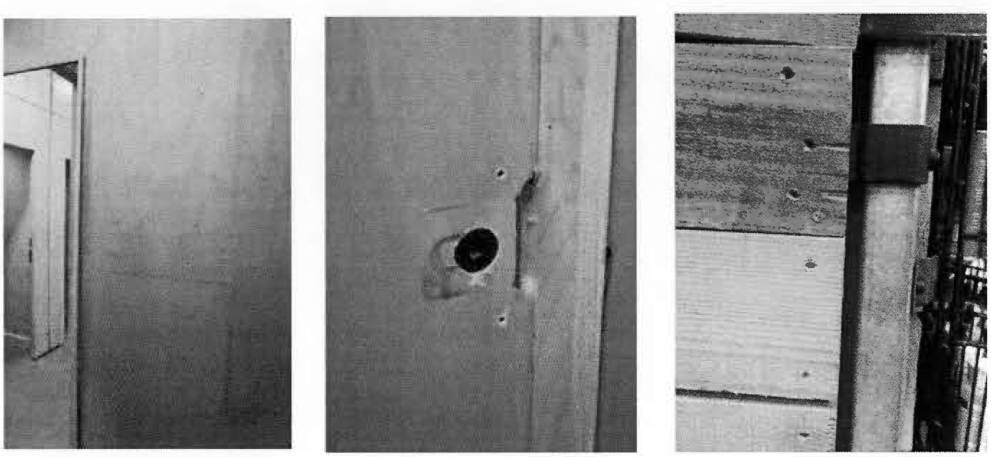

Figure 3.37. These photos present materials used in the partition system with hole marks, MEC store, Montreal. Photos by S. Sadraee, 2018.

3.5.5.5 Comparison of the MEC partition system with other cases and suggestions

Similar to the MEC partition system, Cellophane House and DIRTT both have an aluminum structural frame and panels attached to the frame. However, the disassembly processes in both cases showed that components can be recovered intact and can be reused. The same presentation method was used to show the interaction between the partition system in the structure for DIRTT systems and the relationship between the components of the partition system in Cellophane House.

As analyzed in section 3.5.4.3, using screw jacks to fix DIRTT partitions to the floor without anchoring or making holes allows the system to be uninstalled with less damage to the structure. Figure 3.39 shows the interaction between the partition system and the floor in a space where DIRTT systems are installed. To explain the diagram an exploded isometric view of the DIRTT partition system is presented in Figure 3.38.

1: Partition system

1a: aluminum channels

1b: screw jacks

1c: metal stud on the floor

1d: panels

2: floor

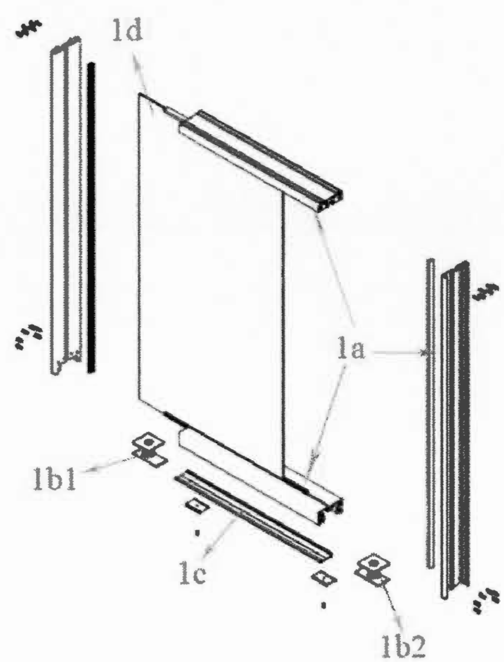

Figure 3.38. This schema shows the exploded isometric view of the DIRTT partition system and components identification. © DIRTT

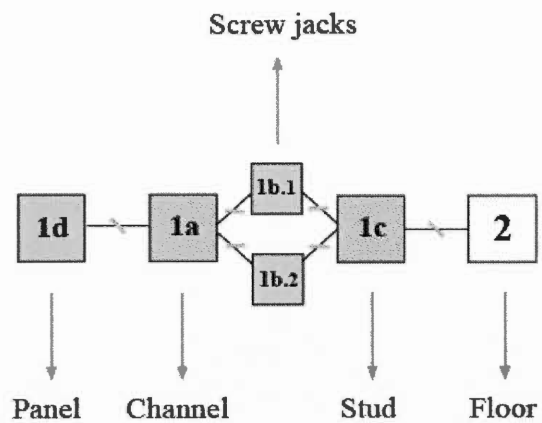

Figure 3.39. This schema presents the interaction between components of the DIRTT partition system and the floor. The green tick marks show that all the components can be separated and recovered intact. Schema created by S. Sadraee, 2019.

The relationship between the components in the partition system in Cellophane House is shown in Figures 3.40 and 3.41. The partition system in Cellophane House is composed of a metal frame, sliding panels and fasteners.

1: Partition system

1a: channels

1b: fasteners

1c: panels

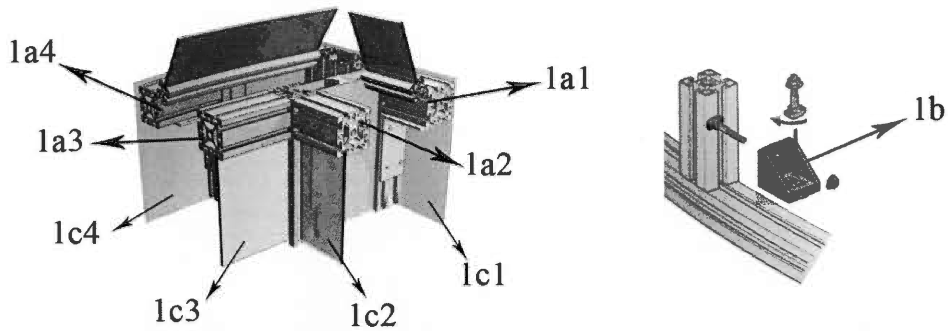

Figure 3.40. This figure shows the identification of components in the Cellophane House partition system (Kieran & Timberlake, 2011).

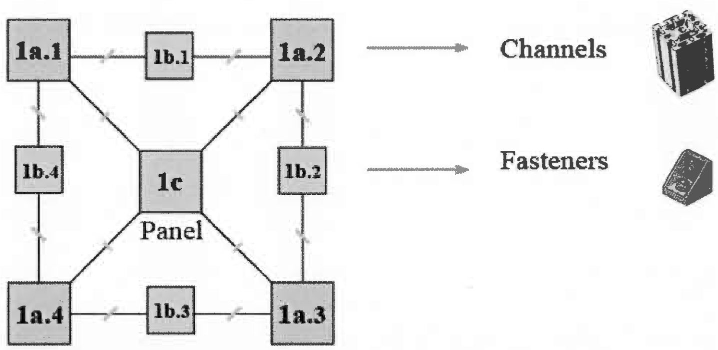

Figure 3.41. This figure presents the connection between components in Cellophane House, the green tick marks show that all the components can be separated and recovered intact. Schema created by S. Sadraee, 2019.

The schema in Figure 3.41 shows that the connection method used in this system does not affect materials physically. Green tick marks in Figure 3.41 show that all components in the partition system can be disassembled without affecting or damaging each other. Two factors allow for the separation of the partition system's elements with no physical changes; the architecture of the components and the type of connections.

The T-shaped slot designed in the architecture of the aluminum channels allows panels to slide into the slot and no connector is used to fix these two components together. The same principle is used for the gussets that attach two channels together. The gussets fix two channels together with T-bolts that slide into the channel T-slots.

The comparison between the partition system in the MEC store and systems used in Cellophane House and in DIRTT products show that, in terms of reducing waste, DfD is more effective if component assembly and connection methods are designed in a way that allows materials to be disassembled and recovered in the same physical state they were used the first time in a system.

In all the three systems, components are mechanically connected, and no adhesive or chemical substances are used. However, the methods applied in Cellophane House and DIRTT are distinguished from the MEC partition system because they allow for materials to be recovered in the state they were originally used in the systems after the systems are disassembled. No drilling, anchoring or any interaction causing holes or damage is used to connect components. Recovering intact components in their original state increases reuse potentials. By reusing components and materials we save raw materials, energy, the embodied energy of materials, and reduce the amount of waste.

The analysis of different assembly methods shows that not all of the mechanical fastening techniques that can be applied have effective results from disassembly. Using information technology for 3D modelling, and the simulation of assembly and disassembly of Cellophane House and DIRTT allowed for the visualization of the assembly and disassembly processes as well as the physical interaction between components before choosing materials and components and defining the connection techniques.

CHAPTER IV
DISCUSSION AND CONCLUSION

4.1 Discussion

The results of the case study reveal limitations for design for disassembly (DfD) to reduce waste and identify potential areas for improvements. The in-depth analysis of the partition system in the MEC building presented a gap between the theories related to DfD and its implementation. This analysis showed that the goal of DfD, which is to reduce the amount of waste by increasing reuse potentials, may not be achieved due to some technical inefficiencies in the design strategy. The analysis of other cases demonstrated opportunities to bridge the present gap in the MEC partition system.

Three major factors may influence the effectiveness of design for disassembly; 1) the context, 2) the assembly techniques and the architecture of the components, and 3) the selection of materials. The following questions related to these factors form the discussion framework: *How can context incentivize the designer to apply DfD? How should design for disassembly address assembly methods to reduce waste? How can the type of selected materials limit waste mitigation?*

As discussed previously in the methodology section and shown in experimental cases, context is a driving force for implementing design for disassembly efficiently. Efficiency in the implementation of DfD means that, in addition to planning for disassembly, the designer suggests the destination of materials and components after disassembly in the design phase, so that each material or component can be reused or entered into an identified recycling stream at the end of the building's life span instead of being sent to a waste stream. In the three experimental cases, context-related constraints motivated designers to design for disassembly and to plan for materials and components at the end of the buildings' operational life. For example, ICEhouse and Cellophane House designed respectively for the World Economic Forum annual meetings, and the MoMA exhibition are structures that were erected for short time periods on temporary sites. Their context associated with time and site constraints, required structures that could be mounted and demounted quickly, and strategies that could restore the sites in their original condition after the structures were disassembled. Both projects were zero-waste as all materials and components had been either reused or recycled after disassembly.

Office building vacancy in the Netherlands forms the context for the implementation of DfD in Office XX. High vacancy and demolition rates and large amounts of construction waste from office buildings in the Dutch context led to investigations and pilot projects to mitigate these effects. In these projects, buildings are designed with a shorter life span to preserve materials and reduce waste. The Office XX designer specified a 20-year life span for the building to prevent vacancy based on estimated functional life spans of office buildings in the Netherlands. He then applied assembly techniques so that the parts can be separated, and selected materials and components can be recovered and reused or recycled in the local streams.

The second important factor that influences the effectiveness of DfD is the assembly method and the architecture of the components. As discussed in Chapter 2, DfD suggests a system that has a high transformation capacity to provide flexibility and adaptability. A system with high transformation capacity should be composed of modular components assembled with reversible and mechanical connectors. In such a system, composite components should be avoided so parts can be changed independently, and fasteners should be accessible. In the literature, the separability potential of components and materials is presented as the basis for reusing components and reducing the quantity of waste. However, the result of the partition system analysis in the MEC store reveals that mechanical fasteners and reversible assembly methods, connecting modular and independent elements, provide disassembly potentials but they do not necessarily provide potentials for reusing disassembled components.

The MEC partition system is completely demountable and composed of independent modular elements. Parts are assembled with mechanical and reversible fasteners such as bolts and nuts that are accessible. No adhesive, glue or welding was applied to connect parts, and no finishing was applied on the components. However, the disassembly simulation shows that when bolts are removed, holes will remain in the separating panels. Components with holes may be considered damaged because of their lower physical and visual quality. Some of the plywood panels used in the current partition system have holes in them. Holes show that they had been recovered and reclaimed to be reused in the MEC partition system. Although these materials have been reused in this project, the reuse process cannot continue indefinitely in different use cycles. Perforating panels several times causes degraded visual and physical quality. Reclaiming damaged materials requires cutting and eliminating holes from the panels which is a wasteful process that creates offcuts. Moreover, it is challenging to adapt reclaimed panels to other projects as they lose their standard dimensions. This analysis confirms that the disassembly potential of buildings and their systems is not the only factor that makes components and materials reusable or recyclable. It highlights how the recovery of materials and components from a disassembly process is also a determinant for their reuse. It is important to note that material damage is not only limited to breaking or contaminating materials with hazardous substance. Any process that creates marks, holes or scratches on materials and components can be considered damage and makes materials and components un-reusable.

In Cellophane House, ICEhouse and DIRTT systems, in addition to the use of reversible connections, the shape and the architecture of components contributed to an efficient assembly, disassembly and recovery of components free of damage and physical degradation. Recovering components without physical damage increases the possibility for reuse. For example, in Cellophane House, using aluminum channels with T-shaped slots as negative receptors for sliding panels and T-shaped bolts is a method to connect components without making physical changes that would damage or degrade the quality of the components. Another example is the installation method of the DIRTT system in the space. Using screw jacks instead of wedge anchors for installing the aluminum frame to the main structure prevents damage to the structural elements.

The case analysis shows that in designing for disassembly, designers should not limit their consideration only to the type of connectors but should consider the interaction between materials and components. In systems where the interaction between components results in their physical or visual degradation, there are high risks that components cannot be reused, and will enter the waste stream. To recover materials without physical or visual degradation, designers should avoid assembly methods that perforate or cut materials. DfD is efficient in terms of reducing waste when it applies an assembly and connection method which allows for the recovery of components and materials intact after disassembly. DfD is not efficient if components or materials cannot be reused because they are considered damaged and waste due to small holes.

The third important factor that makes DfD effective is the type of materials that are selected. It is important to choose materials that can be returned to a local recycling stream if they cannot be reused in the state in which they are recovered and need to be repurposed. Therefore, in addition to strength, durability and cost, local availability and potential for future reuse and recycling in the local context were considered in material selection in experimental projects. Procuring materials from the local feedstock has the benefit that there are regulations for their management after use. The designers of ICEhouse are conducting research to adapt the frame to a variety of materials in different contexts so the structure can be erected using local materials which can enter the local reuse and recycling streams.

When designing for disassembly, to reduce waste, designers should not only focus on construction methods. Instead they should consider other factors, such as the estimated life span of the building and its systems according to the context in which the building is built, components they choose for systems, and the material selection. Integrating all of these factors into the design may make DfD successful in terms of demolition prevention and waste reduction.

4.2 Conclusion

Through different stages, this research project reviewed the current methods and practices of waste management and explored the DfD's potentials for waste reduction in renovation and deconstruction projects in the building sector. Various aspects of DfD were reviewed and a case study explored existing challenges for the implementation of DfD and opportunities for future improvements.

The first chapter provided a review of the waste management sector, policies, regulations, current methods and practices in Quebec to explore *how do policies and regulations contribute to diverting residual materials from landfills?* This review shows that over the last three decades the Quebec government has been adopting strategies to gradually shift the linear model of material consumption and management to a circular model in the construction industry. Therefore, government policies have principally focused on two practices of reuse and recycling. By increasing taxes on elimination practices, requiring certifications for material efficiency, banning some materials such as wood from landfills and developing markets for repurposed and recycled materials, the provincial goal regarding the recovery rate has been surpassed. Although, in Quebec, the reuse and recycling industry has developed and the diversion rate from landfills has risen in recent years, there are still several challenges to the efficient reuse and recycling of materials. We refer to efficient reuse and recycling as keeping materials in use cycles, using them for their original purposes and reducing the demand for raw materials. The current situation of wood management in Quebec shows the existing gaps in the reuse and recycling practices and the potentials for DfD implementation. Statistics on wood recovery and valorization show an inefficiency in reuse and recycling of wood in Quebec. The literature review shows that there are strict regulations regarding wood management in Quebec. Act 13 of the 2011-2015 Action Plan excludes all types of wood from elimination in landfills. All types of wood should be recovered, reused or recycled. However, we noted that in Quebec, only 37% of the recovered wood is recycled and a large portion (63%) is down-cycled and used for energy recovery. The management of engineered wood products which are commonly used in the industry is challenging. Recycling of engineered wood is a complex task as it contains resin and glue in its composition. This may be the cause of using recovered engineered wood for energy recovery. Combustion of wood for energy recovery destroys the physical and economic value of wood in addition to a part of the embodied energy in the material. Although wood is diverted from landfill, it is not used with its original properties and values. Moreover, as recovered wood is down-cycled for energy recovery, there is no reduction in the demand for raw wood. In addition to the complexity of recycling, in most cases, repurposed and recycled materials are more expensive than new materials available on the market (Mamfredis, 2017). This can cause lack of interest for recycled materials. The efficient reuse and recycling of wood is essential as wood (hardwood, softwood, engineered wood) is widely used in the building industry.

The existing gap in wood management represents an opportunity for designers; they can design to increase disassembly potentials in systems and parts built with wood so wooden components can be reused without entering a recycling stream.

The second section of the project presented a review of the relevant literature and a theoretical exploration of design for disassembly, its origins and principles. To explore *How design for disassembly considers waste mitigation in the decision and planning* *phases of a project*, we discussed different aspects of DfD such as flexibility and adaptability, transformation capacity, modularity and accessibility of components and parts, connection methods, and material selection. To examine DfD theories in practice, the case study section followed the literature review.

In Chapter 3 we carried out the case study to examine *what aspects of design for disassembly promote the reuse and recycling of components and materials?* The case studies showed that preserving materials for reuse in more than one life cycle requires reforming design methodologies. Designers can integrate strategies to preserve materials and components so they can be reused as products for their original purpose in other use cycles instead of being down-cycled for lower usages. The analysis of the interior partitions of the MEC store where a large number of plywood panels is used allowed us to identify the gap between the design and the recovery of the panels. We discussed earlier that the plywood panels used in the MEC store may be considered damaged because of the holes in them, and we assume that a large number of panels will be down-cycled or reused for a lower usage at the end of the partition system's operational life.

The DfD approach can be efficient in terms of reducing waste through reusing materials and components in more than one life cycle. Integrating disassembly potentials that favor reusing materials for their original purpose is especially essential for materials that cannot be easily recycled in local waste management facilities. Therefore, designers should focus on small-scale interventions such as assembly methods, component architecture, and material selection to increase the potential for reuse. Despite the lack of a standard framework for DfD and the complexity of its implementation as a method, designers can identify gaps and limitations in the waste management sector and consider them in their design to move towards a circular economy in the construction industry.

4.3 Recommendations

This research project presented an opportunity to explore potentials and limitations of design for disassembly to bridge existing gaps in the waste management sector in Quebec. Following this study, some potential future research directions are expanded on below.

Design for disassembly is an integrated design approach that requires the collaboration of a variety of professionals such as researchers, designers, architects, construction engineers, contractors, material suppliers, landlords, and the waste management sector during the whole life cycle of a building. In that regard, there should be instructions and directions for its implementation within a standard framework accessible to all the stakeholders mentioned. Moreover, DfD is an approach for the entire life cycle of a building, and it requires the stewardship of the building and its components and materials during its life span. As building ownership may be transferred several times during its life cycle, instructions should be provided by designers and engineers for the disassembly of parts when renovation or maintenance is required or for the end of life of a building. To develop a standard framework for DfD requires more research and the collaboration between designers and professionals in the waste management sector.

Regulations should require disassembly potentials in building codes because regulations can help to effectively implement design strategies. Disassembly potentials should also be required for construction permits or tax reduction. Moreover, certifications can incentivize owners, designers and contractors to consider design for disassembly. For example, LEED certifications that integrate DfD criteria could give points to buildings with disassembly potentials.

We noted that computer technology, such as 3D modelling has an important role in optimizing the manufacturing and use of materials and reducing offcuts. Disassembly simulation of buildings and systems through 3D modelling should also be a part of the design process so the disassembly sequences can be documented and accessible for the renovation or deconstruction phases. Moreover, aspects of DfD can be integrated into design programs and processes such as CAD or BIM.

I hope that this research project contributes to future research and to the development of a design approach for creating zero-waste buildings and systems.

REFERENCES

Arcspace. (2012, August 29). *Jean Prouvé: Tropical House*. Retrieved from Arcspace: https://arcspace.com/exhibition/jean-prouve-tropical-house/

ARUP. (2016, September 1). *Circular Economy in the Built Environment.* Retrieved 2017, from ARUP: https://www.arup.com/perspectives/publications/research/section/circular-economy-in-the-built-environment

Berge, B. (2009). *The Ecology of Building Materils* (2 edition ed.). (C. Butters, & F. Henley, Trans.) Amsterdam: Architectural Press.

Bogue, R. (2007). Design for disassembly: a critical twenty-first century discipline. *Assembly Automation, 27*, pp. 285-289.

Boisvert, M., Bosniak, D., & Dallaire, P.-O. (2014). Gestion des résidus du secteur de la construction, de la rénovation et de la démolition (CRD). Québec, Québec, Canada.

Bosma, K., Hoogstraten, D. v., & Voos, M. (2000). *Housing for millions : John Habraken and the SAR (1960-2000).* Rotterdam: NAi Publishers.

Brand, S. (1994). *How Buildings Learn: What Happens After They're Built.* New York: Viking Press.

Bureau d'Audience Publiques sur l'Environnement (BAPE). (1997). *Déchets d'Hier, Ressources de Demain.* Quebec: Bureau d'Audience Publiques sur l'Environnement.

Bureau de normalisation du Quebec (BNQ). (n.d.). *Aggregates- Recycled Materials Produced from Concrete Residues*. Retrieved from Bureau de normalisation du Quebec (BNQ): https://www.bnq.qc.ca/en/standardization/civil-engineering-and-urban-infrastructure/aggregates-recycled-materials-produced-from-concrete-residues.html

Canada Green Building Council (CaGBC). (2010). *LEED® Canada for new construction and major renovation.* Ottawa: Canada Green Building Council (CAGBC).

Canada Green Building Council. (2010). *Building Design and Construction.* Retrieved from Canada Green Building Council: https://www.cagbc.org/CAGBC/Programs/LEED/LEED_Canada_Rating_System/Building_Design_and_Construction_LEED_Canada_NC_v2009.aspx

Canada Green Building Council. (2015, June 4). *DIRTT Environmental Solutions' Enzo™ system announced as winner of the CaGBC 2015 Green Building Product of the year*. Retrieved from Canada Green Building Council: https://www.cagbc.org/News/EN/2015/20150604_News_Release_2.aspx

Canada Green Building Council. (2019). *Building Design and Construction.* Retrieved from Canada Green Building Council: https://www.cagbc.org/CAGBC/Programs/LEED/LEED_Canada_Rating_System/Building_Design_and_Construction_LEED_Canada_NC_v2009.aspx

Canadian Standards Association (CSA). (2004). *Draft CSA Guideline on Design for Disassembly and Adaptability in the Built Environment.* Mississauga: CSA.

Carroon, J. (2010). *Sustainable Preservation: Greening Existing Buildings.* New Jersey: John Wiley & Sons.

Casciato, M. (1997). Construction objective et prefabrication. *Les cahiers de la recherche architecturale, 40*, pp. 67-78.

Catalli, V., & Williams, M. (2001, January 1). *Designing For Disassembly*. Retrieved from Canadian Architect: https://www.canadianarchitect.com/designing-for-disassembly/

CMHC. (2003). *Recycle: Lifecycle- How to Renovate for Change.* Ottawa: CMHC.

CMHC. (2012). *Renovation and Home Purchase Report.* Ottawa: CMHC.

Commercial Real Estate Loans. (2018, June 25). *GLA: Gross Leasable Area in Commercial Real Estate*. Retrieved from Commercial Real Estate.loans: https://www.commercialrealestate.loans/commercial-real-estate-glossary/gla-gross-leasable-area

Conserve energy future. (2019). *The 'Reduce, Reuse, Recycle' Waste Hierarchy.* Retrieved from Conserve energy future: https://www.conserve-energy-future.com/reduce-reuse-recycle.php

Delta Institute. (2018). *Deconstruction & building material reuse: a tool for local governments & economic development practitioners.* Delta. Delta Institute.

DIRTT. (2018). *DIRTT's Sustainability Story.* Retrieved from DIRTT: https://www.dirtt.net/assets/attachments/119f43bd0e/DIRTTSustainabilityStory_v1.pdf

Durmisevic, E. (2006). *Tranformable Building Structures : design for disassembly as a way to introduce sustainable engineering to building design & construction.* Delft University of Technology. Delft: Verheijen, A.P.J.M.

Durmisevic, E., & Yeang, K. (2009, november 6). Designing for Disassembly (DfD). *Patterns of Architecture, 79*, pp. 134-137.

Ecohome. (2013, October 1). *Green energy doors open 2013.* Retrieved from Ecohome: https://www.ecohome.net/events/1194/green-energy-doors-open-2013/

ÉcoRéno. (n.d.). *Produits.* Retrieved from ÉcoRéno: http://ecoreno.com/produits.html

Environdec. (2019). *The International EPD System.* Retrieved from Environdec: https://www.environdec.com/

Environment Canada. (2014). *Characterization & Management of Construction, Renovation & Demolition Waste in Canada.* Lake Louise: Environment Canada.

EPA. (2010). *Design for Disassembly in the Built Environment.* EPA.

Fikkert, R., & Otheguy, M. E. (2013). Design for Disassembly as a Method to Improve the Sustainability of Offshore Accommodations. *KOMtech Technology Review*, 91-103.

Fortier, R. (2011, April 28). *Le Mountain Co-op Equipment de Longueuil*. Retrieved from Voirvert: http://www.voirvert.ca/projets/projet-etude/le-mountain-co-op-equipment-de-longueuil

Friends of the Earth Europe. (n.d.). *OVERCONSUMPTION? Our use of ther world's natural resources.* Friends of the Earth Europe.

Gagné, S. (2008, November 08). *Donner une seconde vie aux résidus de construction*. Retrieved from Les affaires: https://www.lesaffaires.com/archives/generale/donner-une-seconde-vie-aux-residus-de-construction/499462

Geoffrey Holton & Associates. (n.d). *Avanced Framing Techniques: Optimum Value Engineering (OVE).* Retrieved from Geoffrey Holton & Associates: http://www.ghadesign.net/TOOL-AdvancedFramingTechniques_1.pdf

Giroux, L. (2014). *State of Waste Management in Canada.* Winnipeg: Canadian Council of Ministers of the Environment.

Gorgolewski, M. (2008). Designing with reused building components: some challenges. *Building Research and Information* , 175-188.

Gorgolewski, M. (2017). *Resource salvation: the architecture of reuse.* Wiley.

Gorgolewski, M., Straka, V., Edmonds, J., & Sergio, C. (2006). *Facilitating greater reuse and recycling of structural steel in the construction and demolition process.* Ryerson University. Toronto: Ryerson University.

Groat, L., & Wang, D. (2013). *Architectural Research Methods* (2 ed.). New Jersey: John Wiley & Sons.

Guequierre, N., & Kristinsson, J. (1999). Product features that influence the end of a building. In M. A. Lacasse, & D. J. Vanier (Ed.), *Durability of Building Materials & Components 8 : Service Life and Asset Management. 1*, p. 898. Ottawa: NRC Research Press.

Guy, B., & Ciarimboli, N. (2007). Design for disassembly: a guide to closed-looped design and building. (K. Hendrickson, Ed.) Pennsylvania, US.

Habitat pour l'humanité. (2019). *Centre de rénovation ReStore*. Retrieved from Habitat pour l'humanité: ReStore: https://habitatqc.ca/campaign/2019/index_fr.html

Habraken, N. J. (n.d.). *Open Building; brief introduction*. Retrieved from N. John Habraken: https://www.habraken.com/html/introduction.htm

Habraken, N. J., Boekholt, J., & Thijssen, A. (1976). *Variations: The systematic Design of Supports*. Cambridge, Massachusetts: The MIT Press.

Hub Culture. (2019). *Collaborate in a virtual state*. Retrieved from Hub Culture: https://hubculture.com/hubs/hub/projects/62/wiki/

Hydes, K. (2005). Energy Environment and Buildings. (p. 13). Montreal: McGill University.

Jackson, T. (1996). *Material concerns: Pollution, profit and quality of life*. Abingdon and Stockholm: Routledge and Stockholm Environment Institute.

Jeffrey, C. (2011, September). Construction and Demolition Waste Recycling. *A Litterature Review*. Halifax, Nova Scotia, Canada: Dalhouise University's Office of Sustainability.

Keeler, M., & Burke, B. (2009). *Fundamentals of Integrated Design for Sustainable Building.* New Jersey: John Wiley & Sons.

Kendall, S. (1999). Open Building: An Approach to Sustainable Architecture. *Urban Technology*, 1-16. Retrieved October 05, 2016

Kendall, S. (2015). *Reflections on the History and Future of the Open Building Network.*

Kibert, C. J. (2013). *Sustainable Construction* (third edition ed.). Wiley.

Kieran, S., & Timberlake, J. (2011). *Cellophane House™.* Philadelphia: KieranTimberlake.

Kyle, B. R., Foo, S. H., & Torrey, D. (2012). *Standards Development Leading to Change in Design and Deconstruction Practices.*

Légis Québec. (2019, January 1). *Q-2, r. 43 - Règlement sur les redevances exigibles pour l'élimination de matières résiduelles*. Quebec: Publications Québec.

Légis Québec. (2019, January 1). *Q-2, r. 19 - Règlement sur l'enfouissement et l'incinération de matières résiduelles*. Quebec.

Légis Québec. (2019, April 1). *Publications Québec*. Retrieved from Légis Québec: http://legisquebec.gouv.qc.ca/fr/ShowDoc/cr/Q-2,%20r.%2035.1

Lehmann, S., & Crocker, R. (Eds.). (2012). *Designing for Zero Waste: Consuption, Technologies and the Built Environment* (1 edition ed.). London: Routledge.

Mamfredis, V. (2006). *Gestion de déchets CRD sur un chantier résidentiel urbain - Projet Cuvillier.* Montreal: Studio MMA.

Mamfredis, V. (2017, January 6). Gestion de déchets de construction. (S. Sadraee, Interviewer) Montreal.

Marshall, C., & Rossman, G. B. (2010). *Designing Qualitative Research* (5 ed.). Thousand Oaks: SAGE Publications.

McCarthy, J. (2018, May 14). *The US Is Rapidly Running Out of Landfill Space.* Retrieved from GLOBAL CITIZEN: https://www.globalcitizen.org/en/content/us-landfills-are-filling-up/

McDonough, W., & Braungart, M. (2002). *Cradle to Cradle: Remaking the Way We Make Things.* New York: North Point Press.

Mckinsey & Partners. (2015). *Growth within: A circular economy vision for a competitive Europe.* Mckinsey & Partners, Ellen McArthur Foundation.

MEC. (2007). *Greening our operations.* MEC. Retrieved from https://www.mec.ca › MEC_Acct_Report_Ch5_v2_m56577569831501454

MEC. (2014). *2014 MEC Annual Report.* Vancouver: MEC.

MEC. (2019). *Green building features.* Retrieved from MEC: https://www.mec.ca/en/stores/montreal?utm_medium=organic&utm_source=google&utm_campaign=my-business-listings&utm_content=montreal

MEC. (2019). *Green Building Features*. Retrieved from MEC: https://www.mec.ca/en/stores/victoria?utm_medium=organic&utm_source=google&utm_campaign=my-business-listings&utm_content=victoria

MEC. (2019). *Mission and values*. Retrieved from MEC: https://www.mec.ca/en/explore/mission-and-values

Melnyk, R. (2016, January 21). *Building Strategies+Sustainability*. Retrieved from REMI network: https://www.reminetwork.com/articles/designing-buildings-for-better-waste-management/

Ménard, K. (2008). Un regard sur la Politique québécoise de gestion des matières résiduelles 1998-2008. In Collective, *L'état du Québec 2009* (pp. 239-244). Montreal: Fides.

Millette, J. (2010). Réemploi des résidus de construction, de rénovation et de démolition au Québec. Université de Sherbrooke.

Ministère de l'Environnement et Lutte contre les Changements Climatiques. (2019). *Sustainable development: historical markers*. Retrieved from Ministère de l'Environnement et Lutte contre les Changements Climatiques: http://www.environnement.gouv.qc.ca/developpement/reperes_en.htm

Ministère du Développement durable, de l'Environnement et des Parcs (MDDEP). (2011). *Politique Québécoise de gestion des matières résiduelles : Plan d'action 2011-2015*. Quebec: Ministère du Développement durable, de l'Environnement et des Parcs.

MoMA. (2008, July 14). *Home Delivery: Fabriacating the Modern Dwelling.* Retrieved from MoMa: https://www.moma.org/calendar/exhibitions/50

Morneau, L. (2009). *Les résidusde construction, de rénovation et de demolition.* Québec: RECYC-QUÉBEC.

Mountain Equipment Co-op. (n.d.). *Project Directory.* Mountain Equipment Co-op.

Ordonez, I., & Rahe, U. (2013, March). Collaboration between design and waste management: Can it help close the material loop? *Resources Conservation and Recycling*, pp. 108-117.

Pistorino, M. (2011, May 31). *How Wedge Anchors Work.* Retrieved from Concrete Fasteners: https://www.concretefasteners.com/diy-articles-how-wedge-anchors-work

Project XX. (2019). Retrieved from Mi Modern Architecture: https://www.mimoa.eu/projects/Netherlands/Delft/project%20XX

Q-2, r. 19. (2005). Règlement sur l'enfouissement et l'incinération de matières résiduelles (REIMR). Québec: Légis Québec. Retrieved from Règlement sur l'enfouissement et l'incinération de matières résiduelles (REIMR)

Q-2, r.43. (2006). Règlement sur les redevances exigibles pour l'élimination de matières résiduelles. Québec: Légis Québec.

REBRI. (2014, March). *REBRI Guides.* Retrieved from Branz: https://www.branz.co.nz/cms_display.php?sn=240&st=1&pg=12648

Recycling Council of Alberta. (2014). Characterization & Management of Construction, Renovation & Demolition Waste in Canada., (pp. 1-22). Lake Louise.

RECYC-QUÉBEC. (2014, February 12). *Bourse des résidus industriels du Québec: nouveau service de mise en valeur et de recherche de débouchés des résidus CRD*. Retrieved from RECYC-QUÉBEC: https://www.recyc-quebec.gouv.qc.ca/haut-de-page/salle-de-presse/archives-presse/2014-bourse-residus-industriels

RECYC-QUÉBEC. (2016). *Appel de proposition sur la reduction a la source: Ecogestion de chantier.* Quebec: RECYC-QUEBEC.

RECYC-QUÉBEC. (2018). *Residus de construction, de renovation et de demolition (CRD).* Quebec: RECYC-QUEBEC.

Regroupement des Récupérateurs et des Recycleurs de Matériaux de Construction et de Démolition du Québec (3R MCDQ). (2019). *Le 3R MCDQ*. Retrieved from 3R MCDQ: https://www.3rmcdq.qc.ca/le-3r-mcdq/a-propos

Remøy, H. T. (2010). *Out of office.* Amsterdam: IOS Press.

RiDR. (2016). *Lieu d'enfouissement.* Retrieved from RiDR: http://www.ridr.qc.ca/site/le-lieu-denfouissement/

Rios, F. C., Chong, W. K., & Grau, D. (2015). Design for Disassembly and Deconstruction - Challenges and opportunities. *International Conference on Sustainable Design, Engineering and Construction* (pp. 1296-1304). Chicago: Elsevier.

Rowley, J. (2002, November 1). Using Case Studies in Research. *Management Research News, 25*, pp. 16-27.

RPBW. (2019). *IBM Travelling Pavilion*. Retrieved from RPBW: http://www.rpbw.com/project/ibm-travelling-pavilion

Ruuska, A., & Häkkinen, T. (2014). Material Efficiency of Building Construction. *Buildings*, 266-294.

Sabic. (2016, June 14). *ICEhouse™ Building using Sabic's LEXAN™ sheet signifies innovation for the circular economy*. Retrieved from Sabic: https://www.sabic.com/en/news/4331-icehouse-building-using-sabic-s-lexan-sheet-signifies-innovation-for-the-circular-economy

Saotome, T. (2007). *Development of Construction and Demolition Waste Recycling in Ontario.*

SCS global Services. (2019). *Indoor Air Quality Certification*. Retrieved from SCS global Services: https://www.scsglobalservices.com/services/indoor-air-quality-certification

Smith, R. E. (2010). *Prefab Architecture.* New Jersey: John Wiley & Sons.

Studio MMA. (2019). *Mountain Equipment Coop Store - Marché Central*. Retrieved from Studio MMA: https://studiomma.ca/en/projects/commercial-office/mountain-equipment-coop-store-marche-central/

Thormark, C. (2001, May 22). *Recycling Potential and Design for Disassembly in Buildings.* Lund Institute of Technology. Lund: Lund Institute of Technology.

Thormark, C. (2007, January). Motives for design for disassembly in building construction. 607-611.

TU Delft. (n.d.). *TU Delft Campus*. Retrieved from TU Delft: https://www.tudelft.nl/en/technology-transfer/tech-investment/cooperation/tu-delft-campus/

Unistrut. (2017). *Literature.* Retrieved from Unistrut: https://www.unistrut.us/resources/literature

US EPA. (2018, October 16). *Fact Sheets on Designing for the Disassembly and Deconstruction of Buildings.* Retrieved from EPA: https://www.epa.gov/smm/fact-sheets-designing-disassembly-and-deconstruction-buildings

US EPA. (2019, February 15). *Energy Recovery From the Combustion of Municipal Solid Waste (MSW)*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/smm/energy-recovery-combustion-municipal-solid-waste-msw

USGBC. (2019). *LEED*. Retrieved from U.S. Green Building System: https://qas.usgbc.org/leed

USGBC. (2019). *Resources.* Retrieved from USGBC: https://www.usgbc.org/search?Search+Library=%22green+building+facts%22&Library=%5B%22Resources%22%5D

USGBC. (2019). *USGBC History*. Retrieved from U.S. Green Building Council: https://qas.usgbc.org/about/history

Vachon, J.-F., Beaulne-Bélisle, K., Rosset, J., Gariépy, B., & McGrath, K. (2009). *Profile de la gestion des débris de construction, rénovation et démolition (CRD) au Québec.* Montreal: Recyc Québec.

Vierra, S. (2016, September 12). *Green Building Standards And Certification Systems.* Retrieved from Whole Building Design Guide: https://www.wbdg.org/resources/green-building-standards-and-certification-systems

Ville de Montréal. (2019). *Environnement.* Retrieved from Ville de Montréal: http://ville.montreal.qc.ca/portal/page?_pageid=7237,75371973&_dad=portal&_schema=PORTAL

Ville de Montréal. (n.d.). *Environnement.* Retrieved from Ville de Montréal: http://ville.montreal.qc.ca/portal/page?_pageid=7237,75371973&_dad=portal&_schema=PORTAL

William McDonough + Partners. (2019). *ICEhouse™.* Retrieved from William McDonough + Partners: http://www.mcdonoughpartners.com/projects/icehouse/

William McDonough + Partners. (2019). *People.* Retrieved from William McDonough + Partners: http://www.mcdonoughpartners.com/team/

William McDonough. (2017, September 6). *Architects William McDonough + Partners and Universidad EAN Announce Project Legacy: Cradle to Cradle® Dedign Embraced in Colombia.* Retrieved from McDonough: http://www.mcdonough.com/architects-william-mcdonough-partners-universidad-ean-announce-project-legacy-cradle-cradle-design-embraced-colombia/

World Economic Forum. (2019). *History*. Retrieved from World Economic Forum: https://www.weforum.org/about/history

World Green Building Council. (2019, February 4). *William McDonough's ICEhouse constructed for fifth time at World Economic Forum Meeting in Davos*. Retrieved from World Green Building Council: https://www.worldgbc.org/news-media/william-mcdonough%E2%80%99s-icehouse-constructed-fifth-time-world-economic-forum-meeting-davos

Worldwatch Institute. (2019, June 28). *Mission*. Retrieved from Worldwatch Institute: http://www.worldwatch.org/mission

WRAP. (2009). *Material change for a better environment.* Retrieved from WRAP: http://www.modular.org/marketing/documents/designingoutwaste.pdf

WRAP. (n.d.). *Designing for deconstruction and flexibility case study: Project XX, Netherlands.* Banbury: WRAP.

Yin, R. K. (2017). *Case Study Research and Application, Design and Methods* (6 ed.). Thousand Oaks: SAGE Pblications.

Zelechowski, E. (2012, October 26). *Go Guide.* Retrieved from delta institute: https://delta-institute.org/delta/wp-content/uploads/DeconstructionAndReuseGoGuide2ndEd_Web.pdf

Zezhou, W., Liyin, S., Ann T.W., Y., & Xiaoling, Z. (2016). A comparative analysis of waste management requirements between five green building rating systems fornew residential buildings. *Cleaner Production*, 895-902.