Methodology for improving the net environmental impacts of new buildings through product recovery management

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

Chapter 4 has been incorporated within a paper that has been submitted for publication. The paper is co-authored by my supervisor (Dr. Carl Haas), Mansour Esnaashary Esfahani, a PhD student and myself. Dr. Haas and I developed the methodology and experimental design. I carried out the lab experiments, collected, and analyzed the experimental data, and assisted with the writing of the paper. The PhD student Mansour Esnaashary Esfahani developed the cost analysis for the proposed building models.

Chapter 6 has been incorporated within a paper that has been submitted for publication. The paper is co-authored by my supervisor (Dr. Carl Haas), a PhD student, Mr. Christopher Rausch, and myself. Dr. Haas and I developed the methodology and experimental design. I carried out the lab experiments, collected, and analyzed the experimental data, and assisted with the writing of the paper. The PhD student Christopher Rausch developed the framework related to modularization for selective deconstruction of buildings, and assisted with the writing of the paper.

Chapter 7 has been incorporated within a paper that will be submitted for publication. The paper is co-authored by my supervisor (Dr. Carl Haas), Dr. Rebecca Saari, a PhD student, Mr. Christopher Rausch, and myself. Dr. Haas and I developed the methodology and experimental design. I carried out the lab experiments, collected, and analyzed the experimental data, and assisted with the writing of the paper. The PhD student Christopher Rausch developed the framework related to retrieving BIM meta-data for adaptive reuse of buildings, and assisted with the writing of the paper. Dr. Rebecca Saari provided contributions towards the life cycle analysis and social carbon cost analysis described in this thesis.

Abstract

Buildings contribute significantly to the global environmental load caused by human activities. There has been a growing interest in improving a building's performance over all of the life-cycle stages (production, construction, operation, and End-of-Life [EoL]). Several studies have recognized the importance of the EoL stage in buildings in terms of sustainability and Circular Economy (CE). A methodology for improving the net environmental impacts of new buildings through Product Recovery Management (PRM) is presented in this thesis. It starts with a CE perspective that emphasizes the importance of adaptive reuse of buildings over new construction. Context is established with a relevant case study in the Waterloo Region. Then, product recovery planning methods that meet environmental life-cycle objectives as well as cost objectives are presented that enhance the attractiveness of adaptive reuse as an alternative. Validation of the proposed methods is achieved through functional demonstration with case studies. Together, these methods form a rational approach to improve the net environmental impact of buildings in our economy. The overall proposed framework in this thesis have demonstrated to be effective to improve sustainability in the construction industry by providing a better understanding of the net environmental impacts and economic potential benefits of buildings' adaptive reuse. Finally, this thesis marks a reference for the development of innovative user-friendly methods and tools for reducing inefficiencies in the process of adaptive reuse through PRM.

Keywords: adaptive reuse, sustainable development, circular economy, product recovery management, selective disassembly planning, deconstruction, life cycle assessment.

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Chapter 1: Introduction

1.1 Background and motivation

In an era of climate change mitigation and adaptation, efficient use of the earth's natural resources is considered as a practical means to increase sustainability in urban settlements. Buildings contribute significantly to the global environmental load caused by human activities. Buildings are the largest energy-consuming sector in the world. From a life-cycle perspective, the building industry is responsible for about 30% of global annual Greenhouse Gas (GHG) emissions and 40% of energy consumption (Unalan, Tanrivermis, Bulbul, Celani, & Ciaramella, 2016). Also, buildings are responsible for 32% of world resource depletion, 12% of water consumption, and 40% of waste to landfill (Langston, Wong, Hui, & Shen, 2008).

On the last two decades, there has been a growing interest in improving a building's performance over its life-cycle stages (production, construction, operation, and End-of-Life [EoL]) in order to move towards a more sustainable environment in the construction industry (Asdrubali, Baldassarri, & Fthenakis, 2013; Aye, Ngo, Crawford, Gammampila, & Mendis, 2012; Cabeza, Rincon, Vilarino, Perez, & Castell, 2014; Fay, Treloar, & Iyer-Raniga, 2000; Gustavsson & Joelsson, 2010; Kneifel, 2010; Ramesh, Prakash, & Shukla, 2010; Ramesh, Prakash, & Shukla, 2012; Zabalza Bribian, Valero Capilla, & Aranda Uson, 2011). Buildings play an important role in the total natural resource depletion and in the production of negative environmental impacts. Therefore, there is an urgent need to mitigate these undesirable problems arising from the neglecting of the direct or indirect processes involved along the chain supply of this sector.

Several studies have recognized the importance of the EoL stage in buildings, and the opportunity of their adaptive reuse as a superior alternative to new buildings in terms of sustainability and Circular Economy (CE) (Bullen, 2007; Cantell, 2005; Conejos, Langston, & Smith, 2015; DHUD, 2001; Douglas, 2006; Geissdoerfer, Savaget, Bocken, & Hultink, 2017; Highfield & Gorse, 2009; Huovila, 2007; Lacy & Rutqvist, 2015; Langston, 2008; Langston et al., 2008; Pomponi & Moncaster, 2017; Schultmann & Sunke, 2007; Tan, Shen, & Langston, 2014; Wilkinson, James, & Reed, 2009; Wilson, 2010). Adaptive reuse, identified as a process to improve the financial, environmental, and social performance of buildings, involves restoring and in some cases changing the use of existing buildings that are obsolete or are nearing their disuse stage (Bullen, 2007; Langston et al., 2008). There is good potential for enhancing the social, economic, and environmental benefits of adaptive reuse of buildings. The same methodologies used to quantify the social and economic benefits of new building projects have been applied to justify the feasibility of adaptive reuse. In a parallel way, technical regulations for adaptive reuse have been created in recent years under the rubric of "smart growth" and "smart codes" (Cantell, 2005; DHUD, 2001).

However, the current implementations of adaptive reuse rely on descriptive approaches with little objective measurement that depends on the intuition and experience of practitioners (Mohamed, Boyle, Yang, & Tangari, 2017; Sanchez & Haas, 2018a; Volk, Luu, Mueller-Roemer, Sevilmis, & Schultmann, 2018). Intuitive planning procedures are easy to apply but often lead to suboptimal plans. In a similar way, the lack of knowledge of monetizing environmental impacts produced during the process of adaptive reuse has led to underestimating and misunderstanding the complete financial value of the building stock. Hence, a well-known and widely accepted sustainability framework rooted in physics, as well as the development of user-friendly standardized procedures and tools for environmental and economic evaluation of adaptive reuse projects, can serve as the technical basis to characterize the benefits of adaptive reuse in a way that would be understood by the general public and that would have a credible scientific basis.

The potential benefits of adaptive reuse rely on the fact that it is possible to take away components from an existing asset and then repair, reuse, remanufacture, or recycle them. Planning for selective disassembly plays a key role in the adaptive reuse process, where the disassembly planning sequence and deconstruction methods for recovering targeted components, have to be performed efficiently. The field of planning for selective disassembly has been studied in the manufacturing industry over the last decade, with the purpose of improving the processes involved (S. Smith & Hung, 2015). However, the development of research on selective disassembly planning for buildings has been scarce and limited (Hübner, Volk, Kühlen, & Schultmann, 2017; Sanchez & Haas, 2018b).

1.2 Research objectives

Based in this motivation, the current study has the following objectives:

- Development of a capital project planning framework for adaptive reuse construction projects in terms of Circular Economy (CE).
- Development of a decision-making methodology for adaptive reuse of buildings, with a life-cycle perspective.
- Development of a technical framework for selective disassembly planning inside the adaptive reuse process.
- Development of structured strategies and methods that allows the quantification of benefits of adaptive reuse building projects through computer-aided semi-automated approaches during the disassembly planning stage of building assets.

These issues are addressed through four related parts of this thesis. First, an investigation of related studies, underpins the capital project planning framework for adaptive reuse of buildings and the research that must still be accomplished to enable a more CE in the capital projects sector (Chapter 3). Then an LCA-based decision-making methodology for adaptive reuse of buildings is developed with the purpose of evaluating the environmental and economic performance of adaptive reuse building projects, with a life-cycle perspective (Chapter 4). In the next stage, and as a contribution for improving the project planning for adaptive reuse projects, a user-friendly disassembly planning method for finding an efficient selective disassembly sequence for retrieving target components from buildings is developed and validated (Chapter 5) as well as a semi-automated selective deconstruction programming method for buildings (Chapter 6). In the final stage of this study, a multi-objective optimization analysis for minimizing the environmental impact and economic cost is developed for obtaining several effective selective disassembly plans for the adaptive reuse of an existing asset through the combination of different deconstruction methods (Chapter 7).

1.3 Research scope

The research proposed here is divided into three distinct phases. The phases and their corresponding objectives are illustrated in Figure 1-1.

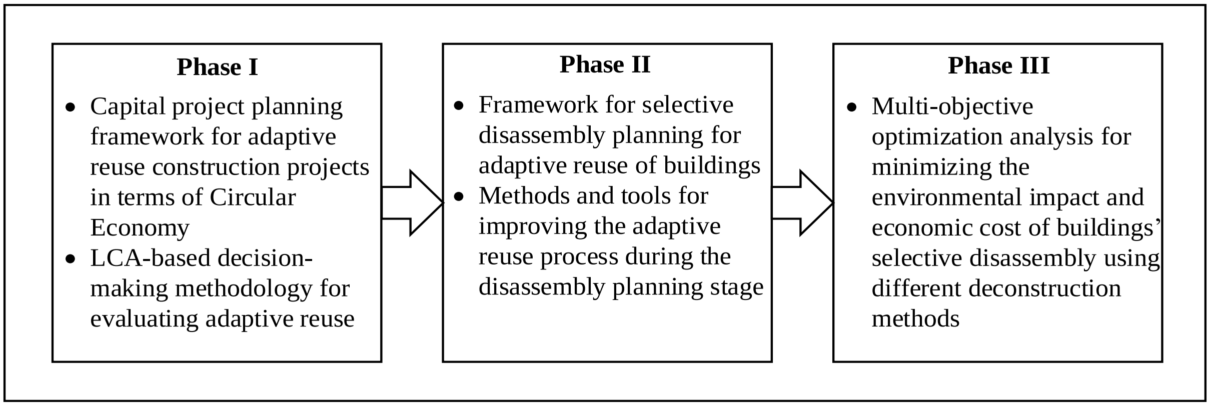


Figure 1-1: Research phases and corresponding objectives

In the first stage of this study, an overall framework of capital project planning for a CE is presented including the implications of circular building principles in capital project delivery as well as the key role that adaptive reuse of buildings plays into the CE construction value chain. Also, a comprehensive methodology for evaluating the benefits of adaptive reuse of existing assets is presented and validated in terms of LCA and CE. After establishing the importance of adaptive reuse in an overall scheme, in the second stage of this study the approach is narrowed down in order to develop tools and methods to improve the outcomes of adaptive reuse building projects through appropriate disassembly planning and deconstruction programming. The adaptive reuse building project outcomes are considered in terms of sustainability and CE in the construction industry. In the third and final stage, the concepts and methods developed in the previous stages are complemented with a multi-objective optimization analysis. The multi-objective analysis is carried out in terms of technical, environmental, and economic constraints.

1.4 Methodology

The methodology of this thesis for improving the net environmental impacts of new buildings through PRM is showed in Figure 1-2. The methodology starts with a CE perspective that emphasizes the importance of adaptive reuse of buildings over new construction, and context is established with a relevant case study in the Waterloo Region. Then, product recovery planning methods that meet environmental life-cycle objectives as well as cost objectives are presented that enhance the attractiveness of adaptive reuse as an alternative. Validation of the proposed methods is achieved through functional demonstration with case studies. At the end, conclusions, limitations, and areas for future research are presented.

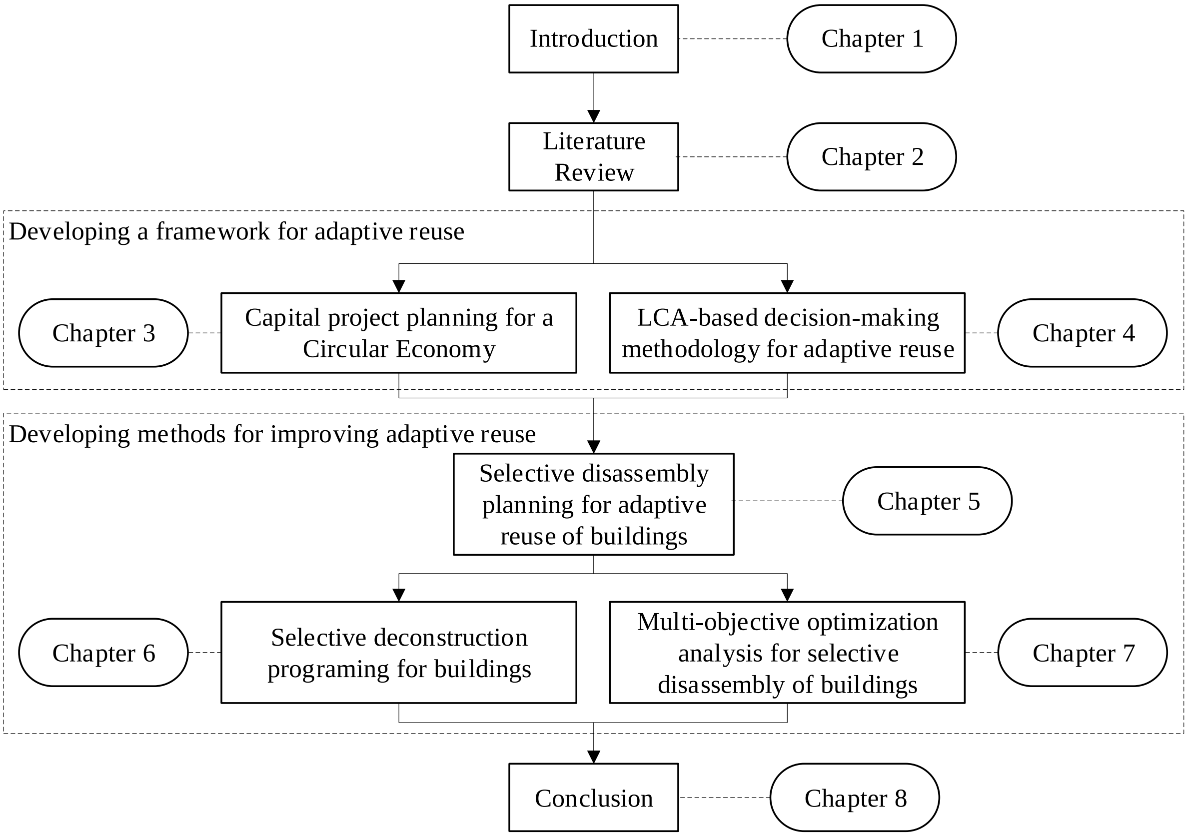


Figure 1-2: Thesis methodology and structure

1.5 Thesis organization

An outline of the thesis chapters is presented in Figure 1-2. Chapter 1 provides an overview of the research problem, motivation, objectives, scope, and structure of the thesis. In order to highlight the knowledge gap, the related literature and background is described in Chapter 2. The literature is investigated from different viewpoints toward the framework proposed in this research.

Chapter 3 of this study, starts with the argument of the main tenets of the CE in the construction industry with the purpose of creating a framework of 1) circular building features and principles to analyze the content of a pre-project planning tool for buildings and 2) CE principles in the construction value chain for greenfield construction and adaptive reuse of existing assets. In this chapter, it is argued that the early capital projects delivery phases for a CE should have distinct stages, decision gates, and more appropriate planning methods, such as selective disassembly, LCA monetization protocols, and optimization methods.

In Chapter 4, an LCA-based decision-making methodology for evaluating the performance of adaptive reuse building projects is presented. The purpose is to develop a well-known and widely accepted sustainability framework rooted in basic scientific concepts which can serve as the technical basis for characterizing the sustainability benefits of adaptive reuse in a way that would be understood by the general public and that would have a credible rational basis. The aim of this study is to develop a case study of the net environmental impacts and building cost performance of an adaptive reuse building project in the Region of Waterloo, Ontario, Canada.

In the subsequent three chapters of this thesis, computational tools and methods are developed with the purpose of assisting in minimizing the net environmental impacts, as well as the construction cost, in the process of adaptive reuse. The main goal is to recover as much of the economic and ecological value as possible during the selective disassembly process of existing assets, that are suitable for adaptive reuse. In Chapter 5 the first-in-its-class Sequential Disassembly Planning for Buildings (SDPB) method for adaptive reuse is presented. The SDPB method is used to generate optimized disassembly plans for retrieving targeted building components. The method seeks to minimize environmental impact and cost of the selective disassembly of building's components to retrieve, based upon physical, environmental, and economic constraints. In Chapter 6, the SDPB method is enhanced for the development of a multiple-target sequential disassembly planning model for buildings, as well as a novel approach for selective deconstruction programming for adaptive reuse. In Chapter 7 the selective disassembly study is extended with the purpose of including more than one deconstruction method per component. At the end, a weighted multi-objective optimization analysis is incorporated to generate the set of noninferior solutions that minimizes environmental impacts and building cost for the different alternatives.

Finally, Chapter 8 presents a summary of the findings and conclusions, as well as areas that have been identified for future research.

Chapter 2: Literature Analysis

The proposed model for improving the environmental and economic performance of buildings is based on the valuation of the built environment and the possibilities to take advantage of any residual benefit embedded in the components of an existing asset. An introduction to the basic concepts, general context, and some related prior studies are reviewed in this chapter to identify the knowledge gaps. The research is organized into two main topics 1) Sustainable Development and the Building Industry and 2) Designing for a CE in Construction. Each stream breaks down the necessary subtopics for understanding the potential benefits of improving the net environmental impacts of new buildings through Product Recovery Management (PRM). In the first section, the context, framework, and relevance of the proposed research are established. In the second section, the current advances in the matter as well as the emergent technologies applied in this context are presented in detail.

2.1 Sustainable development and the building industry

The term sustainable development or sustainability can be defined as the progressive development of human settlements that allows the inhabitants to live in a healthy environment, improving the social, economic, and environmental conditions for present and future generations. According to the International Institute for Sustainable Development (2016), sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainability is based on the simple principle that everything that humanity needs for survival and well-being depends, either directly or indirectly, on the natural environment (USEPA, 2016). The core of sustainability includes the environmental, social, and economic dimensions as equal. Therefore, the success of sustainable development depends on the proper integration and balance of these three objective dimensions.

The definition of sustainability has evolved during the last 40 years under the premise that it is possible to achieve economic growth and industrialization without environmental damage. During this time the mainstream of sustainable development thinking has been progressively developed through international historical agreements, such as, the United Nations Conference on the Human Environment in Stockholm in 1972, the World Conservation Strategy in 1980, the Brundtland Commission in 1984, the Montreal Protocol in 1987, the United Nations Conference on Environment and Development in Rio 1992, the Kyoto Protocol in 1997, the United Nations Framework Convention on Climate Change Conferences from 2007 to 2013, and the most recent United Nations Paris Agreement on Climate Change in 2016 (Adams, 2006; Keeler & Vaidya, 2016; United Nations, 2016). The understanding of the paradox of sustainable development, as well as the implementation of strategies to tackle this global concern has continuously changed due to technological advances and interdisciplinary applied research all around the globe. The world of today is facing immense social, economic, and environmental challenges like never before (UN, 2015). Billions of human beings live in poverty without a life of dignity due to the enormous disparities of opportunity, wealth, and power. There are rising inequalities within and among countries leading to global health threats, spiraling conflict, violent extremism, terrorism, wars, forced displacement of people, and humanitarian crises. More frequent and intense natural disasters, products of climate change, in synergy to natural resource depletion and adverse impacts of environmental degradation, including desertification, drought, land degradation, freshwater scarcity, and loss of biodiversity, have pushed to the limit the ecologic equilibrium in the Earth. Therefore, on April 2016 as part of the Paris Agreement, the United Nations General Assembly formally adopted the universal, integrated, and transformative 2030 Agenda for Sustainable Development, along with a set of 17 Sustainable Development Goals (United Nations, 2016). The 17 Sustainable Development Goals are:

1. End poverty in all its forms everywhere.
2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.
3. Ensure healthy lives and promote well-being for all at all ages.
4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
5. Achieve gender equality and empower all women and girls.
6. Ensure availability and sustainable management of water and sanitation for all.
7. Ensure access to affordable, reliable, sustainable, and modern energy for all.
8. Promote sustained, inclusive, and sustainable economic growth, full and productive employment and decent work for all.
9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
10. Reduce inequality within and among countries.
11. Make cities and human settlements inclusive, safe, resilient, and sustainable.
12. Ensure sustainable consumption and production patterns.
13. Take urgent action to combat climate change and its impacts.
14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
15. Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive institutions at all levels.

17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development.

Even though the accomplishment of these goals could sound challenging, there are high expectations to be met. The new generation of governments in alliance with civil society and business have embraced the idea of sustainability and have devised several novel strategies for increasing human welfare within natural resources constraints (Adams, 2006). This significant progress in the field of sustainability has been largely due to the spread of information and communications technology, the global interconnectedness, and scientific and technological innovation (UN, 2015).

The importance of buildings in the matter of sustainable development is such that three of the seventeen goals of the Paris Agreement transformative 2030 Agenda for Sustainable Development are related to them (United Nations, 2016). On one hand, buildings contribute significantly to the global environmental load caused by human activities. Buildings are the largest energy-consuming sector in the world. From a life-cycle perspective, the building industry is responsible for about 30% of global annual GHG emissions and 40% of energy consumption (Unalan et al., 2016). In absolute terms GHG emissions were estimated to be around 8.6 million metric tons CO_2 equivalent in 2004 (UNEP, 2009). Also, buildings are responsible for 32% of world resources depletion, 12% of water consumption, and 40% of waste to landfills (Langston et al., 2008). On the other hand, in economic terms construction is a major industry throughout the world accounting for a sizeable proportion of the Gross Domestic Product (GDP) for most of developed and underdeveloped countries (Crosthwaite, 2000). The building sector is estimated to be worth 10% of global GDP or $7.5 trillion USD. Also, the building industry employs 111 million people; on a global average that represents 10% of country-level employment (UNEP, 2016; UNEP, 2009). From 2011 to 2015 Canada’s construction industry accounted for from 7.2% to 7.5% each year of the national GDP, contributing $118 billion CAD in 2015 (Statistics Canada, 2015). Historically, the construction industry in Canada has been the largest industrial employer accounting for 1.4 million operatives in 2014 that represents the 7.7% of the total employment in the economy. Therefore, since the last five decades, the global building industry has been a main objective in terms of sustainability.

According to the United Nations Environmental Programme (UNEP, 2009) the building sector has the largest potential for significant reduction of GHG emissions compared to other major emitting sectors. With proven and commercial available technologies, and research in the field of sustainable building design, the natural resource consumption in both new and existing buildings can be cut with potential net profit during the building lifespan. The vision for sustainability in the building and construction sector is summarized in the next objectives according to the Sustainable Buildings and Construction Initiative hosted by the UNEP (2009):

- Buildings are routinely designed, constructed, and maintained to be optimized over their entire life span.
- Legislation and building standards include sustainability considerations and requirements.
- Environmental aspects are normally considered in any project and include short-term as well as long-term aspects.
- Policies and incentives provided by the government support sustainable building and construction practices.
- Investors, insurance companies, property developers, and buyers/tenants of buildings are aware of sustainability considerations and take an active role in encouraging such practices.

2.1.1 The role of sustainable building design in sustainable development

The contemporary definition of sustainable building design, or green building, stands for the integrated whole building approach, which considers life-cycle at all levels (Keeler & Vaidya, 2016). According to the US Environmental Protection Agency (USEPA): "Green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation, and deconstruction. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort" (USEPA, 2016b). Along the life-cycle of a building, natural resources are consumed including energy, water, land, and minerals. As part of the conventional processes, inevitably the outputs of this consumption is the generation of pollutants to the environment with the associated negative impacts like global warming, air pollution, damage on human health, among others. Green buildings aims to balance the natural resources consumption as well as its regeneration in order to secure the future of the next generations. According to Singh (2013), the primary objective is that buildings need to be designed under the premise of reducing the overall impact of the built environment on human health and the natural environment by 1) efficiently using energy, water, and other limited resources, 2) protecting occupant health and improving occupant productivity, and 3) reducing waste, pollution, and environmental degradation.

Buildings consume energy directly due to their operation along their lifespan, and indirectly due to the embodied energy in the materials and components (Ramesh et al., 2010). Energy use has been a widely used measure of the environmental impact of buildings. Energy use in buildings has been the most important parameter to optimize because of its global significance in gross terms (Fay et al., 2000). In 2010 buildings accounted for 32% of total global final energy use, 24% for residential, and 8% for commercial buildings

(IPCC, 2015). Improving energy efficiency in buildings encompasses the most diverse, largest, and most cost-effective mitigation opportunities in buildings (Intergovernamental Panel on Climate Change (IPCC), 2007). Also, energy consumption is the main reason of exploitation of natural resources and pollutant emissions (Beccali, Cellura, Fontana, Longo, & Mistretta, 2013). According to the UNEP (2009), GHG emissions from buildings primarily arise from their consumption of fossil-fuel based energy. In a life-cycle approach, the energy use during a building's operational phase accounts for 70-90% of the total, and it produces over 80% of GHG emissions, to meet the user's needs of heating, ventilation, air conditioning, water heating, lighting, entertainment, and telecommunications (Beccali et al., 2013; Ramesh et al., 2010; UNEP, 2009). The rest of the energy used, with its corresponding GHG emissions, is distributed in the phases of material extraction, construction, and EoL. A building's energy use is an appropriate simplified measure for the environmental impact because it takes away the complication in determining the impact by measuring emissions to the atmosphere and waste accumulation during the life-cycle (Schultmann & Sunke, 2007). These are the main reasons why most of the research in sustainable building design has targeted the operational phase of buildings, reaching extraordinary results.

It is well known that the largest savings in energy consumption along the life-cycle of a building occur for buildings that have been designed and operated as complete systems under the principles of sustainable building design. These principles include passive solar design, bioclimatic design, high-efficiency lighting and appliances, highly efficient ventilation and cooking systems, solar water heaters, high-performance building insulation materials, high-reflectivity building materials, suitable design for glazing, occupants' behavior, and appropriate green technology such as photovoltaic and wind energy systems (Intergovernamental Panel on Climate Change (IPCC), 2007; Keeler & Vaidya, 2016; Sanchez Andrade, Hoepfl, Garcia Maldonado, & Corona Vasquez, 2014). Depending on the integration of the sustainable building design with the green technology, the energy savings of a highly-efficient new building can reach 75% or even higher of the total operational energy consumption (Intergovernamental Panel on Climate Change (IPCC), 2007). In existing buildings, the energy savings have been reported from 50% to 90% through deep retrofits (IPCC, 2015). Despite the high potential that the operational phase in buildings has demonstrated and the notable progress in buildings' energy performance, this just represents a portion of the whole spectrum of sustainable building design.

A shift in thinking in the perception of sustainable building design has arisen in the last ten years, switching from a creative and innovative approach to a restorative and regenerative one. This change of perception is founded in the fact that an enormous proportion of all of the materials ever extracted along human history are in today's built environment and that the understanding of the real value of this built environment in terms of sustainability has improved through technological development and research in the field. As Yeung

(2016) points out, in the building industry there are two different types of monetary cost the stakeholders incur. Private cost is incurred by the owner, and public cost is assumed to be paid by society. The private cost is related to the material, labor, and machinery involved, among others. The public cost is related to the economic damages to society due to the negative effects of environmental impacts on agricultural productivity, human health, property damage, flood risk, and ecosystem services (Shindell, 2015). Novel research has been done to understand the complex dynamic of the environment and the global economy, as well as the monetization of environmental impacts produced by human activities (Shindell, 2015; Viscusi, 2005; Yeung, 2016). These studies aim to characterize the benefits of sustainability with a credible scientific basis in a way that can be understood by the general public. In this way, it can be possible to address the global environmental issues in a fair, effective, and equitable way. Consequently, growing research interest looks at improving buildings performance as well as reducing the negative environmental impacts over all life-cycle stages (production, construction, operation, and EoL) in order to move towards a real sustainable development in the construction industry (Asdrubali et al., 2013; Aye et al., 2012; Cabeza et al., 2014; Fay et al., 2000; Gustavsson & Joelsson, 2010; Kneifel, 2010; Ramesh et al., 2010; Ramesh et al., 2012; Zabalza Bribian et al., 2011).

Studies have revealed that the turn-over rate of buildings is quite low and does not exceed more than 3% yearly, so it will take perhaps up to a century or more, before the energy efficient strategies of new building construction can reach full potential to decrease the amount of GHG generated, from a global perspective (Beccali et al., 2013; Conejos, Langston, & Smith, 2014; Sandin, Peters, & Svanstrom, 2014; Wilkinson et al., 2009). In 2010 the total building stock in the United States was estimated at 300 billion ft^2 (27 billion m^2) and that 1.75 billion ft^2 (162 million m^2) of buildings were torn down while 5 billion ft^2 (464 million m^2) were renovated and/or newly built facilities every year. Also, it was reported that for every four commercial buildings constructed, one is demolished, and for every six houses built, one is demolished (Conejos et al., 2014). According to Yudelson (2009) approximately 75% of the buildings expected to be operating in the year 2040 are already built. Existing buildings that are approaching the end of their lifespan could become a “mine” of raw materials, since it is more effective to recuperate the components through PRM than extracting the raw materials to produce new ones (Langston et al., 2008; Schultmann & Sunke, 2007). The main goal of PRM is to recover as much of the economic as well as ecological value of a product and its components as possible (Schultmann & Sunke, 2007). Conejos (2014) claims that demolition and new construction of energy-efficient buildings would require decades to equal the energy savings of rehabilitating and reusing existing buildings. Hence in a life-cycle perspective, the largest portion of natural resources savings as well as the minimization of the environmental impacts are in retrofitting and redeveloping existing buildings rather than producing new energy-efficient buildings (Conejos et al., 2014; Intergovernamental Panel on Climate Change (IPCC), 2007).

Likewise, the relative importance of the production, construction, and EoL stages of the life-cycle of buildings has increased because of the reduction of the energy loads in the operational phase and the trade-off between the operational energy and the embodied energy (Beccali et al., 2013). This trade-off means that in the way that a building can achieve high energy-efficiency levels through a set of energy retrofits, the committed embodied energy will increase due to the higher environmental burden during the production, on-site construction, transportation, final demolition, and final disposal of these energy retrofits (Jalaei & Jrade, 2014). Thus, the lower the operational energy, the more important it is to adopt a life-cycle approach for sustainable building design, in order to reduce the amount of waste at the end of a building's life as well as to avoid or at least to reduce the rate of depletion of resources (Blengini & Di Carlo, 2010). There is a need for effectively upgrading older building stock based on the amount of consumed resources and materials (Conejos et al., 2014).

Finally, the price of materials extraction is increasing as are the negative environmental impacts due to the natural constraints of the more dilute and distant stocks of ores and other resources (Kibert, 2007). The reasons mentioned, a relatively new area of research in sustainability in construction has focused on emerging themes such as deconstruction, durability, adaptability, design for the environment, design for deconstruction, closed materials loops, dematerialization, and PRM (Kibert, 2007; Langston et al., 2008). This trend will keep gaining more and more relevance in the construction industry in the way that the cost of natural resources and environmental impacts increases as well (Yeung, 2016).

2.1.2 Sustainability measurement tools for buildings

To achieve sustainability in building industry it is necessary to assess the environmental, economic, and social performance of human settlements and buildings along their life-cycle, which will support the appropriate decision-making of the stakeholders. Srinivasan et.al. (2014) described some of the most relevant building assessment methods in the matter of sustainability as well as a novel classification for them. Their classification is based on the analysis criteria and the targeted objectives of each one of the assessment methodologies.

Building assessment methods have accelerated the shift from conventional practices to high-performance green buildings in an attempt to enhance sustainability on the building industry. Two of the most commonly adopted assessment methods in North America are Green Building Initiative's Green Globes and Leadership in Energy and Environmental Design or LEED^{TM} (Kibert, 2007; Srinivasan et al., 2014). One of the main reasons of their acceptance in the market has been the simplification of the analysis, due to the adopted approach of a single-number scoring system (Jalaei, 2015). This approach means that the scoring system results in a single number that determines the final score or rating of the building under analysis. The rating of the building is determined by the accumulation of points from a set of credit requirements defined by the assessment system. In the end, it is claimed that the more points the building earns, the more energy efficient and sustainable it is. In spite of their success, the referred assessment systems, like many other similar in the market, lack a scientific framework that underpin them. These systems have been developed using a consensus-based approach that focuses on market transformation (Kibert, 2007). These methods are rather subjective scoring systems that assign point values to a number of selected parameters on a scale range (Jalaei, 2015). As a matter of fact, studies have demonstrated that the buildings actually being developed under green rating systems are not the most effective because they have only marginally less impact than standard building code compliance buildings (Kibert, 2007). Therefore, these existing rating systems need to realign the intent of their credits with a well-known and widely accepted sustainability framework rooted in physics.

Consequently, in the latest versions of green building rating systems, there has been a strong push to include quantitative measurement of the performance of a building along its life-cycle. For example, the most recent versions of Green Globes and LEED^{TM} encourage the study of building energy use and environmental impacts by assigning credits if it the use of LCA is demonstrated in the design process (Srinivasan et al., 2014). Similarly, they have incorporated into their rating scales the use of virtual simulation to measure the building's performance, as well as the use of BIM to assist the decision-making on the design process. Green building certification systems have demonstrated to be an efficient way to provide design and operations guidance, to document progress toward a design operational performance target, to compare buildings using the certification systems structure, and to document what design and operations outcomes and strategies are being used in the building (Jalaei, 2015). Nevertheless, these building certification systems have to keep improving the way the structure of the credits represents the actual sustainability of buildings, by continuous incorporation of new research findings in the matter.

The ICC/ASHRAE 700-2015 National Green Building Standard (NGBS) is the most recent version of a residential green building rating system that covers the categories of energy, water, indoor environmental quality, site, and building materials (NAHB, 2016). This rating system can be used for new construction or renovations, for both single and multi-family homes. The ICC/ASHRAE 700-2015 has been developed by the National Association of Home Builders (NAHB), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and the International Code Council (ICC). This standard has been created in reference to the newest version of the International Energy Code Conservation (IECC) and it has been approved by the American National Institute of Standards (ANSI). The ICC/ASHRAE 700-2015 has the objective to integrate sustainability and high performance at a level most appropriate for the businesses and specific housing markets. It is worthy pointing out that the sustainability measurement tools have been voluntary systems since their creation. The strategy has been intending that into the future most of the building market would adopt the best practices naturally and gradually. However, the rate of change has been far too slow to offset both the depletion of resources and environmental degradation. It is time for a significant shift in government policy from voluntary to mandatory measures coupled with incentives that would help to accelerate the transformation in the construction industry (IPCC, 2015; Kibert, 2007).

2.1.3 Life cycle assessment in sustainable building design

LCA is a methodology that accounts for the materials and energy involved in a product or service along its life-cycle, and then measures the associated environmental impacts. According to the International Organization for Standardization (ISO, 1997) in its norm ISO-14044: “LCA is a technique for assessing the potential environmental aspects associated with a product (or service) by compiling an inventory of relevant inputs and outputs, evaluating the potential environmental impacts associated with these inputs and outputs, and interpreting the results of the inventory and impact phases in relation to the objectives of the study”. An LCA shall include definition of goal and scope, inventory analysis, impact assessment, and interpretation of results (ISO, 1997). LCA has been used for environmental evaluations of product development processes in different industries for a long time, but it has only been applied into the building construction sector in the last decade (Cabeza et al., 2014). Through applying this methodology to the construction industry, it is possible to make important decisions during the design stages of a building, based in a holistic approach that involves the stakeholders of a global society. LCA represents a rational standardized approach which can evolve with the development of knowledge and it may help the stakeholders to agree upon common strategies (Peuportier, 2001). Nowadays, LCA is considered as one of the main tools used to help achieve sustainability in the building industry (Jalaei, 2015; Srinivasan et al., 2014; Zabalza Bribian, Aranda Uson, & Scarpellini, 2009). When LCA is incorporated into the decision-making process for buildings, the stakeholders can asses the life-cycle impacts of building systems, materials, and components, and then select the alternatives that could decrease the net environmental impact of them.

As a part of defining the goal and scope of any kind of LCA, it is necessary to define the product system to be studied as well as its boundaries (ISO,1997). The system boundaries determine which unit processes of the final product shall be included within the LCA. The determination of these system boundaries depends on different factors, including the intended application of the study, the assumptions made, cut-off criteria, data and cost constraints, and the intended audience (ISO, 1997). Several research (Asdrubali et al., 2013;

Asif, Muneer, & Kelley, 2007; Blengini & Di Carlo, 2010; Cabeza et al., 2014; Densley Tingley & Davison, 2012; Fay et al., 2000; Gustavsson & Joelsson, 2010; Ortiz, Castells, & Sonnemann, 2009; Peuportier, 2001; Ramesh et al., 2010; Ramesh et al., 2012; Silvestre, de Brito, & Pinheiro, 2014; Zabalza Bribian et al., 2009; Zhang, Wu, Yang, & Zhu, 2006) have demonstrated the functionality of setting the system boundaries for buildings in four main stages with their respective sub processes 1) product stage (raw materials supply, transport, and manufacturing), 2) construction stage (transport and construction/installation on-site processes), 3) use stage (maintenance/replacement and operational energy use), and 4) EoL (deconstruction/demolition, transport, and recycling/reuse/disposal). The environmental impact of building components or processes are evaluated on the basis of inventories. An inventory is a table of impact factors that measures the quantity of emitted or used substance per unit of the component or process (Peuportier, 2001). The impact factors depend on the subject and intended use of the study. This last point could be controversial because the environmental impact factors of the same product or service could be relevant or irrelevant to include in the analysis depending on the particular goal and scope.

Several studies in this field have used energy consumption as the main and unique impact factor to include in LCA (Aye et al., 2012; Cabeza et al., 2014; Fay et al., 2000; Gustavsson & Joelsson, 2010; Ramesh et al., 2010; Ramesh et al., 2012; Zabalza Bribian et al., 2011). This kind of assessment is well known as life cycle energy analysis (LCEA). LCEA is a simplified form of LCA that uses energy as the only measure of environmental impact, and one which is particularly relevant to the building industry due to energy efficiency efforts over the last few decades. In contrast, other studies have applied more sophisticated LCA in construction. Such is the case of Peuportier (2001) who included thirteen environmental themes in an LCA comparative evaluation of single family houses (1. energy consumption, 2. water consumption, 3. depletion of abiotic resources, 4. waste creation, 5. radioactive waste creation, 6. global warming, 7. depletion of the ozone layer, 8. acidification, 9. eutrophication, 10. aquatic ecotoxicity, 11. human toxicity, 12. photochemical oxidant formation, and 13. malodorous air). In 2006 Zhang, Wu, Yang, and Zhu developed a Building Environmental Performance Analysis System (BEPAS) including twelve environmental impacts (1. global warming, 2. ozone layer depletion, 3. acidification, 4. eutrophication, 5. airborne suspended particles, 6. solid waste, 7. photochemical smog, 8. waterborne toxicities, 9. waterborne suspended substances, 10. fresh water depletion, 11. fossil energy source depletion, and 12. other resources depletion). BEPAS is a methodology for LCA focused in three main aspects of a building (1. building facilities, 2. building materials, and 3. location). In their work Blengini and Di Carlo (2010) presented an interesting variation of the common system boundaries of LCA for buildings. They split the building arrangement under study into phases and subsystems. Then, they estimated the percentage contribution of each phase/subsystem for every environmental impact assessed. They adopted eight environment indicators as the basis of their work (1. gross energy requirement, 2. non-renewable energy, 3. global warming potential (GWPf) excluding the contribution of biogenic carbon dioxide, 4. global warming potential (GWPb) including the contribution of biogenic carbon dioxide, 5. ozone depletion potential, 6. acidification potential, 7. eutrophication potential, and 8. photochemical ozone creation potential). In his work, Jalaei (2015) developed a Decision Support System (DSS) to help design teams choosing and selecting the most sustainable building components based on three main criteria (1. environmental impact, 2. economical factor, and 3. social wellbeing). The DSS estimates seven different environmental impacts using a specialized LCA software (1. air and water pollution, 2. solid waste, 3. global warming potential, 4. primary fuel consumption, 5. weighted resource use, 6. embodied energy, and 7. annual operating energy). The literature shows that the variety and quantity of the environmental impacts selected for LCA of buildings could vary depending on the interest, scope, and objective of the research.

Some authors (Zabalza Bribian et al., 2009) argue that the indicators and the impact categories selected should be simple so that architects, engineers, and end-users can easily understand the results. For example, if eutrophication is selected as an impact category few people will understand the result in comparison to water consumption, embodied energy, and carbon emissions. Therefore, the U.S. Environmental Protection Agency has categorized the “top ten” impacts as 1) global warming potential, 2) ozone depletion potential, 3) photochemical oxidant potential, 4) acidification potential, 5) eutrophication, 6) health toxicity (cancer), 7) health toxicity (non- Cancer), 8) health toxicity (air pollutants), 9) eco-toxicity potential, and 10) fossil fuel use (Jalaei, 2015). Considerable work has been done to develop LCA software tools that measure and assess a building’s environmental performance during its life-cycle based on the main environmental impact categories mentioned above. Examples of these LCA tools are SimaPro®, GaBi®, Revit Plugin-Tally®, Athena Impact Estimator®, and NIST BEES®. All of these tools are ISO-14044 compliant and accepted by the most important green building rating systems, as well as national and international institutions like U.S EPA.

2.1.4 Life cycle assessment measurement tools for buildings

LCA is considered to be one of the most comprehensive tools used to help achieve sustainable building practices. Nevertheless, to perform these kinds of assessments for an entire building is challenging due to the amount of information that has to be processed depending on the system boundaries. Setting up inventory data can be one of the most labor intensive and time demanding steps in an LCA, as well as gathering the appropriate data for the product system under study (Finnveden et al., 2009). Similarly, the evaluation of the environmental impacts becomes complicated due to many changes that could occur along the lifespan of the building. Predicting life-cycle as "cradle-to-grave" is very difficult to perform accurately for a long lifetime, such as 50 years (Schultmann & Sunke, 2007). For example, the EoL stage of buildings is probably the most difficult part of an LCA, since that phase is quite separated in time from the rest (several years to decades). Also, there is a variety of EoL paths for each building material or component that depends on the final decision of the owner. Some of the most common EoL for building materials/components are direct reuse, repairing, refurbishing, remanufacturing, cannibalization, recycling, combustion with heat recovery, composting, incineration, and landfilling (Schultmann & Sunke, 2007). Studies have demonstrated the potential benefits of all of these EoL techniques applied to an industry and a global society that is shifting towards increased sustainability (Blengini & Di Carlo, 2010; Sandin et al., 2014; Schultmann & Sunke, 2007; Silvestre et al., 2014). However, there is limited quantitative information of the actual EoL processes (Blengini & Di Carlo, 2010) and few studies that contain methodological information applied in the industry of construction.

In order to deal with the complications mentioned above, many LCA software tools, in combination with public and private databases, have been developed in the last decades. These databases include national or regional databases, industry databases, and consultant databases (Finnveden et al., 2009). According to the National Green Building Standard, all of the tools used to perform LCA must be ISO-14044 compliant or fulfill another well-known and widely accepted equivalent standard. Some of the most common LCA software that satisfy this condition are SimaPro®, GaBi®, Tally®, Athena Impact Estimator®, and NIST BEES®. Due to their proven accuracy and effectiveness, all of these computer tools have been used in LCA models worldwide in industrial and scientific applications, as well as in published studies (Jalaei, 2015; Kumar, Hewage, Haider, & Sadiq, 2016; Srinivasan et al., 2014). Other specialized tools that integrate BIM with LCA studies have been developed to streamline LCA processes and facilitate the rigorous management of the environmental footprint of constructed facilities (Jalaei & Jrade, 2014; Jalaei, 2015; Kokkos, 2014; Wu & Issa, 2015).

2.1.5 Integrating Building Information Modeling and sustainable buildings design

BIM is defined by international standards as “shared digital representation of physical and functional characteristics of any built object [...] which forms a reliable basis for decisions” (Volk, Stengel, & Schultmann, 2014). BIM is a realistic and detailed virtual representation of buildings. BIM is accomplished with object-oriented software and consists of parametric objects representing building components that may have geometric or non-geometric attributes with functional, semantic or topologic information (Volk et al., 2014). For example, functional attributes can be construction time, labor demand, and building cost; semantic information can be interdependency of elements, hosting components, and incompatibility between objects; and topologic attributes can be universal positioning, coplanarity, and perpendicularity of objects. According to Jalaei (2015) BIM is an organizing concept that contributes in the life-cycle of a facility to create and manage building data in a convenient way.

From the perspective of the US General Services Administration: "Building Information Modeling is the development and uses of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility. The resulting Building Information Model is a data-rich, object-based, intelligent, and parametric digital representation of the facility, from which views appropriate to various users' needs can be extracted and analyzed to generate feedback and improvement of the facility design" (GSA, 2007). Numerous researchers have reported benefits from implementing BIM in diverse research fields in construction such as preconstruction, design visualization, construction reviews, design coordination, planning of trades and systems, construction scheduling and sequencing, quantity surveys estimating, prefabrication and modularization, as-built modeling for facilities operations and maintenance, built environments and its processes partly integrating sustainability issues, remote sensing technologies, LCA studies, and rubble management (Jalaei, 2015; Volk et al., 2014). For all of these benefits, the implementation of BIM is becoming a cornerstone of the modern construction market as well as construction project management.

Currently, considerable research is done in the area of integration of sustainability in construction and BIM. Project teams have found that synergies between green building and BIM can help to improve the accomplishment of sustainability goals (Wu & Issa, 2015). This interdisciplinary synergy is well known with the name of "green BIM" or "6D BIM". Researchers are still working to deliver the full potential of green BIM. The objective is to efficiently integrate the modeling systems, the specialized tools for sustainability, and the databases needed to perform a realistic simulation. Examples of BIM tools available in the market are Revit®, Bentley®, Vico®, and ArchiCAD®. In North American market Autodesk Revit® is the most prevailing BIM tool. Some of the most common modeling systems specialized in energy analysis are Ecotect®, Green Building Studio®, eQuest, EnergyPlus®, and Integrated Environmental Solutions®. Similarly, some of the most developed software for performing LCA in buildings are SimaPro®, GaBi®, Tally®, Athena Impact Estimator®, and NIST BEES®. Some researchers have pointed out that a unique software package does not exist that can provide all of the needed functions at all of the stages of an LCA for buildings (Jalaei, 2015; Wu & Issa, 2015). Yet, through interoperability and data exchange between applications it is possible to develop integrated green BIM tools. This is possible due to data models have become the international standard for data exchange in the building industry (Jalaei, 2015).

Finally, despite the increasing usage of all of these kinds of computer tool technologies in new structures, their implementation in existing buildings is still limited. Research approaches are intensifying to harness BIM for application in existing buildings by capturing building data into BIM, as well as implementing deconstruction functionalities and reuse of materials/components (Kokkos, 2014).

2.2 Designing for a Circular Economy in construction

Conceptualization of the CE has evolved through the years, and it has been gaining momentum since the late 1970s (Geissdoerfer et al., 2017). Among the schools of thought on the CE, shared founding principles lie in the better management of resources and waste by minimizing (or closing) material and energy loops (Geissdoerfer et al., 2017; Lacy & Rutqvist, 2015; Pomponi & Moncaster, 2017). CE is conceived as the main condition for sustainability in the construction industry (Geissdoerfer et al., 2017).

Due to the growing concern for the environment, sustainability has become a requirement rather than just a desirable characteristic for products and services. To remedy this situation, the construction industry is implementing designs and systems with improved long-term life-cycle performance. The main objective is to consider closed-loop circular design principles (World Economic Forum, 2016). Closed-loop Cycle Material Construction (CLMC) can be defined as recovering construction composing materials and building elements from old buildings and infinitely recycling them through natural or industrial processes (Sassi, 2008). Sassi (2008) defined criteria by which building materials can be assessed in terms of forming part of a CLMC, drawing on existing research on natural recovery, design for deconstruction, and recycling. According to Kibert (2007) themes such as deconstruction, durability, adaptability, design for the environment, design for deconstruction, closed materials loops, and dematerialization, are not yet woven into the fabric of sustainable construction, but they certainly play an important role in this topic. Jaillon and Poon (2014) developed a couple of case studies of recently completed institutional buildings using prefabricated precast concrete building structures, located in dense high-rise building environments in Hong Kong. The study concluded that the promotion of a closed-loop material cycle is critical to contribute to sustainability thus minimizing carbon emissions and natural resource consumption. Silvestre, de Brito, and Pinheiro (2014) demonstrated that assessment of waste flows is an important source of data for decision-making at the EoL of building materials to maximize their cradle-to-cradle environmental performance through the minimization of waste flows, maximization of the reuse/recycling operations, or increasing the recycled content. Shultmann and Sunke (2007) discussed energy savings in terms of embodied energy that could be afforded through using different recovery techniques on deconstruction projects. All of these studies support the idea that there are areas of opportunity to maximize the benefits of the resources on the EoL stage of buildings that should be improved. Also, it is necessary to include all of the stakeholders in the process with the final goal of producing far superior buildings that represent a realistic alternative.

2.2.1 Current trends for closed-loop cycle in the construction industry

Green design methods have become an important part of the design process in most industries, including construction. Green design methods are design to reduce environmental cost and increase economic benefits over the entire product or service life-cycle (S. Smith, Hsu, & Smith, 2016). Examples of green design methods are design for assembly, design for disassembly, design for remanufacture, and disassembly planning. According to Soh, Ong, & Nee (2016), assembly is a process essential for remanufacturing, and assembly being a value-added process has to be carried out in its most efficient manner to maximize cost effectiveness, as more time required for assembly means higher manufacturing cost. Therefore, design for assembly has the potential of shorten the product cycle, minimize development cost, and ensure a smooth transition from prototype to production stage (Khan, 2008). Disassembly is also another process essential for remanufacturing, and design for disassembly is practice to ease the deconstruction processes and procedures through planning and design. Design for disassembly is an important strategy to conserve raw materials by preserving the residual value of disassembled components (Rios, Chong, & Grau, 2015). Design for remanufacture is defined as the product design that facilitates any of the steps involved in the process of returning a used product to like-new condition with a warranty to match (Hatcher, Ijomah, & Windmill, 2011). The remanufacturing steps include parts' sorting, inspection, disassembly, cleaning, reprocessing, reassembly, and replacing. Design for remanufacture can benefit the environment because it demands less energy and materials in comparison to new manufacture, and reused components reduce the waste generation. Disassembly planning is used to efficiently retrieve parts from a product for repair, reuse, remanufacturing, or recycling. Appropriate disassembly planning can reduce the time and cost associated with disassembling products (S. Smith & Hung, 2015).

In the field of design for disassembly or deconstruction in buildings, improvements can be achieved by considering future disassembly of building elements at the planning stage of new buildings (Gorgolewski, 2008). For example, researchers studied the cost-effectiveness of deconstruction compared with traditional demolition of wood-frame residential construction (Guy & McLendon, 2000). The study showed that the initial cost of the deconstruction process is higher than demolition, but the net cost after factoring in the revenue from sales is lower. Using software simulation, Tingley and Davidson (2012) developed an LCA methodology to account for the environmental benefits of design for deconstruction of a hypothetical three story building, non-composite structure, made up of 6 by 6 meter bays, with a 1,620 m^2 total floor area. Akbarnezhad, Ong, and Chandra (2014) demonstrated the efficiency of using BIM on economic and environmental assessment on construction strategies to quantify the affordable benefits accurately. This study included the effect of prices and energy embodiment of the materials and components, the travelling distances, energy use and cost associated with the recycling processes, inflation rate, costs of designing the components for reuse-ability, and costs of disassembly and re-assembly. In his work, Kokkos (2014) developed a sophisticated parametric and associative toolbox that exposes the environmental and financial impacts of the concept of Design for Deconstruction.

Another strand of research has delved on the amount of the steel that is recycled or reused in the construction industry and the areas of opportunity in this fields. It is a recent trend in the building industry to reduce GHG emissions by saving on primary steel production due to the great environmental impact produced by the steel industry and the affordability for recovering this construction material (Gorgolewski, 2006). For example, LEED® rating provides available points for the storage and collection of recyclables, reuse of buildings, and reuse of resources, as a stimulus for promoting the conservation of materials and resources. According to the Steel Recycling Institute (2016), steel is the most recycled material in North America and, indeed, the world. Around the 59% of the total recycled steel is derived from Construction and Demolition (C&D) waste and only around 10% of structural steel is currently being reused.

Even though steel reuse requires minimal reprocessing and it produces low environmental impact, it is still rare in the construction industry. In his work, Gorgolewski (2006; 2008) discusses the issues relevant for designing to enable future reuse as well as the change on the approach for the stakeholders (owner, designer, builder, etc.). Ness et al. (2015) proposed digital tracking of structural steel members to facilitate steel reuse in new buildings. Yeung, Walbridge, and Haas (2015) explored the geometric characterization of structural steel as a key role in the decision process for potential steel reuse. In his work, Yeung (2016) contributed to the understanding of life-cycle impacts of steel reuse as an alternative to recycling. His research presented a streamlined life-cycle analysis methodology based on process models and by analyzing the influence of prices placed on the environmental impacts produced.

2.2.2 The role of adaptive reuse in the modern construction

Adaptive reuse of buildings is considered by most as a superior alternative to new construction in terms of sustainability (Conejos et al., 2015; Douglas, 2006; Langston, 2008). Adaptive reuse improves the financial, environmental and social performance of buildings. It takes existing buildings that are obsolete, restores them, and in some cases changes their use (Bullen, 2007; Langston et al., 2008). Adaptive reuse takes advantage of any of the green design methods mentioned in the last section, in order to restore and redevelop existing buildings. As part of their life-cycle, buildings' operational and commercial performance decreases over the years until the performance fall below the expectations of owners. In consequence, the owners face the decision to finish with the life-cycle of the building choosing from one of the different EoL options. Some of the most common EoL options for building materials are direct reuse, repairing, refurbishing, remanufacturing, cannibalization, recycling, combustion with heat recovery, composting, incineration, and landfilling (Schultmann & Sunke, 2007). However, the decision to choose any of these EoL options may be premature if it ignores the residual utility and value of buildings that could be optimized by "giving them new life" using the process of adaptive reuse. Because of the great impact that the building industry has in the environment, failing to optimize buildings' useful life can result in their residual life-cycle expectancy not being fully exploited, and with it, wasting the resources embedded.

The decision-making processes associated with the planning, design, and construction of a building are diverse and dynamic. Therefore, choosing adaptive reuse for a building project is complex as well. The difficulty lies in all of the different aspects that have to be taken into account, such as the physical integrity of the building, economic issues, functionality, technological retrofits, social impact, and legal and political issues. For this reason, little research has been done regarding establishing feasible methodologies for the assessment of adaptive reuse of buildings. Some authors stress that intuition and experience are the only guides in making decisions about adaptive reuse (Highfield & Gorse, 2009).

In 2008, Langston et al. developed the Adaptive Reuse Potential (ARP) model. Through the ARP model, existing buildings can be ranked based on their adaptive reuse potential over time. The ARP model predicts useful life as a function of physical life and obsolescence. In consequence, the right timing for future adaptive reuse can be predicted (Conejos et al., 2015). The model can be applied to all building typologies and all countries (Langston et al., 2008). Also, this model has been validated using a new multi-criteria decision analysis tool called iconCUR (Langston & Smith, 2012; Langston, 2012). Another recent contribution to this field is the adaptSTAR model. The adaptSTAR model is a decision-making tool that aims to help the climate change adaptation of built assets (Conejos et al., 2014). This model provides a weighted checklist of design strategies that assist in the development of new buildings that can be adaptively reused in the future (Conejos et al., 2015). This model's approach strives on the intuition and experience of the stakeholders. The adaptSTAR model was based on survey results collected from selected practitioners of the Australian architectural profession. The model is composed of 26 design criteria with weighted percentages that are organized into seven categories. The performance of any newly designed building is scored against these weighted criteria that sum to a total.

In a parallel way, technical regulations and normativity for adaptive reuse have been created in the last decade. The aim of these regulations is making adaptive reuse of the building stock an integral part of the infill development. These regulations are known as "smart growth" and "smart codes" (Cantell, 2005). "Smart codes" is the term used to describe building codes that encourage the alteration and reuse of existing buildings (DHUD, 2001). Examples of these smart codes are the reformed article 22 of the building code of the State of Massachusetts in 1979, the Uniform Code for Building Conservation (UCBC) in 1985 with the last update in 2000, the New Jersey Rehabilitation sub code in 1998, the Nationally Applicable Recommended Rehabilitation Provisions (NARRP) in 1997, the Uniform Code for Existing Buildings (UCEB) in 2000, the International Existing Building Code (IEBC) in 1999, the National Fire Protection

Association 5000 building code (NFPA 5000) in 1999, the Maryland Building Rehabilitation Code (MBRC) in 1999, and Wichita Rehabilitation Code in 2000.

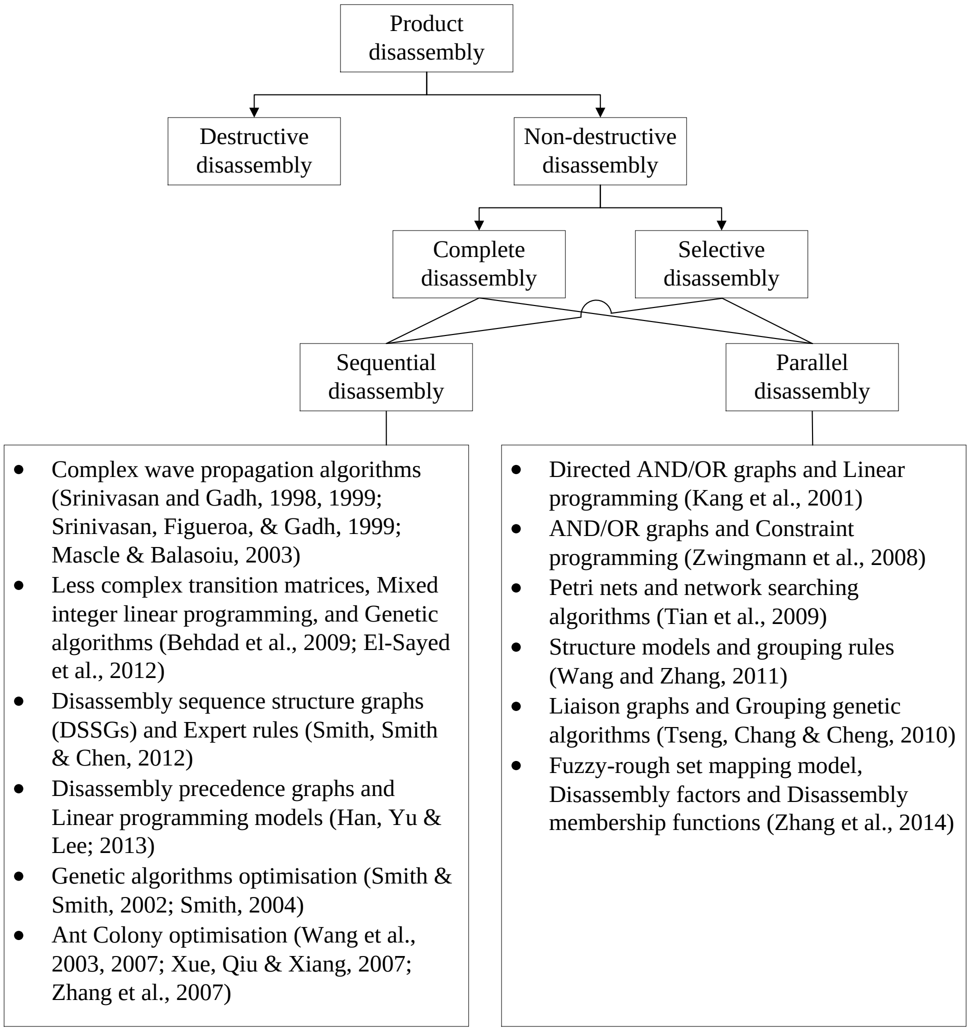
Even though all of the methods and regulations mentioned have the objective of increasing the sustainability of human settlements through adaptive reuse, there is still a lack of knowledge about the environmental and economic performance of the adaptive reuse process in terms of life-cycle. Adaptive reuse could be expensive and it has a high impact on the EoL stage of buildings. If a building is difficult and inconvenient to be renovated, it might increase the environmental and economic cost in comparison to a new building. Therefore, it is necessary to develop methods to estimate the net environmental impacts and economic performance of adaptive reuse building projects through PRM. Only in this way it could be possible to understand objectively if an existing building asset is worthy to be redeveloped and to define the optimal level of intervention. All of the methods and regulations mentioned above in this section relies on conventional intuitive planning procedures by professionals in the construction industry to determine the scope and convenience of adaptive reuse projects. Conventional intuitive planning procedures are easy to apply but must of the times lead to suboptimal plans or plans ranked with little quantitative or objective measure (Lin & Haas, 1996). There is no evidence of methods that can objectively demonstrate the optimum, or near to optimum, balance of the net environmental and economic performance for adaptive reuse projects with a life-cycle perspective.

2.2.3 Disassembly planning of products and buildings

The potential benefits of adaptive reuse rely on the fact that it is possible to take away components from an obsolete building and then repair, reuse, remanufacture, or recycle them. In this matter, some of the most important green design methods include design for disassembly, design for maintainability/serviceability, design for reuse, design for remanufacturing, and design for recyclability (S. Smith & Hung, 2015). For existing assets, complete design for disassembly is not possible, and the process is reduced to planning for disassembly. Planning for disassembly plays a key role in the adaptive reuse design process where the disassembly planning sequence, as well as the disassembly methods to recover target components, have to be performed in an efficient way. The objectives are to reduce building costs and to increase the building components' life-cycle times. If the design for disassembly is too complex or time-consuming, the associated economic and environmental costs could be higher than installing new components. This field has been studied in the manufacturing industry since the last decade, concluding that disassembly planning can reduce the time and cost associated with disassembling products (S. Smith & Hung, 2015).

According to Smith & Hung (2015) the different types of disassembly planning methods can be classified as follows destructive and non-destructive disassembly planning methods, complete and selective disassembly planning methods, and sequential and parallel disassembly planning methods. They explain that destructive methods destroy the functional capabilities of the disassemble components and that selective disassembly planning methods only remove specific high-value parts. Also, they explain that sequential methods remove parts one at a time while parallel methods remove multiple parts at the same time. The authors describe the benefits of each method highlighting that selective disassembly planning methods can be used to minimize environmental impacts and economical cost in practical applications such as products' refurbishment and for the reclaiming of high-valued components from an assembly. Figure 2-2 shows the generic classification of product disassembly methods, as well as the literature review of the applied theories to find the optimum, or near to optimum, disassembly path for non-destructive disassembly methods.

In the construction industry disassembly planning approaches have been developed attending to the particularities of construction building projects. The process of planning the dismantling of an existing assent is well known as deconstruction project planning. Deconstruction planning refers to the process of preparation and outlining every deconstruction activity before its execution in order to meet projects' objectives and deliverables. Huber et al. (2017) provide a comprehensive literature overview of project planning methods for deconstruction of buildings as well as some research gaps in this field. The authors classified the existing deconstruction planning methods according to specific construction project objectives. The proposed project objectives are time, cost, resources, risk, and quality, which, in turn, have been the main performance indicators on the field of construction project management. Their study presents a full-range variety of methods for the decision-making process on strategic and operational deconstruction planning, based on the optimization of single or multiple project objectives. However, none of these methods and approaches have been developed for the renovation or repurposing of buildings. In other words, the existing methods for deconstruction planning has focused either on the complete or partial deconstruction of buildings with the purpose of finishing with the lifespan of the fixed asset. Therefore, there is a lack of knowledge in the development of deconstruction planning models for adaptive reuse of buildings.



- Complex wave propagation algorithms (Srinivasan and Gadh, 1998, 1999; Srinivasan, Figueroa, & Gadh, 1999; Mascle & Balasoiu, 2003)
- Less complex transition matrices, Mixed integer linear programming, and Genetic algorithms (Behdad et al., 2009; El-Sayed et al., 2012)
- Disassembly sequence structure graphs (DSSGs) and Expert rules (Smith, Smith & Chen, 2012)
- Disassembly precedence graphs and Linear programming models (Han, Yu & Lee; 2013)
- Genetic algorithms optimisation (Smith & Smith, 2002; Smith, 2004)
- Ant Colony optimisation (Wang et al., 2003, 2007; Xue, Qiu & Xiang, 2007; Zhang et al., 2007)

- Directed AND/OR graphs and Linear programming (Kang et al., 2001)
- AND/OR graphs and Constraint programming (Zwingmann et al., 2008)
- Petri nets and network searching algorithms (Tian et al., 2009)
- Structure models and grouping rules (Wang and Zhang, 2011)
- Liaison graphs and Grouping genetic algorithms (Tseng, Chang & Cheng, 2010)
- Fuzzy-rough set mapping model, Disassembly factors and Disassembly membership functions (Zhang et al., 2014)

Figure 2-1: Disassembly planning methods and models for non-destructive disassembly optimization. Source: Own elaboration based on (Han, Yu, & Lee, 2013; S. Smith & Hung, 2015)

2.2.4 Selective disassembly planning for adaptive reuse of buildings

The potential benefits of adaptive reuse rely on the fact that it is possible to retrieve valuable components from an existing building. The objective of adaptive reuse is to refurbish, and in sometimes to reconfigure the entire existing asset. Unfortunately, there is a lack of methods for deconstruction planning for adaptive reuse such as selective sequential disassembly planning and selective parallel disassembly planning. In comparison to the construction industry, the research field of selective disassembly planning for manufactured products have been developed substantially in along the last decade. This study focuses on selective sequential disassembly planning since this is the most basic form of selective disassembly planning.

Smith et al. (2012) did an exhaustive comparison between the different theories applied for the optimization of selective sequential disassembly planning of products demonstrating the Disassembly Sequence Structure Graphs (DSSG) method as an optimal approach. The DSSG model is a user-friendly heuristic optimization technique for quickly finding an efficient selective disassembly sequence for products recovery given specific constraints (S. Smith et al., 2012; S. S. Smith & Chen, 2011). The DSSG model is defined as a rule-based recursive method for finding a near-optimal heuristic selective disassembly sequence for green design (S. Smith et al., 2012; S. S. Smith & Chen, 2011). In mathematical optimization, a heuristic is a technique designed for solving a problem more quickly in comparison to classic methods (such as enumerative or stochastic methods) by finding a near to optimal solution. This is achieved by trading off the optimality, completeness, accuracy, or precision of the problem's solution for the speediness in the calculations (Zanakis & Evans, 1981). Heuristic methods are used when classic methods fail to find any exact solution or they demand an excessive amount of computational resources. Examples of other common heuristic optimization methods applied in engineering systems are evolutionary algorithms, such as Genetic Algorithms (GA) and ant colony optimization. The DSSG approach is able to find an optimized solution for a number of parts, part orders, and part disassembly directions, in a minimum amount of time. In their work, Smith et al. (2012) tested and compared the performance of other optimization methods applied on selective sequence disassembly planning for products, such as, the Enumeration DG method, the Smith's method, the Enumeration DCG method, the Search DCG method, the Wave propagation method, Garcia's method, the DSSG method, and the DSSG-S method.

Disassembly sequence planning consists in creating a disassembly model and then generating disassembly sequences (S. Smith et al., 2012). A disassembly model is a graph with nodes and links, where the nodes represent the different parts of an assemblage and the links represent the constraints between parts. The parts of the assemblage should be identified as components or fasteners. Graphs are converted into constraint matrices for computing processing. Disassembly sequence planning consists of finding an optimal and feasible path for disassembly. According to Smith et al. (2012) the quality and complexity of disassembly models affect the solution quality and searching time. For instance, a model that contain more information improve solution quality but it increase searching time. In their work Smith et al. (2012) demonstrated that their DSSG model approach improve solution quality and searching time for disassembly models in comparison to prior techniques. The DSSG model optimizes the number of removed parts, part order, part disassembly directions, and reorientations, in order to create high quality, practical, realistic, and time-efficient disassembly sequence planning (S. Smith & Hung, 2015; S. Smith et al., 2012; S. Smith et al., 2016). To find solutions, the DSSG model first creates a Disassembly Graph (DG) model. The DG model contains five matrices, a contact matrix for components, a motion constraint matrix for components, a contact constraint matrix for fasteners, a motion constraint matrix for fasteners, and a projection matrix for components. These matrices are also known with the name of initial matrices or constraint matrices. The matrices contain all contact and motion constraints for components and fasteners in the principle Cartesian extraction directions $\{+x,-x,+y,-y,+z,-z\}$. Components create constraints by occupying volumes and fasteners create constraints by connecting components to other components. After defining the DG model, the DSSG model is created from the DG structure based on realistic part disassembly directions and expert rules. According to Smith et al. (2012) choosing directions before searching disassembly paths reduces model complexity and searching time, while expert rules secure that the found solutions are feasible, practical, realistic, and efficient.

The DSSG model approach has been developed and successfully tested in several case studies for the manufacture industry (S. Smith & Hung, 2015; S. Smith et al., 2012; S. Smith et al., 2016). The DSSG model approach has been adapted in each study to optimize specific goals such as minimize the searching time, minimize the number of removed parts, minimize the number of changes on the reorientation for extracting parts, minimize the amount of labor for disassemble based on the difficulty of dismantling parts or modules, minimize the disassembly cost, maximize the Recycle Value (RV), and optimizing the cost-benefit of partial disassembly planning with a LCA approach. The referred studies have implemented different optimization techniques, solving single and multi-objective optimization problems.

The DSSG method uses certain disassembly rules to eliminate uncommon or unrealistic solutions. The rules were developed defining the recursive selective disassembly planning process, based on the analysis of the disassembly characteristics of manufactured products, and according to the corresponding unique matrix representations of the method. This method considers the geometric relationship between parts and its neighboring parts rather than considering geometric constraints between a part and the entire assembly. If a part can be disassembled, its geometric relationships with the neighboring parts will be dynamically updated. The topological information and part accessibility of a product is examined from inside to outside. The approach gets parts (components or fasteners) from the DG model, arranges and orders the parts in levels, and adds the parts to a disassembly sequence. According to Smith et al. (2012; 2011) the operation of the single-target DSSG approach is the next. First, the process creates a root node which is the query component, assigns the best disassembly direction, and puts the constraining parts in a queue. Then, the process examines each part in the queue at a time, assigning the best disassembly direction (for the queue's part under study), adding the examined part to the disassembly sequence, and adding all of the new constraining parts (that are not already in the disassembly sequence or the queue) to the queue. The process repeats, until all parts are added to the disassembly sequence. During the iterative process the expert rules improve solution quality, minimize graph complexity, and reduce searching time. According to the DSSG's expert rules, the best disassembly direction for removing a part under study is the direction with the least number of obstacles (Rule 1), all of the fasteners that constraint a component must be removed first (Rule 3), all of the components that constraint a part under study in a given extraction direction must be removed first (Rule 2), and the best direction for removing all parts is the direction with the least number of obstacles unless the part under study have pre-assigned disassembly directions (Rule 4). For a single query component that has two or more “best directions”, the approach can choose one of the directions, or create multiple single-target DSSGs and choose the best DSSG. In their work (S. Smith et al., 2012), the authors also proposed an approach for creating a multiple target DSSG. This approach merges single-target DSSGs to create one multiple-target DSSG. The approach merges identical nodes within the DSSGs. The effectivity of the DSSG approach for manufactured products has been validated through several case studies and it represents a realistic alternative to improve the efficiency of PRM through selective disassembly planning (S. Smith & Hung, 2015; S. Smith et al., 2012; S. Smith & Chen, 2012; S. Smith et al., 2016; S. S. Smith & Chen, 2011; Zhou et al., 2018).

The field of selective disassembly planning in the construction industry has remained underexplored and underdeveloped in comparison to the manufacturing industry. In this respect, the studies presented in Chapters 5 to 7 represent pioneer advances in the field of selective disassembly planning for buildings. In Chapter 5, the first-in-its-class Sequential Disassembly Planning for Buildings (SDPB) method for adaptive reuse of buildings is presented (Sanchez & Haas, 2018b). The SDPB method is a selective disassembly sequence planning approach, based on the DSSG theory, by environmental impact, building cost, and rule-based analysis for adaptive reuse of building. The SDPB method is used in order to generate optimized disassembly plans for retrieving single targeted components from buildings assemblies. The method seeks to minimize environmental impact and deconstruction cost of the selective disassembly planning based upon physical, environmental, and economic constraints. In Chapter 6, the SDPB method is enhanced for the development of a multiple target selective disassembly planning model for buildings, as well as the development of a novel approach of selective deconstruction programming for adaptive reuse of buildings (Sanchez, Rausch, & Haas, 2019). This approach is able to create the programming of deconstruction work for retrieving multiple components of a building assembly in a semi-automated way. Finally, in Chapter 7 the SDPB method is extended with the purpose of including more than one deconstruction method per building component (Sanchez, Rausch, Haas, & Saari, 2019). In this study, a weighted multi-objective optimization analysis is incorporated to generate the set of noninferior solutions that minimizes environmental impacts and building cost for the different alternatives of deconstruction plans.

Based on the results, approach, and building assemblage archetype presented in the SDPB study (Sanchez & Haas, 2018b), Denis et al. (2018) proposed an alternative optimization method for selective disassembly planning for buildings by using Network Analysis. Their method is called Disassembly Network Analysis (DNA) and it is yet in a preliminary stage of development. The DNA approach involves specific disassembly parameters such as accessibility, transportability, resistance factor, weight, reversibility of connection, and disassembly/demolition time, to define the optimization analysis model. Even though the DNA approach represents a feasible alternative, the method is limited by the considerable amount of data to enter manually. In addition, the DNA optimization model (for a building assembly under study) must be created according to disassembly parameters which need the interpretation from practitioners (e. g. the definition of the accessibility space for disassembling a component, the estimation of a connection's reversibility, and the definition of sequential dependence of structural and nonstructural elements). As a result, the DNA approach is set in complex fundamentals that could be hardly improved by automation in the short and mid-term. Therefore, the practical application of this approach could not be affordable since real buildings' assemblages are integrated by a large number of components (hundreds or thousands).

2.3 The knowledge gap and contribution

As described in this chapter, green design methods are becoming an important part of the design process in buildings due to the growing concern for the environment. Adaptive reuse of buildings has been demonstrated to be a superior alternative to new construction in terms of sustainability and CE. Nevertheless, its current implementation relies on conventional intuitive planning procedures by professionals in the construction industry, leading to suboptimal results with little quantitative or objective measure. Comparatively, PRM and green design methods have focused on the environmental and economic optimization of the recovery of the building components for new purposes, rather than expanding the life-cycle of the whole building (Hübner et al., 2017; Kokkos, 2014; Sandin et al., 2014; Schultmann & Sunke, 2007; Yeung, 2016). The decision-making processes associated with the optimized planning, design, and construction of an adaptive reuse building project are complex, diverse, and dynamic (Conejos et al., 2015; Conejos et al., 2014). Furthermore, the quantity of data processing required to perform the optimization process in terms of life-cycle assessment is large. The coordination of new technologies such as computational power, 6D BIM, cloud databases, and automation algorithms can help in finding the optimum, or near to optimum balance for adaptive reuse of buildings in an affordable and realistic way. However, it seems that the studies that approach the problem of the closed-loop cycle in buildings solve the problem in a fragmented and dispersed way. There is no evidence of any study that combines all of the technologies mentioned above that resolves the PRM problem of the built environment through adaptive reuse.

In a parallel way, research on PRM in the manufacturing industry has addressed the problem of product closed-loop cycles of specific high-value components through disassembly planning optimization models (Han et al., 2013; S. Smith & Hung, 2015; S. Smith et al., 2012; S. Smith et al., 2016). The solution quality, model complexity, and searching time have been considered and solved successfully for manufactured products (S. Smith et al., 2012). Current research has included LCA tools to perform cost-benefit analysis to find an optimum disassembly stopping point that reduces environmental cost and increases economic benefits (S. Smith et al., 2016). Therefore, there is a need to improve, modify, and adapt the current methods applied in the manufacturing industry in order to create an appropriate methodology for adaptive reuse of buildings. This thesis aims to address the above-mentioned challenges for adaptive reuse of buildings. The proposed research here mainly aims to employ recent selective disassembly planning advances in order to create a framework and methods that can optimize the environmental and economic performance of the process of adaptive reuse of buildings.

While the algorithms developed are to some extent generalizable, validation experiments in this thesis are focused on disassembly planning of existing buildings given its fundamental role for the reuse of the build environment. The experimental results show that the proposed method is affordable enough to be applied in the current building market and applied to unique fixed assets (in contrast to disassembly of large numbers of identical manufactured products).

Chapter 3: Capital project planning for a Circular Economy in the construction industry[1]

3.1 Abstract

Adaptive reuse synthesizes many of the CE principles and methods in order to restore, reconfigure and repurpose existing buildings. An urgent need exists to develop and validate effective planning principles, methods and tools for adaptive reuse building projects. In particular, while the PDRI for buildings is known to be an effective planning tool for green-field building projects, it has limited applicability to the circular model. Complimentary tools are also required such as selective disassembly planning methods, LCA analysis procedures, and methods to justify development incentives offered by government. Thus, in this chapter it is proposed a capital project planning framework and related research that must be accomplished to enable a more CE in the capital projects sector. This chapter provides a short introduction to the main concepts addressed in this study, the CE in construction, CE for the built environment, and the implications of circular building principles in capital project delivery.

3.2 Introduction

Sustainability in construction has shifted from an original focus on cleaner and leaner delivery of conventional projects to a restorative and regenerative approach. Sustainable construction had been mainly focused on the development of new high-performance green buildings and retrofitting, rather than research in life-cycle performance in terms of sustainability (Kibert, 2007; Ofori, 1998; Plessis, 2007; Pomponi & Moncaster, 2017). This change is grounded in the recognition that an enormous proportion of all of the materials ever extracted are in today's built environment, that the current economic model is reaching its limits, and that a new circular model should be the path to true sustainability (Costantino, 2006; Hill & Bowen, 1997; Kibert, 2007; Lacy & Rutqvist, 2015; Ofori, 1998). Therefore, circular building principles and green design methods need to become a more central part of the capital building project process (Kibert, 2007; Sassi, 2008; Shiers, Rapson, Roberts, & Keeping, 2006; S. Smith & Hung, 2015; Volk et al., 2014). They have the purpose of reducing environmental impacts and increasing economic benefits from a total life-cycle perspective (S. Smith & Hung, 2015).

While circular paradigms of project cost, quality, and schedule have always played a part in capital projects delivery, essential to the definition of a project is that it has a beginning and an end. This presents a dilemma. How it could a project delivery process be managed that has phases in a cycle, rather than an obvious

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[1] This is an Accepted Manuscript of an article published by Taylor & Francis in Construction Management and Economics on 15 February 2018, available online: https://www.tandfonline.com/doi/abs/10.1080/01446193.2018.1435895. B. Sanchez, and C. Haas, “Capital project planning for a circular economy”. Only minor editorial changes are applied for being consistent with the University of Waterloo thesis format.

beginning or end? When a new need for infrastructure or space arises, how it could a solution be developed? And, what role does early planning play? Noteworthy are several studies that have recognized the importance of the EoL stage in buildings, and the opportunity of their adaptive reuse as a superior alternative to new buildings in terms of sustainability (Bullen, 2007; Cantell, 2005; Conejos et al., 2015; DHUD 2001; Douglas, 2006; Highfield & Gorse, 2009; Huovila, 2007; Langston, 2008; Langston et al., 2008; Schultmann & Sunke, 2007; Tan et al., 2014; M. M. M. Teo & Loosemore, 2001; Wilkinson et al., 2009; Wilson, 2010).

It is also widely known that an appropriate "pre-project" planning or "front-end" project management leads to improved project performance in terms of cost, schedule, and operational characteristics (Ballard, 2000a; Cho, 2000; CII 1994; Dumont & Gibson, 1996; Edkins, Geraldi, Morris, & Smith, 2013; Morris, 2011). According to Edkins et al. (2013), despite evidence of the importance of the pre-project planning, it is still poorly understood, not well documented in the literature review, and inconsistent from project to project and between sectors. For that reason, over three decades, diverse industries have implemented practical solutions in the field of front-end project management showing their value to the planning process (Cho, 2000). For the building industry in North America, one of the most important referent in this matter is the Project Definition Rating Index (PDRI) for buildings, which was developed by the Construction Industry Institute (CII) (Bingham & Gibson, 2017). While the PDRI and the early project processes it supports (such as need identification, project definition, and basis of design) have been effective for conventional capital project planning, they are insufficient in a CE approach.

Thus, the purpose of this chapter is to develop an argument that starts with the main tenets of the CE in the construction industry and the built environment, as defined and understood in a selection of academic literature. This creates a framework of circular building features and principles that are used to analyze the content of a pre-project planning tool for buildings. The comparison between the features associated with circular buildings and conventional ones enables us to identify dissonances or gaps between the different scenarios for the pre-project planning stage. The empirical contribution of the argument resides in the integration of the lessons learned and findings related to circular building principles and green design methods applied in an adaptive reuse case study. The theoretical contribution underlines a contextual and process-based understanding of capital project planning for a CE. As well, this study contributes to the theoretical foundations of pre-project planning and a stepping stone to shape future research initiatives on the topic.

3.3 Problem statement

Adaptive reuse synthesizes many of the CE principles and methods in order to restore, reconfigure and repurpose existing buildings. An urgent need exists to develop and validate effective planning principles, methods and tools for adaptive reuse building projects. In particular, while the PDRI for buildings is known to be an effective planning tool for green-field building projects, it has limited applicability to the circular model. Complementary tools are also required such as selective disassembly planning methods, LCA analysis procedures, and methods to justify development incentives offered by government. Thus, it is proposed a capital project planning framework and related research that must be accomplished to enable a more CE in the capital projects sector. This section provides a short introduction to the main concepts addressed in this chapter, the CE in construction, CE for the built environment, and the implications of circular building principles in capital project delivery.

3.3.1 Designing for a Circular Economy in construction

The conceptualization of CE has evolved through the years and it has been gaining momentum since the late 1970s (Geissdoerfer et al., 2017). The shared founding principles lie in the better management of resources and waste by minimizing (or closing) material and energy loops (Geissdoerfer et al., 2017; Lacy & Rutqvist, 2015; Pomponi & Moncaster, 2017). In their work, Pomponi and Moncaster (2017) developed an exhaustive critical literature review to categorize CE research in the last three decades. They concluded that green supply chains and waste reduction have been the main drivers of research due to the evident opportunities, such as reductions in energy use, environmental impacts, and waste production.

By definition, the strategies for engaging a CE in the construction industry are long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling (Geissdoerfer et al., 2017; World Economic Forum, 2016), and the mechanisms to afford it are design for deconstruction, durability, adaptability, the environment, closed materials loops, and dematerialization (Kibert, 2007). Therefore, construction as an industry is implementing designs and systems with improved long-term life-cycle performance. The main objective is to consider closed-loop design principles. These principles can be defined as a construction involving materials and building elements from old buildings that can infinitely be recycled or reused through natural or industrial processes (Sassi, 2008). In a similar way, recognition of the potential of reusable building materials toward a CE in construction has driven diverse research in this field (Gorgolewski, 2006). However, much of the potential for reuse depends on the state of the existing building stock as a raw material bank for new buildings (Ortlepp, Gruhler, & Schiller, 2016; Stephan & Athanassiadis, 2017).

In essence, the most eco-effective sustainable strategies in a CE, are those that are conceptualized from the beginning to create positive impacts and beneficial footprints, rather than focusing just on doing as little damage to the environment as possible (Guldager Jorgensen & Somme, 2016; Lyngsgaard & Guldager Jorgensen, 2013). Adaptive reuse of buildings is often superior to new construction in terms of sustainability (Conejos et al., 2015; Douglas, 2006).

3.3.2 Analysis of the existing building stock

An accurate inventory analysis of the building stock must be a fundamental part of strategic planning for a CE in construction and of planning for particular capital projects. It will provide decision makers with the necessary financial, social, and environmental information to maximize project performance in terms of sustainability. Advances in Building Information Modeling (BIM), City Information Modeling (CIM), and the Internet of Things (IoT), as well as the enormous amount of data already available in virtual platforms such as Google Earth, real estate data-bases, and public Geographical Information Systems (GIS), are enabling a realistic, dynamic, and up-to-date inventory analysis of buildings stocks. It is still a challenge, however, to perform this kind of analysis, because the information is dispersed and non-unified. For example, it is difficult to know which buildings in a region are at the end of their lifespan.

Existing buildings approaching the end of their lifespan could become a “mine” of materials, since it is often more effective to recover the components through PRM than to produce or extract the raw materials for new ones (Langston et al., 2008; Schultmann & Sunke, 2007). In fact, Conejos (2014) claims that demolition and equivalent new construction of energy-efficient buildings would require decades to equal the energy savings of rehabilitating and reusing existing buildings. Hence, the largest portion of natural resources savings as well as the minimization of the environmental impacts are in retrofitting and redeveloping existing buildings rather than producing new energy-efficient buildings (Conejos et al., 2014; IPCC 2007), in essence “re-using” existing buildings. Thus, adaptive reuse for buildings has emerged as a broadly growing practice. However, there can be a resistance from builders and owners when they have the alternative of reusing materials. Part of this is due to the knowledge gaps about reused materials' reliability (Yeung, 2016), lack of science-based user-friendly methodologies in the field (Conejos et al., 2015; Conejos et al., 2014), and the underestimation of the embedded resources in the building components and materials (Langston et al., 2008; Schultmann & Sunke, 2007; M. M. M. Teo & Loosemore, 2001).

3.3.3 The importance of pre-project planning and circular building principles in capital project delivery

The capital project delivery system is a complete series of operations leading to the occupancy of a finished building. It is well known that a total project delivery system encompasses the pre-project planning, design, and construction phases of the project life-cycle. It can be argued that the pre-project planning phase is the most important in a project life-cycle in terms of determining the success of its outcomes (Cho, 2000; CII 1994; Johansen & Wilson, 2006; M. A. Smith, 1983). Pre-project planning is focused on setting the major decisions of a project scope that will affect the cost and schedule performance, operating characteristics, as well as the overall financial success of the project.

For three decades, a number of research studies have investigated and demonstrated the importance of the pre-project planning phase in different industries and sectors (Ballard, 2000a; Bingham & Gibson, 2017; Cho, 2000; Edkins et al., 2013; Johansen & Wilson, 2006; Morris, 2011). In the early 1990s, Morris (2013) proposed an alternative project management model named Management of Projects (MoP). In this model, Morris settled the framework for managing the preconstruction planning as well as downstream execution. The MoP model focuses on the project in its context, particularly on early definition of the project success factors, rather than the execution and delivery stages, as is the case in traditional project management (Morris & Edkins, 2013). In 2000, Ballard termed the preconstruction planning process as "front-end" planning, and he identified this process as a fundamental part of the project definition and design phases of the Lean Construction Institute's Lean Project Delivery System. In his work, Ballard (2000b) developed and tested an approach to increase plan reliability during design processes, named the Last Planner System. Similarly, due to concerns of poor prediction of client cost and construction duration, the Egan Report (1998) Rethinking Construction proposed a specific set of performance measures of time and cost predictability. This set of performance measures is well known as the Key Performance Indicators (KPIs), and they have been studied, implemented, and extended by numerous organizations. The Construction Best Practices Programme (CBPP) is recognized as the leading organization involved in the production of KPIs (Beatham, Anumba, Thorpe, & Hedges, 2004). In North America, for over three decades the Construction Industry Institute (CII) studied the pre-project planning phase for new buildings. In 1998, CII developed a pre-project planning tool called the Project Definition Rating Index (PDRI) for buildings, as part of a series of PDRI's for different construction industry sectors. In this chapter, it is considered the PDRI and its derivatives an important and representative applied tool set for this domain, as its use on hundreds of building projects has been well documented by the CII.

Despite its efficacy, a linear project life-cycle paradigm still dominates the pre-project planning for capital project delivery. Linear project life-cycle stages include extraction, construction, operation, and EoL. An unlimited amount of natural resources is assumed, and their restoration or preservation, as a part of a sustainable cycle, is neglected. The evidence shows that when having strictly commercial objectives, externalities as well as environmental and social impacts, are neglected (Mokhlesian & Holmén, 2012).

Under a linear project life-cycle approach, even the conceptualization of a green building could result in a paradox. This approach is focused on the construction of new high-efficient eco-friendly buildings. However, according to circular building principles, a shift of thinking in the perception of sustainability in construction is necessary; switching from the traditional creative and innovative approach to a restorative and regenerative one. This change of perception is founded on the facts that an enormous proportion of all of the materials ever extracted are in today's built environment (Kibert, 2007), and the turn-over rate of buildings is considered relatively low (Beccali et al., 2013; Conejos et al., 2014; Sandin et al., 2014; Wilkinson et al., 2009). As well, the price of materials extraction is increasing, as are the negative environmental impacts, due to the natural constraints of the more dilute and distant stocks of ores and other resources (Kibert, 2007). Understanding the real value of the built environment in terms of sustainability through merging cutting-edge technology with the most updated and realistic buildings' databases (Langston, 2013; Ortlepp et al., 2016; Stephan & Athanassiadis, 2017), and the improvement on the monetization of environmental impacts through technological development and research in the field (Shindell, 2015; Viscusi, 2005; Yeung, 2016) could well be improved. It is clear that while useful to date, the current implementation of pre-project planning is insufficient for capital project planning for a CE.

Central to this chapter, is the recognition of inadequate development of capital project planning tools for achieving sustainability and CE objectives. As previously described, above, pre-project planning is the most important stage for construction success. Pre-project planning has been defined as, "the process of developing sufficient strategic information for owners to address risk and decide to commit resources to maximize the chance for a successful project" (CII 1994). Pre-project planning is analogous to processes in other sectors and geographic regions of the construction and capital projects delivery industry such as front-end loading (FEL), project programming, schematic design, conceptual planning, feasibility analysis, and early project planning. In spite of its importance, early planning in most cases could be performed much better in the building industry. Some authors attribute this problem to the lack of studies that demonstrate quantitatively the effectiveness of the pre-project definition for buildings (Xia, Xiong, Skitmore, Wu, & Hu, 2016). Other authors claim that it is due to the lack of development of science-based user-friendly tools to assist in developing a clear project definition for buildings (Cho & Gibson Jr., 2001; Dumont, Gibson Jr., & Fish, 1997).

Some of the most important tools available in this domain are the PDRI, Alignment Thermometer, Front End Planning Toolkit, and Shutdown/Turnaround Alignment Review (STAR). All of these tools have been developed to be functional under the traditional conditions of a linear economy approach. There is little or no evidence, however, in their fundamental development about the incorporation of a CE approach. It is argued in the following that the early capital projects delivery phases for a CE should have distinct stages, decision gates, and more appropriate planning methods, such as selective disassembly, LCA monetization protocols, and optimization methods.

The PDRI was developed to assess projects from feasibility through the end of detailed scope and up to the project execution stage. During scope definition, the most relevant information for the project, such as general project requirements, necessary equipment and materials, and construction methods or procedures, is identified and compiled to permit effective and efficient detailed design to proceed (Cho, 2000). The PDRI allows project teams to assess and measure the gaps in scope definition, providing a basis to manage the process. According to Bingham and Gibson (2017), the PDRI estimates an index that measures the relative level of definition for the project, where a lower score indicates a more complete scope definition. It is completed collaboratively and often more than once in the pre-project planning phase. Over the past decades, the PDRI tools have been updated and revised, and data on their efficacy have continued to be captured (Bingham & Gibson, 2017).

While the PDRI and the early project processes it supports (such as need identification, project definition, and basis of design) have been effective for conventional capital project planning, they are insufficient in a CE approach. For example, in a linear construction life-cycle approach, no constraints are recognized for material resources or their final disposal. In contrast, a circular life-cycle approach aims to preserve products, components, and materials at their highest possible utility and value in order to create more sustainable cycles. Tools such as the PDRI have focused principally on the market performance of building projects. Externalities such as social and environmental impacts are not included. While this perspective predominates in North America, it persists worldwide, and it has led to underestimating the real value of reusing existing building stock for an efficient CE. Values must change and a better understanding of capital project planning for a CE is needed to move forward. There are posed questions and proposed a framework for that purpose in the next section.

3.4 The advantages of adaptive reuse over green-field construction

Choosing adaptive reuse for a building project is a complex process. Figure 3-1 shows the role of adaptive reuse in the construction value chain in a CE, and it illustrates the capital project planning framework proposed in this chapter. When a new need for a Capital Project arises, choosing greenfield construction is the most logical option when the main driver of the project is the financial efficiency inside of a resource-based economy, as it is showed in the left part of Figure 3-1. However, the evidence suggests that this model is obsolete, unsustainable, and it is reaching its physical limits. Therefore, it is proposed a capital project planning framework for closed-loop cycle construction projects, as it is showed in the right part of Figure 3-1. The proposed framework must incorporate the vision of the emergent business models in CE to take advantage of the vast build environment. Capital projects delivery for a CE should have distinct stages, decision gates, and planning methods, such as selective disassembly, LCA monetization protocols, and optimization methods. As it is displayed in Figure 3-1, adaptive reuse has the potential of helping in closing the loop for the resources embedded in the build environment through a building inventory analysis. Most of the processes identified as part of the adaptive reuse cycle in Figure 3-1 require further research and development. Many aspects have to be considered, such as the physical integrity of the building, economic issues, functionality, technological retrofits, social impact, and legal and political issues. For this reason, limited research has been done regarding establishing feasible methodologies for the assessment of adaptive reuse of buildings. Some authors stress that intuition and experience are the only guides in making decisions about adaptive reuse (Highfield & Gorse, 2009). Some processes and tools have been developed, such as the Adaptive Reuse Potential (ARP) model (Conejos et al., 2015), the adaptSTAR model (Conejos et al., 2014), and "smart growth codes" (Cantell, 2005; DHUD 2001). However, substantially more research to enable the processes described in Figure 3-1 is required.

As discussed earlier, undervaluing and thus not including social and environmental impacts in existing planning tools is misleading. For example, the lower budget segment of Figure 3-1 summarizes part of the findings in a case study for developing an LCA-based decision-making methodology for evaluating adaptive reuse of buildings. The situation is typical. Despite the fact that the contract value of the adaptive reuse building project did not report a reduction in the final budget in comparison to green-field construction, the distribution of the construction budget was completely different. Construction materials costs were substantially lower for the adaptive reuse project than the green-field alternative. In contrast, the skilled labor expenses increased considerably. The increment of employment represents a completely unrecognized social benefit, and the reduction of the demand for raw materials promotes an intelligent economy instead of a resource based one.

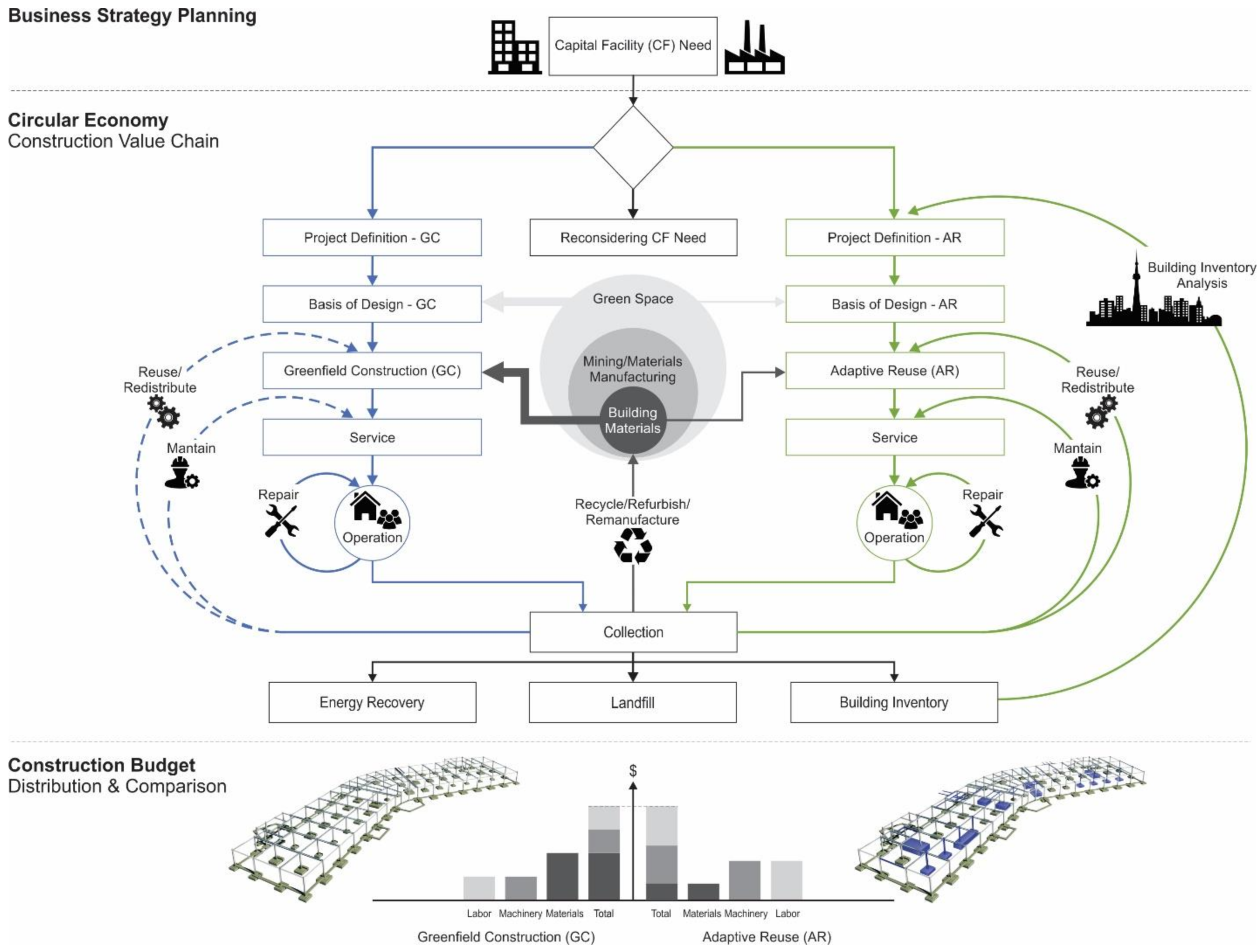

Figure 3-1: Circular economy principles in the construction value chain - Greenfield Construction (GC) vs Adaptive Reuse (AR)

Most sustainable development arguments seem to miss this point and thus lose effectiveness in motivating local change. While the impact of the sheer size of the existing built environment from an energy efficiency and retrofitting perspective has not been neglected, appreciation of the potential for adaptive reuse as opposed to recycling and reconstruction has been missing. That said, adaptive reuse can be expensive. It has a high impact on the EoL value for a building. If a building is technically difficult to recover, it might actually increase its environmental and economic cost in comparison to a new building. Therefore, it is necessary to develop methods to predict the financial, social and environmental performance for adaptive reuse building projects. This makes it possible to understand and justify objectively when a building asset should be redeveloped using adaptive reuse.

This last point is important, because the methods and regulations needed rely on conventional intuitive planning procedures by experienced professionals in the construction industry to determine the scope and convenience of adaptive reuse projects. Intuitive planning procedures are easy to apply but can lead to suboptimal plans, and expertise is in short supply (Lin & Haas, 1996). Many quantitative planning tools for adaptive reuse need to be developed (Figure 3-1), such as selective disassembly planning, and, among them a PDRI for reuse is perhaps the most important.

3.5 Developing a project definition rating index for adaptive reuse

The existing PDRI for buildings consists of 64 scope definition elements grouped into 11 categories in a weighted checklist format. Substantial revisions are required for adaptive reuse projects. For example, the basis of design is more focused on retrieval of existing information and the evaluation of the constraints that this process imposes. Also, the basis of design should assist in mitigating the risk stemming from issues such as technical feasibility, cost effectiveness, environmental impact justification, logistics problems, and permitting requirements. Therefore, in this study it is suggested some modifications to the PDRI for buildings, so that it could be used as a starting point for creating a PDRI for adaptive reuse projects. The modifications are organized into four groups according to planning objectives, as follows.

3.5.1 Basis of project decision

For the first group, the main objective is to develop the basis of project decision. It involves retrieval of the information necessary for understanding the project objectives according to circular building principles. Though the current PDRI includes an option for the evaluation of existing buildings, it does not include any requirement for the justification of the business strategy, owner philosophies, and project requirements in terms of a CE. While a single building project would not justify developing an exhaustive macroeconomic analysis on these topics, a certain level of analysis is necessary in order to understand better the role of each particular project inside the built environment. This information is crucial in setting up the conditions for making strategic decisions aligned to CE principles, such as in the case of adaptive reuse of existing buildings instead of green-field building. This approach will be necessary when as a society it would be decided that all project objectives are not strictly commercial, and when social and environmental factors become monetized.

3.5.2 Basis of design

The second group of modifications has the objective of retrieving existing information for developing the project's basis of design, according to the imposed constraints. Once the basis of project decision has been completed, and the conditions for an adaptive reuse building project have been established, it is possible to develop the basis of design. Typically, for an existing building, most of the information in this matter is already documented. For adaptive reuse projects, the definition elements should be more focused on the affordability of retrieving the existing design documentation, verification of the existing condition's compliance according to the updated construction codes, and analysis of the current physical conditions. This point is important, because a change in the scope and approach of the scope definition elements should change their weights in the overall PDRI score table. A comprehensive study is necessary to determine the element weights for the PDRI for adaptive reuse projects.

3.5.3 Recovery of economic and ecological value

The third group of modifications required has the objective of recovering as much of the economic, social, and ecological value of a building as possible during the process of adaptive reuse. The potential benefits of adaptive reuse rely on the fact that it is possible to take away components from an obsolete building and then repair, reuse, remanufacture, or recycle them. Some of the most important recovery EoL methods include design for disassembly, design for maintainability/serviceability, design for reuse, design for remanufacturing, and design for recyclability (S. Smith & Hung, 2015). For existing assets, complete design for disassembly is not possible, and the process is reduced to planning for disassembly. Planning for disassembly must play a key role in the adaptive reuse process, where the disassembly planning sequence (as well as the disassembly methods used to recover target components) has to be performed in an efficient way. The target components can be architectural, structural, mechanical, or electrical, among others. The objectives should be to reduce building costs and to increase the building components' life-cycle persistence. If the design for disassembly is too complex or time-consuming, the associated economic and environmental costs could be higher than installing new components. Therefore, it is necessary to incorporate a cost-benefit analysis for selective disassembly and demolition planning.

3.5.4 Execution approach

The execution approach definition must have the objective of evaluating the project scope elements that are necessary to fully understand the requirements of the owner's execution strategy, aligned to closed-loop cycle building methods. Groups of elements in the PDRI Execution Plan section include procurement strategy, deliverables, project control, and project execution plan. For the “project execution plan” group, the description of the scope elements in the PDRI has been delineated and weighted according to the most common and effective practices for green-field building. In a CE, the project execution plan faces different challenges due to the inclusion of new techniques for construction (green design methods), more stakeholders in sustainable development (environmental and social stakeholders), and new ways for trading building resources, such as materials, machinery use and labor, due to the increase in the valuation of the net environmental impacts that they produce from a life-cycle perspective.

In summary, redefining, re-weighting, and selectively adding to, as well as deleting from, the current group of 64 scope definition elements of the PDRI tool would make it applicable for planning closed-loop building projects, such as adaptive reuse projects.

3.6 Summary of findings on capital project planning for a Circular Economy in the construction industry

In this chapter it is argued that project planning for capital projects must change as the business models shift from a linear to a CE. While understanding of the real value of the built environment in terms of economic, environmental and social dimensions has improved through technological development and research, more progress is required. In the current linear economy, the economic dimension still drives capital project planning. The evidence suggests this situation is unsustainable, unbalanced, and is reaching its physical limits.

Thus, a capital project planning framework is proposed for closed-loop cycle construction projects. It is argued that the capital projects delivery phase for a CE should have distinct stages, decision gates, definition confidence categories, and planning methods, such as selective disassembly, LCA monetization protocols, and optimization methods. It is also suggested a reference framework for required revisions to develop a planning tool for adaptive reuse projects. This framework identifies the project scope elements from the PDRI for buildings that must be modified in order to align them with circular building principles. Similarly, it is argued that some project scope elements should be completely modified according to the nature of the value chain in a CE. Finally, it is defined another set of project scope elements that should remain without any changes in the approach. However, they should be investigated in order to demonstrate and validate the weight that represents their importance in the performance of a closed-loop cycle construction project. As well, validation is required to examine the hypothesis that the successful completion of a closed-loop cycle building project is positively correlated with the quality of the project definition during the pre-project planning phase. In other words, a well-defined project definition would correspond to a higher probability of project success in terms of sustainability.

In the capital project delivery phase of circular infrastructure, science-based, user-friendly, and fit-for-purpose methods are needed to decide amongst green-field construction versus adaptive reuse, to develop pre-project planning for closed-loop cycle construction, and to plan for the optimization of the benefits of adaptive reuse. Research and development in these areas is required to address the most important missing pieces of a CE value chain in construction. The merging of research in this field and the technological advances in the areas of BIM, CIM, IoT, and the enormous amount of data already available in virtual platforms will be the drivers to complete the reference framework proposed in this article.

Chapter 4: Analysis of the net environmental impacts and buildings cost performance for adaptive reuse of buildings[2]

4.1 Abstract

Adaptive reuse of buildings is considered a superior alternative for the renewal of today's built environment. However, little research has been done for assessing adaptive reuse building projects in terms of life-cycle and CE. Because of the great impact that the building industry has on the environment, failing to optimize buildings' useful life can result in their residual life-cycle expectancy not being fully exploited, and with it, wasting the resources embedded therein, such as Primary Energy Demand. The aim of the study presented in this chapter is to develop a life-cycle analysis of the net environmental impacts as well as the building's cost performance of an adaptive reuse project. This study focuses on the analysis of the structural system. Results show that the adaptive reuse of the building structure produces a considerable decrease on the environmental impacts and the construction building cost. Distribution of cost among materials, labor, and equipment is different than those for a new building. This study objectively demonstrates the considerable benefits of the adaptive reuse of the structure of an existing asset. In contrast, the non-structural building subsystems have been identified as an area with high potential for improving the existing inefficiencies during the adaptive reuse process.

4.2 Introduction

Buildings play an important role in the depletion of natural resources and in the production of negative environmental impacts. Therefore, there is an urgent need to mitigate these undesirable problems, arising from neglecting the direct or indirect processes involved, throughout the building supply chain. Several studies have recognized adaptive reuse of buildings as a superior alternative to new construction in terms of sustainability and CE. Many successful projects of adaptive reuse have been documented around the world including defense estates, airfields, government buildings, industrial buildings, offices, schools, and religious buildings, among others.

Little doubt is expressed about the social, economic, and environmental benefits of applying adaptive reuse. As a matter of fact, the same methodologies used to quantify the social and economic benefits of new building projects have been applied to justify the feasibility of adaptive reuse. However, when proponents

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[2] The contents of this section of the chapter have been incorporated within a paper that has been submitted for publication. B. Sanchez, M. Esnaashary Esfahani, and C. Haas, "Analysis of the net environmental impacts and buildings cost performance of an adaptive reuse project - Case study: Region of waterloo county courthouse renovations" Submitted to the Journal of Environment Systems and Decisions. Submission date Dec. 24, 2018. Only minor editorial changes are applied for being consistent with the University of Waterloo thesis format.

of these projects justify and communicate the environmental benefits to the stakeholders, they do so with a lack of objectivity. Hence, a well-known and widely accepted sustainability framework rooted in physics, can serve as the technical basis for characterizing the sustainability benefits of adaptive reuse in a way that would be understood by the general public and that would have a credible scientific basis. Similarly, there is a lack of studies analyzing adaptive reuse projects outcomes, in terms of construction building cost. The aim of the study presented in this chapter is to develop an analysis of the net environmental impacts and building cost performance of an adaptive reuse project.

Through a case study, the net environmental impacts and the building cost of an adaptive reuse project are quantified and compared with new construction. A consequential substitution Life Cycle Assessment (LCA) is performed in order to quantitatively demonstrate the relevance of each building subsystem, as well as their influence on the net environmental impact and building cost due to adaptive reuse. This study looks to provide objective evidence to help in the understanding of the decision-making for adaptive reuse building projects, as well as the main variables involved throughout the design process. This study aims to develop an accurate case study that serves as an archetype example through the merging of cutting-edge technology in the fields of Building Information Modeling (BIM) and LCA for buildings. The final results showed that the adaptive reuse of the building structure produces a considerable amount of environmental savings, around 35-38% decrease for Primary Energy Demand (PED), Global Warming Potential (GWP), and Water Consumption (WC). The budget analysis revealed an important reduction of the construction cost, around 70% reduction of the construction bare cost, as well as a redistribution of the investment on materials, labor, and equipment. The investigations unveiled a decrease of the investment on construction materials, and an increase for labor and equipment, for the adaptive reuse case study. This finding finally exposes the potential economic benefits of adaptive reuse due to the shifting from a resource-based economy towards a CE in the construction industry.

This study objectively demonstrates that the biggest benefits of the adaptive reuse of an existing asset are in the structure. Consequently, the rest of the building subsystems have been identified with high potential for improving inefficiencies during the adaptive reuse process. These inefficiencies should be addressed from the early stages of the project planning through the implementation of green design methods and tools, such as, PRM, planning for deconstruction, and selective disassembly planning.

4.3 Problem statement

In an era of climate change mitigation and adaptation, efficient use of the earth’s natural resources is considered a practical means to increase sustainability in urban settlements. Many studies have recognized the importance of the EoL stage in buildings, and the opportunity of their adaptive reuse as a superior alternative to new buildings in terms of sustainability and CE (Bullen, 2007; Cantell, 2005; Conejos et al., 2015; DHUD, 2001; Douglas, 2006; Highfield & Gorse, 2009; Huovila, 2007; Langston, 2008; Langston et al., 2008; Schultmann & Sunke, 2007; Tan et al., 2014; Vilches, Garcia-Martinez, & Sanchez-Montañes, 2017; Wilkinson et al., 2009; Wilson, 2010). However, there is a lack of studies for analyzing the performance of adaptive reuse building projects with a life-cycle perspective. Some of the reasons are due to methodological complexities, process inefficiencies, and technological limitations for developing studies with these kind of characteristics (Sanchez & Haas, 2018b), as well as the lack of understanding of the real value of the built environment in terms of CE (Sanchez & Haas, 2018a). The study presented in this chapter aims at addressing this gap by performing a thorough life-cycle analysis of the net environmental impacts and buildings cost performance of an adaptive reuse project.

4.3.1 Embodied environmental impacts in the built environment

Over the course of the last three decades, several studies have approached the problem of the lack of sustainability in the construction industry through energy-efficiency of buildings in their operational stage. This makes sense, since the energy use of a building's operation accounts for 70-90% of the energy used during its life-cycle. Also, energy consumption is the main factor responsible for natural resource exploitation and pollutant emissions in the construction industry (Beccali et al., 2013). As a result of these studies, there have been significant advances towards the decrease of operational energy consumption in new and existing buildings. Depending on the level of integration of both an appropriate building design and green technologies, the energy use reduction of a high-efficiency new building can reach 75% or even higher, of the typical total operational energy consumption (IPCC, 2007). In existing buildings, the energy reductions have been reported from 50% to 90% through deep retrofits (IPCC, 2015). Because of the advances in this matter, the relative importance of the rest of the life-cycle stages of buildings (production, construction, and EoL) has increased (Azari & Abbasabadi, 2018; Beccali et al., 2013; Moncaster, Pomponi, Symons, & Guthrie, 2018). The energy consumed in all of the life-cycle stages, excluding the operational stage, is collectively stated as embodied energy (Liu, Wang, Xu, Liu, & Luther, 2018). Likewise, the relative importance of the non-operational stages of buildings has increased because of the trade-off between the operational and embodied energy (Beccali et al., 2013). A building can achieve high energy-efficiency levels through energy retrofits; in exchange, the embodied energy will increase due to the higher environmental burden during the production, on-site construction, transportation, final demolition, and final disposal of the building materials and components for the energy retrofits (Jalaei & Jrade, 2014).

The largest quantity of materials ever extracted are in today's built environment (Kibert, 2007). Because the turn-over rate of buildings is considered low (no more than 3% yearly), it would take several decades or more, before the energy efficient strategies of new building construction can decrease the amount of environmental impacts generated, in a global perspective (Beccali et al., 2013; Conejos et al., 2014; Sandin et al., 2014; Wilkinson et al., 2009). Therefore, during the last decade the research has focused on the retrofitting, refurbishing, and renovations of existing assets (Kibert, 2007; Langston et al., 2008).

4.3.2 Life Cycle Assessment in sustainable building design

LCA is a methodology that accounts for the materials and energy involved in a product or service along its life-cycle, and then measures the associated environmental impacts (ISO 1997). An LCA shall include definition of goal and scope, inventory analysis, impact assessment and interpretation of results (ISO 1997). LCA has been used for environmental evaluations of product development processes in different industries for a long time, but it has only been applied to the building construction sector in the last decade (Cabeza et al., 2014). Through applying this methodology to the building and construction industry, it is possible to make important decisions during the design stages of a building, based on a holistic approach that involves the stakeholders of a global society. LCA represents a rational standardized approach which can evolve with the development of knowledge and it may help the stakeholders to agree upon common strategies (Peuportier, 2001). Nowadays, LCA is considered as one of the main tools used to help achieve sustainability in the building industry (Azari & Abbasabadi, 2018; Cabeza et al., 2014; Jalaei, 2015; Moncaster et al., 2018; Zabalza Bribian et al., 2009). When LCA is incorporated into the decision-making process for buildings, the stakeholders can scientifically asses the life-cycle impacts of building subsystems, materials, and components, and then select the alternatives that could decrease their net environmental impact.

Currently, considerable research is being done in the area of integration of sustainability in construction and BIM. Project teams have found that synergies between green building design and BIM can help to improve the accomplishment of sustainability goals (Wu & Issa, 2015). This interdisciplinary synergy is known by the name of “green BIM” or “6D BIM”. The objective is to efficiently integrate model-based technologies (e.g. BIM and Geographic Information System [GIS]), specialized methods for assessing sustainability (e.g. LCA, Life Cycle Cost [LCC], and Energy Analysis software), and existing databases (e.g. building stocks, meteorological information, and real estate databases) which are needed to perform a realistic simulation. Some researchers have pointed out that a unique software package does not exist that can provide all of the required functions for a sustainable assessment for buildings at all of the stages of an LCA (Jalaei, 2015; Wu & Issa, 2015). Yet, through interoperability and data exchange between applications it is possible to develop integrated green BIM tools. This is possible due to data models that have become the international standard for data exchange in the building industry (Jalaei, 2015). Despite the increasing usage of all of these kinds of technological advances in the construction industry, their implementation in existing buildings is still limited. Research approaches are intensifying the application of BIM in existing buildings to capture and integrate building data, deconstruction functionalities, and reuse of materials and components (Kokkos, 2014).

4.3.3 The role of adaptive reuse in the Circular Economy

The restorative and regenerative nature of adaptive reuse of buildings is highly aligned to CE building principles such as better management of resources and waste minimization in the construction industry (Sanchez & Haas, 2018b). On a larger scale, adaptive reuse of buildings is an efficient way to take advantage embedded resources in today's vast built environment, towards more sustainable development (Kibert, 2007; Langston, 2008; Sanchez & Haas, 2018a).

In 2010, it was estimated that the total building stock in the United States was approximately 27 billion m^2, and that annually 0.162 billion m^2 of buildings were torn down, while annually 0.464 billion m^2 were renovated and/or newly built (Conejos et al., 2014). Moreover, for every four commercial buildings constructed, one is demolished, and for every six houses built, one is demolished (Conejos et al., 2014). According to Yudelson (2009), approximately 75% of the buildings expected to be operating in the year 2040 are already built. Existing buildings approaching the end of their lifespan could become a "mine" of raw materials, since recovering the components through PRM is often more efficient than extracting raw materials to produce new ones (Langston et al., 2008; Schultmann & Sunke, 2007). In fact, Conejos (2014) claims that demolition and equivalent new construction of energy-efficient buildings would require decades to equal the energy savings of rehabilitating and reusing existing buildings. Hence, the greatest natural resource savings as well as the greatest environmental impact minimization are in retrofitting and redeveloping existing buildings rather than producing new energy-efficient buildings (Conejos et al., 2014; IPCC, 2007; Vilches et al., 2017), in essence "re-using" existing buildings. Thus, adaptive reuse for buildings has emerged as a broadly growing practice.

In this matter, current research has pointed out that the most accessible existing buildings for adaptive reuse are the ones with reasonable acceptable structural integrity (Conejos et al., 2015; Conejos et al., 2014; Tan et al., 2014; Wilson, 2010). From a life-cycle perspective, several studies have revealed that the structural subsystem of buildings is a main contributor to the negative environmental loads, especially for concrete and steel structures (Asdrubali et al., 2013; Blengini & Di Carlo, 2010; Cabeza et al., 2014; Chastas, Theodosiou, & Bikas, 2016; Moncaster et al., 2018). Therefore, the possibilities for achieving substantial environmental benefits, along the adaptive reuse process, are higher for the structural building subsystem. Due to the high impact that buildings have on the environment, it is particularly important to develop studies and methods to objectively determine the amount of environmental and economic benefits of the adaptive reuse of the structural subsystems of buildings. On the other hand, according to the investigations, the environmental burden from non-structural building subsystems does not appear to be as high as the one from the structural core of the buildings (Blengini & Di Carlo, 2010; Moncaster et al., 2018). Therefore, the potential environmental benefits of the adaptive reuse of non-structural subsystems are more dissipated.

Finally, it has been extensively argued that a main barrier for the implementation of adaptive reuse is the increment of building budget due to high remediation costs and construction delays, complexity and technical difficulties for refurbishment work, and availability of materials and lack of skilled tradesmen, among others (Conejos, Langston, Chan, & Chew, 2016; Hein & Houck, 2008; Shipley, Utz, & Parsons, 2006). Hence, there is an urgent need to develop financial studies to analyze the building cost performance of adaptive reuse projects, as well as the distribution of the construction building cost per building subsystem.

4.3.4 The goal of this study

The goal of the study presented in this chapter is to develop an analysis of the net environmental impacts and the building cost performance of an adaptive reuse project. Through a case study, that may serve as an archetypical example, the net environmental impacts as well as the building cost of an adaptive reuse project will be quantified and analyzed. A detailed consequential substitution LCA is performed in order to quantitatively demonstrate the relevance of each building component, as well as their influence on the net environmental impact and building cost due to adaptive reuse. As explained in the last sections, there is a lack of studies that reveal the advantages of the adaptive reuse of buildings, in terms of sustainability and CE. With the development of this case study, it is provided enough evidence to help in the understanding of the decision-making for adaptive reuse sustainable building projects, as well as the main variables involved through the design process. Finally, this study aims to develop an accurate case study through merging cutting-edge technology in the fields of BIM and LCA for buildings.

4.4 Case study: Region of Waterloo county courthouse renovations

The Region of Waterloo County Courthouse building is located at 20 Weber Street East, Kitchener, Ontario, Canada. It is a mid-20th century building built with a modern architectural style. The building is located on a two-acre parcel of land, situated on the north side of Weber Street East in the City Commercial Core Planning Community of the City of Kitchener, within the Region of Waterloo. The Region of Waterloo County Courthouse building, herein referred to as the courthouse, is recognized for its design, physical, contextual, historical and associative values (Pinard & Wade, 2012). The courthouse is a four-story structure with a basement and has a shape similar to a boomerang with a footprint area of 1,233 m^2 and

5,341 m^2 gross floor area (Appendix A). The primary structural system of the courthouse is a steel frame and the exterior finished with precast concrete cladding. The main entrance consists of a concrete parabolic arch influenced by the Conestoga Wagon used by European settlers to the region. The original courthouse was designed by the architectural firm Snider, Huget and March, and it was built in 1964. The original building replaced a previous County of Waterloo Courthouse and remained in service as a courthouse until 2013. Today, it houses Region of Waterloo offices, including the Region of Waterloo Archives, as well as Provincial Offences staff offices.

The original courthouse was redeveloped using adaptive reuse from 2014 to 2015 by the architectural firm Robertson Simmons Architects Incorporated. According to the Heritage Kitchener report number CSD-12-036 (2012), the courthouse was classified as non-designated property of cultural heritage value. All of the subsystems of the building had modifications in the reuse project. The modifications were principally due to the increment of loads, the complete rearrangement of the floor layouts and the expansion of the gross floor area by 487 m^2. One of the changes included the in-filling of two large double-height courtrooms. The redeveloped courthouse has been rated as a Leadership in Energy and Environmental Design (LEED) Gold Building.

4.4.1 Life Cycle Assessment goal and scope definition

The goal of the LCA in this study is to compare the environmental impacts between an adaptive reuse building project and a new building. The net environmental impacts of both an adaptive reuse and a new building for the project under study are calculated for comparison purposes. The results of both scenarios are compared in order to measure the savings on environmental impacts with a life-cycle perspective. For the purpose of this study it is called the reduction on environmental impacts between scenarios "environmental savings". In the end, the environmental savings are monetized according to the valuation of the natural resources of the region. The analysis is performed per building subsystem with the purpose of defining the importance of their contribution to the total environmental impact, and to determine the convenience of keeping each subsystem for an extended life. The subsystems under study are the substructure and superstructure. A consequential LCA approach is used to quantify the environmental impacts per subsystem. The building's operational phase is dismissed from the LCA system boundaries since this study is focused on the quantification of embodied resources. As a general assumption the operational stage of both approaches is considered the same for the purposes of this study, however a more specific and realistic assessment have to include the operational stage for its analysis. The environmental impacts that are estimated and monetized are Primary Energy Demand (PED) in Mega Joules, Global Warming Potential (GWP) in equivalent kilograms of CO_2, and Water Consumption (WC) in m^3 of water. Also, the building cost of the case study is estimated in terms of material, labor, and equipment.

4.4.2 Methodology for evaluating the net environmental impacts and building cost for adaptive reuse

The methodology for evaluating adaptive reuse of buildings per subsystem is shown in Figure 4-1. The framework provides a decision-making method to determine the environmental savings during the process of adaptive reuse of a building. The lower part of Figure 4-1 shows the construction budget distribution and comparison just for the rehabilitation and renovation of the building structure.

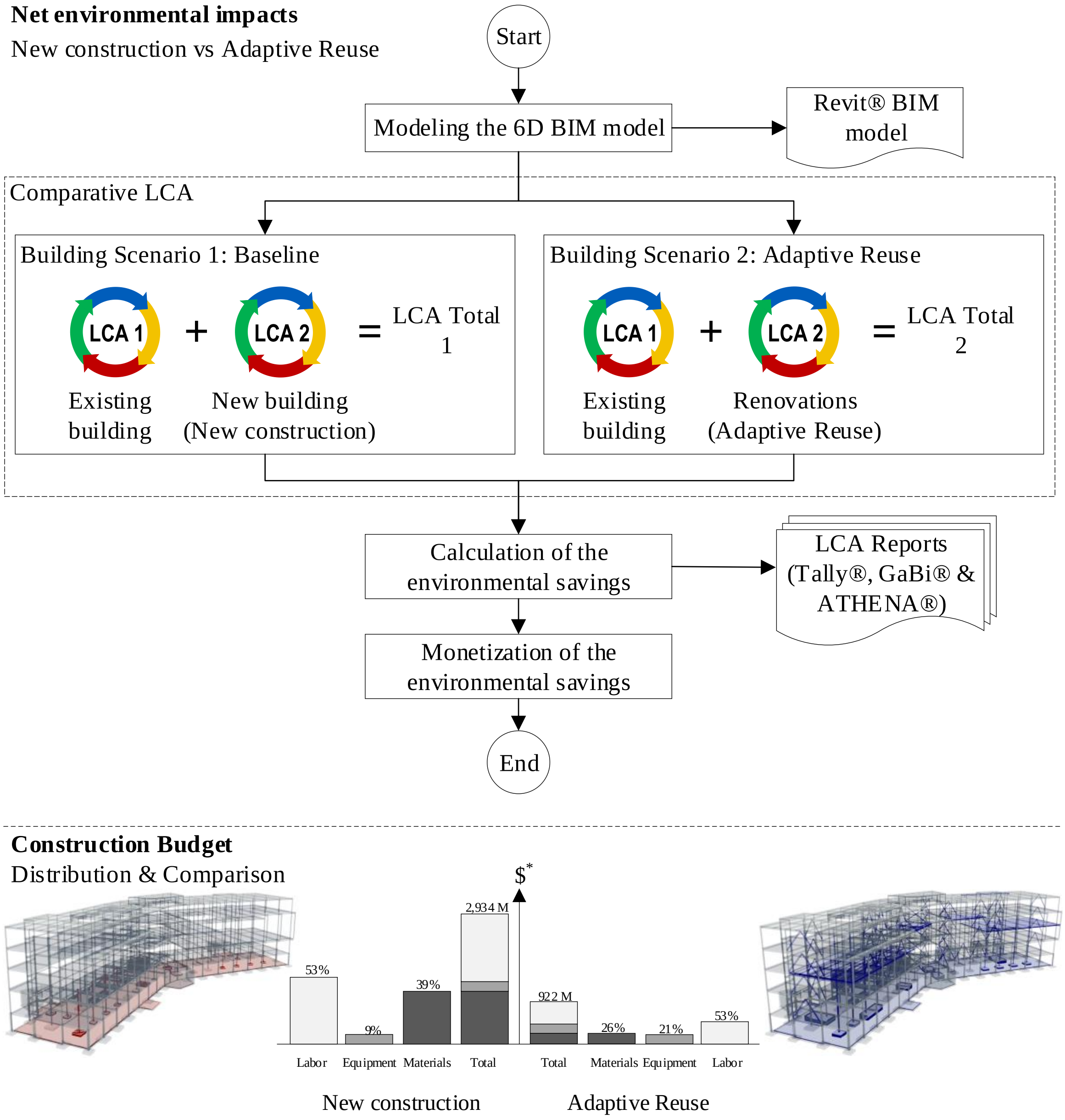

Figure 4-1: Comparative analysis of the net environmental impacts and buildings cost performance of an adaptive reuse project (* Dollars reported as $2018 USD)

4.4.3 Results and discussion

The first steps related to the BIM modeling of the existing and the redeveloped subsystems required a detailed description of the building components as well as the building project. With the project information, the BIM model of the structure was developed using the software Revit Architecture®. The defined phases for the purpose of this study were the existing building, demolition plan, and new building. The BIM model was divided into subsets of components in order to create the breakdown structure for the environmental impacts calculated in the next steps. The component subsets established for the substructure subsystem were isolated foundations, concrete footings, concrete walls, slabs-on-grade, steel columns, steel beams, and concrete slabs. The component subsets established for the superstructure were structural columns, structural beams, and concrete slabs.

In the next step, the LCA of the original and redeveloped subsystems under study were performed. The specialized software used for this purpose were Tally® and ATHENA®. Tally® is a specialized software aligned to ISO 14040-14044, which are the most widely accepted and well-known standards for LCA (KT Innovations®, 2015). The LCA modeling principles are aligned to the characterization scheme and methodology TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) developed by the United States Environmental Protection Agency (US EPA), commonly used for LCA work in North America (US EPA, 2016). The LCA calculation methodology details are explained in the LCA Tally® reports (see Appendix B). In this research, the studied objects were the subsets of the building structure used to compare the relative environmental impacts associated with the building components. The functional unit was the building structure. The reference flow, as well as the system boundaries, included the production, construction, and EoL stages, are in agreement with the defined scope. As part of the modeling process, the most common EoL treatments for the construction materials, such as recycling, incineration, and landfilling disposal, are based on average US construction and demolition waste treatment methods and rates. The software pre-sets for the EoL stage follow. Along with processing requirements, the recycling of materials is modeled using an avoided burden approach or “consequential approach”, where the burden of primary material production is allocated to the subsequent life-cycle based on the quantity of recovered secondary material (KT Innovations, thinkstep, & Autodesk., 2018). Incineration of materials includes credit for average US energy recovery rates.

In the modeling process, the production and EoL stages were calculated using Tally®. Then the construction stage was calculated with the software ATHENA®. The environmental impact categories estimated for the purposes of this study were PED and GWP. The WC was estimated according to literature on the topic and according to the materials quantity take-off retrieved from the BIM model.

Then, it was necessary to calculate two comparative scenarios. The first scenario was the baseline case, and the second scenario was the adaptive reuse case. In the first scenario, the LCA performance of two building structures was accumulated, the existing one and the new design without adaptive reuse. In other words, the baseline case represents the current trends in the construction industry of demolishing the entire building in order to build another one with new characteristics. Therefore, the new subsystem was considered as a completely new construction. Figure 4-2a shows the results per subset for the first scenario in terms of PED for the substructure. The increment from 3.7 million MJ to 4.2 million MJ was due to the features of the second design required by current building codes. The total PED for scenario number one was 7.9 million MJ. In scenario number two, the LCA of the two subsystems was accumulated with the difference being that the second subsystem was adaptively reused according to the specifications of the case study. Figure 4-2b shows the results per subset for the second scenario. The total PED for scenario number two was 5.2 million MJ. Appendix C display the detailed LCA results for the substructure and superstructure. The main difference from both scenarios was the reduction of the PED in the stages of production and EoL of the new building design. The environmental savings were calculated by the difference between both scenarios. The final comparison showed a reduction of 33.8% of PED, or 2.7 million MJ.

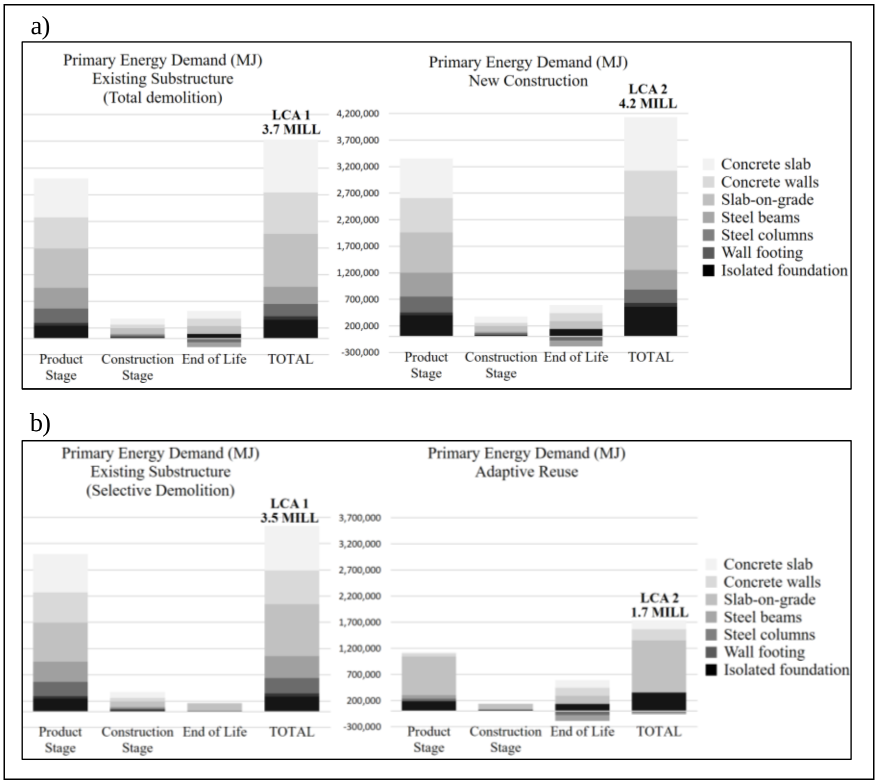

Figure 4-2: Comparison of substructure LCA results based on PED: (a) scenario 1 – total demolition and (b) scenario 2 – selective demolition

Finally, the environmental savings for PED were monetized based on the distribution of energy consumption per source and the average fuel price rates. According to the Canadian Industrial Energy End-Use Data and Analysis Centre (IEEDAC) (2016), the energy consumption for the construction industry in Ontario for 2014 was 20% natural gas, 66% middle distillates, 4% propane, and 10% confidential. The respective prices per unit as well as the prices per Giga Joule of the referred energy products were retrieved from the public databases of the National Energy Board of Canada (2016) and Natural Resources Canada (2016). The average prices were estimated for Ontario for the 2018 year. The final calculations suggest that the environmental savings related to the energy category for the substructure of the adaptive reuse scenario have a current value of $30,851 USD dollars.

The same procedure described above was applied for the superstructure and for the rest of the environmental impacts under analysis, GWP and WC. The monetization of the GWP and WC was estimated according to the available literature on the topic. The cost of air pollution and climate change gases, as well as the cost of water usage, have been investigated comprehensively in several studies (Shindell, 2015; Van Ast, Maclean, & Sireyjol, 2013; Yeung, Walbridge, Haas, & Saari, 2017a; Yeung, 2016). According to that literature a conservative cost for carbon emissions and water consumption in North America for 2015 was $84 US dollars per ton of CO_2 and $1.60 US dollars per m^3 of water, respectively. Table 4-1 shows the summary of the results of the calculation for the net environmental savings and building cost distribution.

Table 4-1: Case Study - Net environmental savings and building cost distribution (substructure and superstructure)

Building Subsystem	Envr. Impact	Envr. Savings	Percentage of Reduction	Monetization Envr. Savings[a]	Bare cost Distribution	Building cost (New Const.)[a]	Building cost (Adaptive Reuse)[a]
Substructure	PED	2.7 million MJ	33.80%	$30,851	Materials	$275,123 (9%)	$68,832 (7%)
	GWP	283,745 Kg CO_2 eq	34.00%	$25,689	Labor	$517,431 (18%)	$222,272 (24%)
	WC	4,511 m^3	35.00%	$7,779	Equipment	$80,139 (3%)	$57,548 (6%)
Superstructure	PED	7.81 million MJ	43.67%	$90,353	Materials	$861,054 (29%)	$168,329 (18%)
	GWP	669,795 Kg CO_2 eq	43.90%	$60,642	Labor	$1’029,620 (35%)	$266,786 (29%)
	WC	9,037 m^3	34.90%	$15,583	Equipment	$171,568 (6%)	$138,018 (15%)
Total				$230,901		$2’934,935 (100%)	$921,785 (100%)

[a] Dollars reported as $2018 USD

As part of the scope of this study, the building cost performance of the adaptive reuse project in comparison to new building construction was also estimated (see Table 4-1). In order to calculate the cost of adaptive reuse and a new building project, the cost of each construction phase was calculated and added together. Selective demolition and selective renovation are the phases for adaptive reuse, while demolition of the entire existing building and construction of a new building are the phases for the new building project. In both scenarios, the cost analysis is limited to the structural system. The 2015 RSMeans® data base was used as a reference for calculating the material, labor and equipment cost of the different construction concepts. RSMeans® is a holistic reference for construction cost estimation in North America, which provides the US national average cost of material, labor and equipment for different construction activities (RSMeans, 2015). At the end the budgets were estimated for the region of Waterloo by using the RS Means city cost index, and their corresponding annual inflation rate.

According to the cost analysis, the total direct costs of the adaptive reuse and new building scenarios are 0.922 and 2.934 million USD dollars respectively. It indicates a considerable cost savings for the adaptive reuse scenario (approximately 70% reduction of the structural system construction cost). According to Conejos et al. (2014), a building in a reasonable structural condition would be a candidate for adaptive reuse since the structural modification cost should be much lower than its demolition and reconstruction. The findings of this study are aligned with the assumptions in the literature review since the conditions of the existing structure were acceptable for its rehabilitation. The cost analysis revealed that the distribution of the bare cost for the construction of the whole structure is similar in labor for both scenarios (See Figure 1). However, there is a significant reduction of 13 percental points on the construction budget for materials. This reduction makes sense because the adaptive reuse is focused in the preservation of building components. In a CE perspective, the decrease in investment on exploitation of raw materials is fundamental in order to move towards a more sustainable environment. In this way, the budget is redistributed for the investment on labor and equipment that strengthens the local economy through increasing the employment in the region.

According to the literature review section, one of the main barriers for implementing adaptive reuse is the increment of construction building costs. This study demonstrates that an appropriate adaptive reuse of the structural system decreases the building budget considerably for that system, in comparison to new construction. In consequence, the evidence suggests that the increment of the building budget for the adaptive reuse of the entire building might be in the non-structural subsystems such as the building envelope, mechanical, electrical and plumbing subsystems. This finding is aligned to the rest of the literature review, since the non-structural subsystems represent an increment in cost, due to risk such as unknown conditions, and physical complexities, including, high remediation costs and construction delays, complexity and technical difficulties for refurbishment work, and availability of materials and lack of skilled tradesmen (Conejos et al., 2016). Also, adaptive reuse of non-structural subsystems requires more meticulous project planning complexities, such as, the fulfillment of new building codes and regulations, accurate information and drawings of the existing conditions, and planning and management tools for deconstruction, disassembly, and refurbishment.

In this matter, the field of adaptive reuse of non-structural subsystems should be studied in depth in order to solve the inefficiencies during the restoration process. This should be done from the early stages of project planning through the implementation of green design methods and tools such as PRM, planning for deconstruction, and selective disassembly planning. In previous studies (Sanchez & Haas, 2018a; Sanchez & Haas, 2018b), it has been pointed out that the implementation of green design methods for adaptive reuse projects have been scarcely investigated. Certainly, the development of this field is promising due to the high impact of the construction industry on the global environmental loads, the enormous volume of built environment, and the transformation towards a CE in the construction industry. In the latter, the construction industry has a considerable delay in comparison to other industries such as manufacturing, automotive, and textile, where the development and implementation of green design methods have demonstrated a huge amount of environmental and economic savings, in small and large scales.

4.5 Summary of findings on analysis of the net environmental impacts and buildings cost performance for adaptive reuse of buildings

Because of the great impact that the building industry has on the environment, failing to optimize buildings' useful life can result in their residual life-cycle expectancy not being fully exploited, and with it, wasting the resources embedded within. In this matter, adaptive reuse of buildings is considered as a superior alternative to new building construction, in terms of sustainable development and CE. Several studies have suggested the possibility of improving the financial, environmental and social performance of buildings, through adaptive reuse. However, to the knowledge of the authors, there are no studies that analyses the environmental and cost performance of adaptive reuse projects in an objective and methodological way.

The study presented in this chapter is a practical way to determine the desirability of applying adaptive reuse for building projects. With the development of a case study, the technical affordability and practicality of applying the proposed methodology was demonstrated using the current technologies and trends in the construction industry. The breakdown structure of the LCA per subsystem and subset is a practical way for practitioners to visualize the impact of their decision-making. This methodology represents an objective approach to find an empirical stopping point for adaptive reuse projects. This means that designers and practitioners can select the necessary changes to the building project in order to increase the environmental savings and to objectively determine when the modifications in the building are creating a larger negative environmental impact than a brand-new building. Therefore, it is a verifiable way to demonstrate the environmental justification of adaptive reuse projects.

In the last stage of this study, the affordability of monetizing the environmental impacts, through the current information technologies and specialized databases applied in the construction industry, is demonstrated.

From an economic standpoint, the advantages of monetizing environmental savings are meaningful, because through this kind of metric, it is much easier to compare benefits with costs and make choices between various alternatives (Viscusi, 2005). Moreover, through these practices it would be possible to create the necessary framework to advance energy policy-making in regards to sustainable building management. Through the findings of these kinds of studies, governments will be able to create regulations to incentivize construction projects that promote adaptive reuse as the first construction option. These regulations would be based on the objective monetization of the environmental savings for the community, city, and nation. The adoption of these practices for buildings can contribute to sustainability and climate change through the mitigation of negative environmental impacts.

Particularly, the case study reveals that a large amount of the environmental savings is due to avoiding the production of new construction materials, as well as the closed-loop of building components in the EoL stage. The conclusions are aligned with the literature review in regards to the distribution of the environmental impacts per building material and the opportunities for product recovery through recycling and reuse. In this matter, concrete is the main source of environmental impacts with around 56% of the total primary energy demand of the existing structure life-cycle. Reuse of steel is the main source for avoided environmental burden when it is recycled, with around 4.8% of the total PED of the existing structure life-cycle. This study is focused on the analysis of the structural system due to its relative importance to the rest of the building in terms of environmental impacts and building cost. However, part of future work should include the analysis of the other subsystems, such as, building envelope, mechanical, electrical, and plumbing subsystems.

Chapter 5: Selective disassembly sequence planning for adaptive reuse of buildings[3,4]

5.1 Abstract

Adaptive reuse of buildings can be an attractive alternative to new construction in terms of sustainability and a CE. Achieving net benefits with adaptive reuse partly relies on efficiently planning building disassembly. The aim of the study presented in this chapter is to describe a new efficient single-target selective disassembly sequence planning method developed for adaptive reuse of buildings. Finding a global optimum disassembly planning solution for buildings can be time consuming and physically impractical due to the high number of possible solutions. The method developed seeks to minimize environmental impact and removal costs using rule-based recursive analyses for planning recovery of target components from multi-instance building subsystems based upon physical, environmental, and economic constraints. Rule-based recursive methods have been demonstrated to be an efficient alternative to find near-optimal disassembly sequences by eliminating uncommon or unrealistic solutions. Validation is achieved through functional demonstration with case studies, where high quality, practical, realistic, and physically feasible solutions for single-target selective disassembly of buildings are found by using the new method. For adaptive reuse of buildings, the new method can be used to reduce the costs of disassembly and demolition and improve the planning process.

5.2 Introduction

Due to the high impact that buildings have on the environment, green design methods as well as circular building principles are becoming an important part of the building design process (Kibert, 2007; Pomponi & Moncaster, 2017; Sassi, 2008; S. Smith & Hung, 2015; Volk et al., 2014). All of these methods and principles have the purpose of reducing environmental impacts and increasing economic benefits in a life-cycle perspective (S. Smith & Hung, 2015). Several studies have recognized the importance of this stage for buildings and the opportunity for their adaptive reuse as a superior alternative in terms of sustainability and CE (Conejos et al., 2015; Douglas, 2006; Kibert, 2007). The potential benefits of adaptive reuse rely on the fact that it is possible to take away components from an obsolete building and then repair, reuse, remanufacture, or recycle them. For existing assets, planning for disassembly plays a key role in the

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[3] This is an Accepted Manuscript of an article published by Elsevier in the Journal of Cleaner Production on 20 February 2018, available online: https://doi.org/10.1016/j.jclepro.2018.02.201. B. Sanchez, and C. Haas, “A novel selective disassembly sequence planning method for adaptive reuse of buildings”. Only minor editorial changes are applied for being consistent with the University of Waterloo thesis format.

adaptive reuse process, where the disassembly planning sequence, as well as the disassembly methods for recovering target components, have to be performed efficiently.

Finding an optimal disassembly sequence for retrieving components from a building is difficult and complex due to multiple factors, such as, physical, environmental, and economic constraints; a high number of possible disassembly paths even for simple assemblages; and various recovery methods. The goal of the study presented in this chapter is to describe the development and validation of a user-friendly disassembly planning method for finding an efficient selective disassembly sequence for retrieving target components from buildings. The new approach is developed by using environmental-impact, building-cost, and rule-based analysis. This novel disassembly method is derived from the Disassembly Sequence Structure Graph (DSSG) model used in the manufactured product sector. In selective disassembly planning, finding a global optimum solution would be very time consuming and physically impractical. Even for simple assemblages, advanced searching enumerative algorithms typically require a tremendous amount of computational resources. Stochastic methods simplify the searching process to find near-optimal solutions; nevertheless, they often fail to find realistic solutions (S. Smith & Hung, 2015; S. Smith et al., 2012; S. Smith et al., 2016; S. S. Smith & Chen, 2011). In this study, an optimized sequential disassembly plan is generated based on expert rules. Rule-based recursive methods are used to find near-optimal heuristic solutions by eliminating uncommon or unrealistic solutions and so reducing computational time and space. The disassembly planning is performed one component at a time and by considering a given disassembly/deconstruction method per component.

5.3 Problem statement

Conceptualization of the CE has evolved through the years, and it has been gaining momentum since the late 1970s (Geissdoerfer et al., 2017). Among the schools of thought on the CE, shared founding principles lie in the better management of resources and waste by minimizing (or closing) material and energy loops (Geissdoerfer et al., 2017; Lacy & Rutqvist, 2015; Pomponi & Moncaster, 2017). CE is conceived as the main condition for sustainability in the construction industry (Geissdoerfer et al., 2017).

Due to the growing concern for the environment, sustainability has become a requirement rather than just a desirable characteristic for products and services. To remedy this situation, the construction industry is implementing designs and systems with improved long-term life-cycle performance (Sassi, 2008). Similarly, green design methods, such as design for disassembly, have become an important part of the design process in most industries, including construction. In the field of design for disassembly or deconstruction in buildings, improvements can be achieved by considering future disassembly of building elements at the planning stage of new buildings (Gorgolewski, 2008). Several investigations have demonstrated through case studies the cost-effectiveness and the environmental impact reduction from the application of design for disassembly in building projects (Akbarnezhad et al., 2014; Densley Tingley & Davison, 2012; Guy & McLendon, 2000; Kokkos, 2014; Schultmann & Sunke, 2007; Silvestre et al., 2014). Adaptive reuse can be similarly attractive.

5.3.1 Disassembly planning in adaptive reuse of buildings

For existing assets, a complete building disassembly is typically not possible since they were not designed for disassembly. However, the process could be reduced to planning for disassembly of building components that have a value for the adaptive reuse of the building. Planning for disassembly plays a key role in the adaptive reuse process, where the disassembly planning sequences, as well as the disassembly methods to recover target components, have to be performed in an efficient way. The objectives are to reduce building costs and to increase the building components' life-cycle times. If the design for disassembly is too complex or time-consuming, the associated economic and environmental costs could be higher than installing new components.

The field of planning for disassembly has been studied in the manufacturing industry over the decade preceding this study, with the purpose of improving the processes involved (S. Smith & Hung, 2015). Disassembly planning consists of finding an optimal and feasible path for disassembly under given constraints. Figure 5-1 shows a generic classification of disassembly planning methods for buildings and manufactured products. Several studies and approaches have demonstrated the effectiveness and feasibility of disassembly planning for manufactured products, in terms of searching time and model complexity (Han et al., 2013; S. Smith & Hung, 2015). In spite of the advances in this matter, there is a lack of knowledge on disassembly planning for buildings. In this study, the framework for analysis and integration of the topics related to disassembly planning for adaptive reuse of buildings is set (see Figure 5-1). Then, a feasible solution for the sequential disassembly for building assemblages is developed, as part of the first steps for solving inefficiencies during the process of adaptive reuse of buildings.

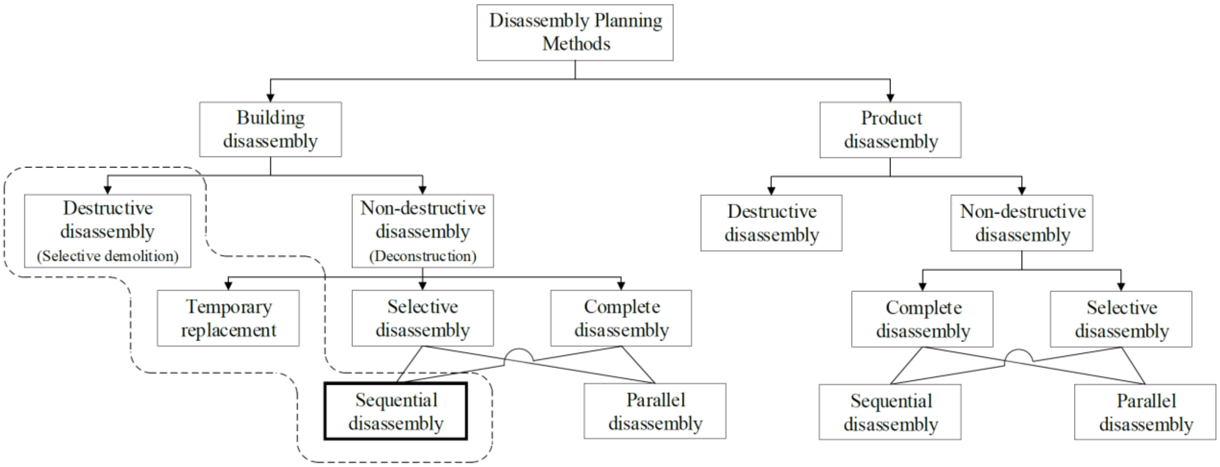


Figure 5-1: Disassembly planning categories for buildings and products

For the purposes of the study presented in this chapter, the term disassembly, or dismantling, stands for the process of taking an assemblage to pieces. According to Smith and Hung (2015) the different types of disassembly planning methods can be classified as destructive and non-destructive. For building projects, non-destructive disassembly is better known as deconstruction. The authors explain that destructive methods destroy the functional capabilities of the components. This destructive process is well-known as selective demolition in building projects. Finally, sequential methods remove one part at a time, while parallel methods remove multiple parts at the same time. Figure 5-1 shows the disassembly planning methods for products and buildings, as well as the processes involved in the adaptive reuse of an existing building.

Adaptive reuse scales the process of disassembly planning to another level of analysis. In this level of analysis, the different options of disassembly plans for targeted components have to be generated and compared. The number of possible solutions will depend on the number of retrieval methods assigned per component in the building assembly. For example, a target component could be retrieved through selective demolition, selective disassembly, or through installing a temporary replacement. Any of the three options mentioned are valid and would generate a different environmental and economic impact in the final disassembly plan. As noted above, the complexity of the analysis increases with the number of components to retrieve. Different complete plans exist for all of the possible combinations. The possible combinations are driven by the dismantling precedence of the components, as well as the interdependence of the dismantling methods.

There are some unique technical aspects that have to be taken into account for developing an efficient disassembly-planning model for buildings. The components' interdependence analysis is critical for finding realistic solutions rather than just looking for non-occlusion between components, which is the approach for manufactured products. Due to scale proportions, the labor is able to perform disassembly/deconstruction tasks from the outside and inside of the assemblage. Therefore, the definition of an appropriate working space and an access route are relevant with the purpose of creating realistic scenarios. Finally, the physical allocation of the resources for disassembly work impact the schedule and cost of the building project. Due to scale proportions of the plan layout, the relocation and reallocation of labor and machinery in a disassembly project must be planned properly with the purpose of avoiding logistics problems such as collisions, over crowdedness, and unnecessary extra displacements.

5.3.2 The role of green design methods for the reduction of environmental impacts for the building stock renovation

Adaptive reuse of buildings has been demonstrated to be a superior alternative to new construction in terms of sustainability. Nevertheless, its current implementation relies on conventional intuitive planning procedures by professionals in the construction industry, leading to suboptimal results with little quantitative or objective measurement or justification. This limited implementation is in part a product of the lack of user-friendly standardized procedures and tools which could assist in the analysis of an adaptive reuse project. Therefore, there is a need to develop a structured strategy that allows the quantification of benefits of adaptive reuse of buildings through a computer-aided method during the disassembly planning stage of building assets. The development of such a method could provide better understanding of the parameters involved in the process of adaptive reuse, in order to improve the benefits and expedite its application towards more sustainable development in the building industry. Figure 5-2 displays the proposed framework of this study as well as the key role of green design methods for the reduction of environmental impacts for the building stock renovation.

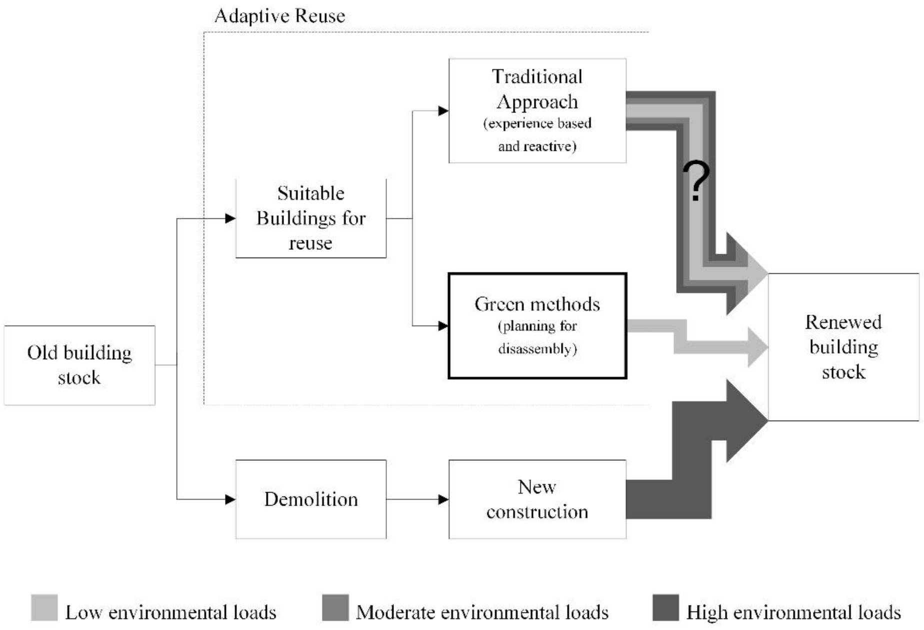


Figure 5-2: The role of green design methods in the reduction of environmental burdens for building stock renovation

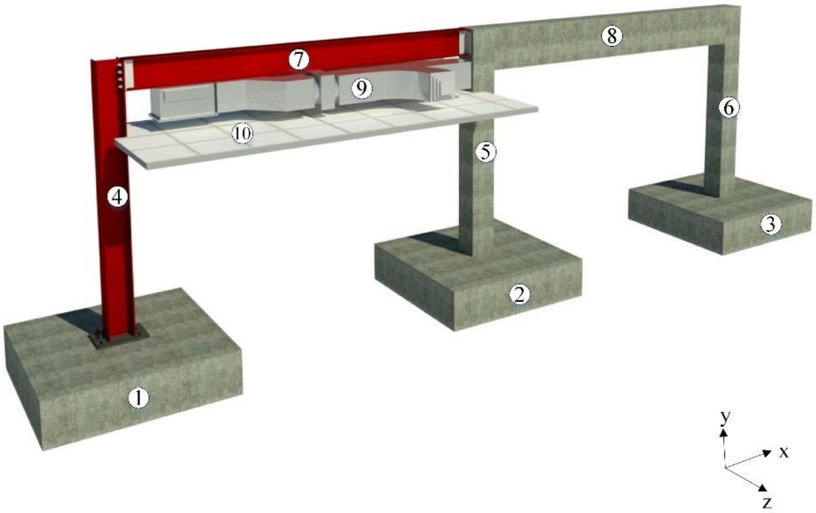
5.4 Disassembly planning approach for buildings

Disassembly planning consists of creating a disassembly model and then generating disassembly sequences (S. Smith et al., 2012). According to Smith et al. (2012), the quality and complexity of disassembly models affect the solution quality and searching time. For instance, a model that contains more information improves the solution quality, however a model that contains less information reduces searching time. In contrast with a manufactured product, a building assemblage has an excessive number of components with their respective fasteners (Kokkos, 2014). However, many of these components are the replication of a standard pattern. Therefore, a group of standardized components can be simplified as one class or module without losing generality. The same simplification could be applied for fasteners, grouping them into a single connection. The disassembly planning approach must set the appropriate level of detail or granularity in the model in order to keep the complexity of the calculations in a reasonable range.

In the field of sequential disassembly planning for buildings, it is critical to group parts into these classes or modules in an appropriate way according to engineering judgment. This judgment requires an understanding of the interaction of the different subsystems embedded in the assemblage as well as particular dismantling project goals, for example retrieving a high-value module in one piece or removing a set of parts that are interlocked or occluded. Through this approach, it is possible to reduce dramatically the disassembly steps and disassembly time, which means a reduction in energy use, environmental impacts, and construction cost. In other words, the process becomes more cost-efficient. Similar reasoning is used in scheduling methodologies, such as the Critical Path Method (CPM), Gantt chart, and Critical Path Segments (CPS), and in costing procedures, such as Unitary Price and Lump-Sum bidding.

5.4.1 The 6D building information modeling prototype

A simplified typical building frame assembly was modeled through a specialized 6D BIM software for the purposes of this study. The software used was Revit® and the add-in Tally®. The 6D BIM prototype contains the three-dimensional geometry, as well as the physical properties per building component of the model (3D). Also, the 6D BIM prototype contains information concerning the construction phases and work schedule (4D), as well as the cost estimating and budgeting (5D). Lastly, the 6D BIM prototype also contains the information concerning the LCA phases (6D). With the development of an accurate 6D BIM prototype, it is possible to have access to the necessary data for the purposes of this study with a powerful and highly organized graphical interface. Figure 5-3 shows the configuration of the final 6D BIM prototype under study.



Assembly components:

1. Concrete isolated foundation 1830x1830x457mm
2. Concrete isolated foundation 1830x1830x457mm
3. Concrete isolated foundation 1830x1830x457mm
4. Steel column W10X49
5. Concrete column 120x120mm
6. Concrete column 120x120mm
7. Steel beam W12X26
8. Concrete column 120x200mm
9. Ventilation ducting system
10. Compound ceiling 2'x4' ACT System

Attachment elements specifications:

The interface between the steel column (4) and the concrete isolated foundation (1) is compounded by a thick base plate, bolts set in pockets, and anchor plates.

The interface between the steel beam (7) and the concrete column (5) is compounded by a connection plate on an epoxy bed, expanding anchors, HSFG bolts, and shims.

The interface between the steel beam (7) and the steel column (4) is compounded by double angles shop-welded to the web of the beam and double angles field-bolted to the web of the column.

The ventilation ducting system (9) is attached to the steel beam (7) through metal duct straps every 900 mm.

The piece of compound ceiling ACT system (10) is attached to the steel beam (7) through hanger wire for drop suspended ceiling grids.

Figure 5-3: 6D BIM building frame structure prototype

According to Smith et. al (2012), for assemblies that have horizontal, vertical or round contact surfaces, all parts can be disassembled in four (*+x, -x, +y, -y*) or six principle directions (*+x, -x, +y, -y, +z, -z*) without losing generality. The two-dimensional representation of the simplified hypothetical building frames assembly under study is shown in Figure 5-4. This could represent a repeated element of many structural bays in a building. The DSSG theory requires specification of all parts of the assembly under study. One of the main assumptions in this study is that any group of fasteners between two components can be represented as just one element. This assumption makes sense, since disassembling a building, bolt by bolt is not necessary, because the structures are much larger in comparison to manufactured products. The aim of this simplification is to create a practical and realistic method applicable to selective disassembly of buildings with an acceptable level of detail.

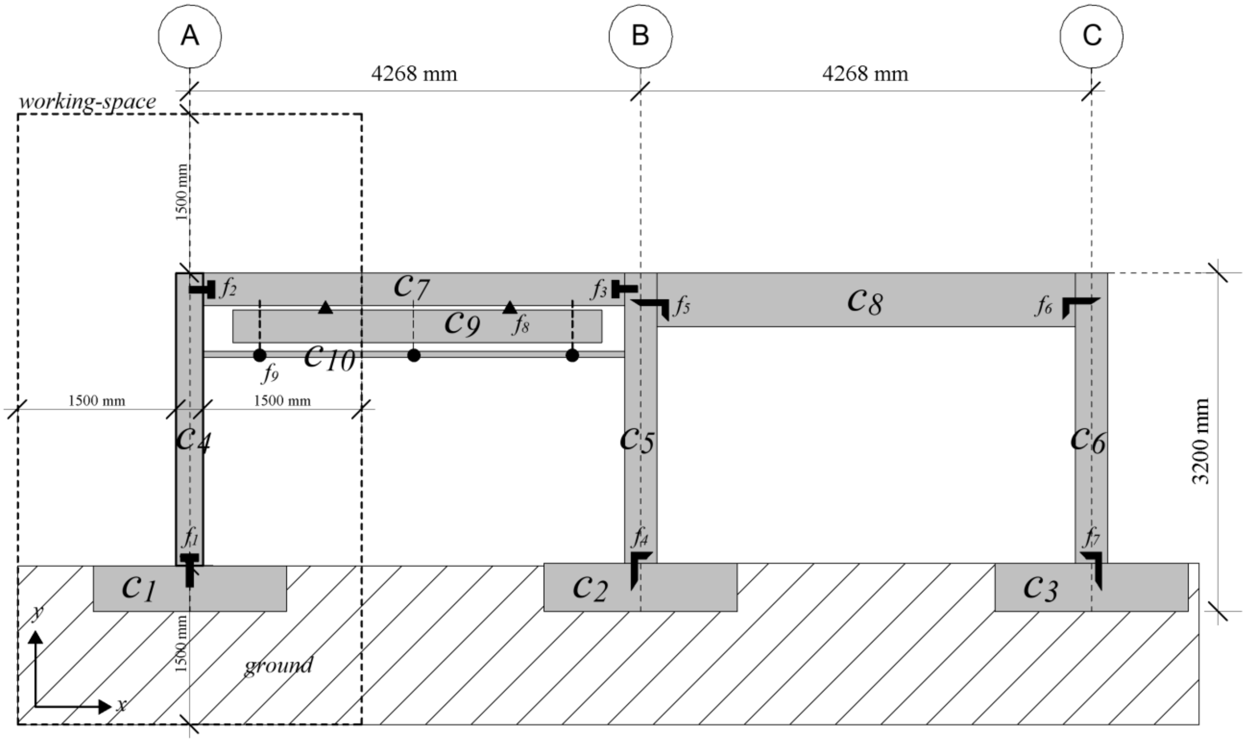


Figure 5-4: Two-dimensional representation of the assembly prototype

5.4.2 The disassembly graph model

In this study, a Disassembly Graph (DG) model is represented by constraint matrices, in which columns represent a constraint, and rows represent a part under analysis. A constraint can be physical, functional, environmental, or economic. For example, components create physical constraints by occupying volumes, while fasteners create the constraints by connecting components to other components. Matrix columns also indicate the disassembly directions. In a two-dimensional application, the disassembly directions include {*+x, -x, +y, -y*} directions. The following are the matrices contained in the DG model in this study.

A contact constraint matrix for components (*CC*) registers the physical contact between parts. Rows indicate the component under study and columns indicate the given disassembly direction. Each cell in the matrix contains links to components that contact the component under analysis, in a given direction. Also, the cells contain the fasteners that connect the component under analysis to another component, in a given direction. A '*c*' followed by a number represents a component and an '*f*' followed by a number represents a fastener. The *CC* matrix for Figure 5-4 is.

$$CC = \begin{bmatrix} CC_1 \\ CC_2 \\ CC_3 \\ CC_4 \\ CC_5 \\ CC_6 \\ CC_7 \\ CC_8 \\ CC_9 \\ CC_{10} \end{bmatrix} = \begin{array}{c} \begin{array}{cccc} \boldsymbol{+x} & \boldsymbol{-x} & \boldsymbol{+y} & \boldsymbol{-y} \end{array} \\ \begin{bmatrix} f_1 & f_1 & f_1, c_4 & f_1, ground \\ f_4 & f_4 & f_4, c_5 & f_4, ground \\ f_7 & f_7 & f_7, c_6 & f_{7,}ground \\ f_1, f_2, c_7, c_{10} & f_1, f_2 & f_1, f_2 & f_1, f_2, c_1 \\ f_3, f_4, f_5, c_8 & f_3, f_4, f_5, c_{10} & f_4, f_5, f_3 & f_3, f_4, f_5, c_2 \\ f_6, f_7 & f_6, f_7, c_8 & f_6, f_7 & f_6, f_7, c_3 \\ f_2, f_3, f_9, f_{10}, c_5 & f_2, f_3, f_9, f_{10}, c_4 & f_2, f_3, f_9, f_{10} & f_2, f_3, f_9, f_{10}, c_9 \\ f_5, f_6 & f_5, f_6, c_5 & f_3, f_5, f_6 & f_5, f_6 \\ f_8 & f_8 & f_8, c_7 & f_8 \\ f_9, c_5 & f_9, c_4 & f_9 & f_9 \end{bmatrix} \end{array} \tag{5-1}$$

A motion constraint matrix for components (*MC*) records motion constraints for each part per disassembly direction. Each row element of the matrix contains first-level-working-space parts, parts that intersect with a part's projection inside the working space for extraction work in any given direction. In contrast to a manufactured product, a building has much more space inside for removing parts. That is the reason why it is not necessary to include all of the first-level parts that intersect all the way along the projection of the part under analysis. For this study, it is defined as a working space, a reasonable physical space for extraction work by a worker using basic equipment or specialized machinery. As an assumption for the first experiments in this study, the working space was set at a perpendicular distance of 1.5 meters from the plane of work of the part under analysis in a given direction. As an example, Figure 5-4 shows the working space defined for the component number four (c_4). It is important to highlight that in contrast to manufactured products, the disassembly of a building has a main movement restriction related to the ground. It is not practical to include component disassembly directions that intersect with the ground. For this reason, the *MC* also records the motion constraint of each part with the ground. The objective is to leave the possible disassembly directions that overlap with the ground as the last option to analyze. For example, in Figure 5-4, $MC_1 = \{f_1\ f_1\ [f_1, c_4]\ [f_1, ground]\}$. Finally, the *CC* and *MC* matrices are combined into a single matrix called physical constraint matrix for components (*PhC*). The *MC* matrix for Figure 5-4 is.

$$MC = \begin{bmatrix} MC_1 \\ MC_2 \\ MC_3 \\ MC_4 \\ MC_5 \\ MC_6 \\ MC_7 \\ MC_8 \\ MC_9 \\ MC_{10} \end{bmatrix} = \begin{bmatrix} f_1 & f_1 & f_1, c_4 & f_1, ground \\ f_4 & f_4 & f_4, c_5 & f_4, ground \\ f_7 & f_7 & f_7, c_6 & f_{7,}ground \\ f_1, f_2, c_7, c_9, c_{10} & f_1, f_2 & f_1, f_2 & f_1, f_2, c_{1,}ground \\ f_3, f_4, f_5, c_8 & f_3, f_4, f_5, c_7, c_9, c_{10} & f_4, f_5, f_3 & f_3, f_4, f_5, c_2, ground \\ f_6, f_7 & f_6, f_7, c_8 & f_6, f_7 & f_6, f_7, c_3, ground \\ f_2, f_3, c_5, c_8 & f_2, f_3, c_4 & f_2, f_3 & f_2, f_3, c_9, c_{10} \\ f_5, f_6, c_6 & f_5, f_6, c_5, c_7 & f_5, f_6 & f_5, f_6 \\ f_8, c_5 & f_8, c_4 & f_8, c_7 & f_8, c_{10} \\ f_9, c_5 & f_9, c_4 & f_9, c_7, c_9 & f_9 \end{bmatrix} \tag{5-2}$$

A contact constraint matrix for fasteners (*CF*) records the direction of extraction of the fastener with respect to the component under study. The *CF* matrix records the direction of extraction of the fastener with respect to a component, according to the contact constraints. For example, constrained fasteners like bolts only have one disassembly direction along their main axis. For a 2D product with n_f fasteners and four-part disassembly directions, the *CF* matrix has n_f rows and one column. For each constrained fastener, the possible disassembly directions are 1, 2, 3, or 4, which represents a disassembly direction, *+x*, *-x*, *+y*, and *-y*. For unconstrained fasteners $CF_i = 0$. For example, in Figure 5-4, $CF_1 = 3$ and $CF_3 = 2$. The *CF* matrix for Figure 5-4 is.

$$CF = \begin{bmatrix} CF_1 \\ CF_2 \\ CF_3 \\ CF_4 \\ CF_5 \\ CF_6 \\ CF_7 \\ CF_8 \\ CF_9 \end{bmatrix} = \begin{bmatrix} 3 \\ 1 \\ 2 \\ 3 \\ 1 \\ 2 \\ 3 \\ 4 \\ 4 \end{bmatrix} \qquad 5\text{-}3$$

A motion constraint matrix for fasteners (*MF*) records motion constraints for each fastener in the extraction direction defined in *CF*. Each cell of the matrix contains first-level-working-space parts, parts that intersect with a part's projection inside the working space for extraction work in any given direction. For a 2D product with n_f fasteners and four-part disassembly directions, the *MF* matrix has n_f rows and one column. For example, in Fig. 4, $MF_2 = [c_9, c_{10}]$ and $MF_8 = [c_{10}]$. For simplification purposes, *MF* just records components. For unconstrained fasteners $MF = 0$. The *MF* matrix for Figure 5-4 is.

$$MF = \begin{bmatrix} MF_1 \\ MF_2 \\ MF_3 \\ MF_4 \\ MF_5 \\ MF_6 \\ MF_7 \\ MF_8 \\ MF_9 \end{bmatrix} = \begin{bmatrix} 0 \\ c_9, c_{10} \\ c_9, c_{10} \\ 0 \\ 0 \\ 0 \\ 0 \\ c_{10} \\ 0 \end{bmatrix} \qquad 5\text{-}4$$

A projection constraint matrix for components (*PC*) registers the intersected components on the projection of each component under study in a given direction and inside of their working space. *PC* is a simplification of *MC*, if along the projection there are not any other components different to the first-level-working-space parts. The approach of this study uses the *PC* matrix to choose optimized part disassembly directions. The *PC* matrix for Figure 5-4 is.

$$PC = \begin{bmatrix} PC_1 \\ PC_2 \\ PC_3 \\ PC_4 \\ PC_5 \\ PC_6 \\ PC_7 \\ PC_8 \\ PC_9 \\ PC_{10} \end{bmatrix} = \begin{bmatrix} 0 & 0 & c_4 & ground \\ 0 & 0 & c_5 & ground \\ 0 & 0 & c_6 & ground \\ c_7, c_9, c_{10} & 0 & 0 & c_{1,} ground \\ c_8 & c_7, c_9, c_{10} & 0 & c_2, ground \\ 0 & c_8 & 0 & c_3, ground \\ c_5, c_8 & c_4 & 0 & c_9, c_{10} \\ c_6 & c_5, c_7 & 0 & 0 \\ c_5 & c_4 & c_7 & c_{10} \\ c_5 & c_4 & c_7, c_9 & 0 \end{bmatrix} \tag{5-5}$$

A hosted component constraint matrix (*HC*) indicates the individual relationship between the host and the hosted components. The component HC_i under analysis is defined as the host component, and the registered elements per host component are the hosted components. For this study, a hosted component is physically attached to the hosting component with a fastener. Also, the static condition of a hosted component depends on the hosting component. These ideas introduce a novel concept called hierarchical liaison graph. Liaison or connection graphs depict physical links between components of an assembly in a graphical representation but do not incorporate any other information of the assembly like precedence or static stability relations. A hierarchical liaison graph establishes dependent disassembly levels to a liaison graph. In this study, a disassembly level is defined as *"the level in which one or more components/subassemblies connected to other components/subassemblies cannot be disassembled without compromising the physical stability of another component in the following upper level"*. A higher disassembly level depends on a lower one. This means that the physical stability of the component in a higher level depends on the existence of a component in the lower level. The components in the level zero are totally physically self-supported.

According to Mandolini et al. (2017), the definition of disassembly levels limits the number of feasible paths for disassembly planning. Therefore, the process of finding a disassembly sequence for a targeted component is improved by avoiding time-consuming calculations of non-optimum disassembly sequences (i.e., non-realistic sequences). This is a consequence of the next intrinsic rule. Considering a generic level *n* for a component under analysis, only components and fasteners belonging to the same level (*n*) or the subsequent level (*n+1*) are considered for the calculation of the feasible disassembly sequence. The concept of disassembly levels has been explored in manufactured products taking into account just the physical obstruction of the components but not the physical stability of the assemblage as is proposed in this study. Figure 5-5 shows the hierarchical liaison graph for the assembly prototype under study.

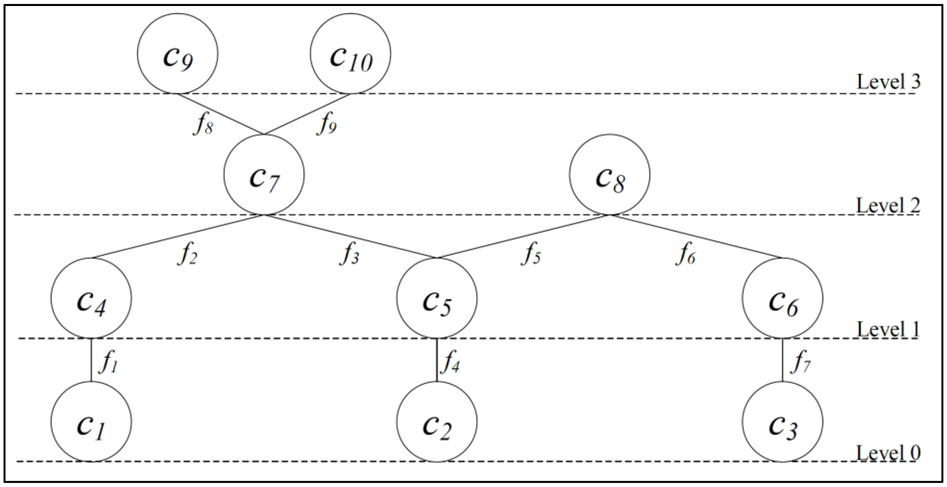


Figure 5-5: Hierarchical liaison graph of the assembly prototype

The information related to the hosting and hosted components can be retrieved directly from a well-structured BIM. The model elements in a BIM software represent more than just the 3D geometry of the building components and their spatial configuration. Model elements are also referred to as families. Technically, all families are hosted. They are either hosted by a level, a wall, a ceiling, a floor, or a surface of another model element. Therefore, with the appropriate approach, it is possible to create an accurate BIM model that contains internally the interdependence data related to the physical stability of the modeled components. For example, in Figure 5-4, $HC_1 = c_4$ and $HC_{10} = 0$. This means that c_1 is hosting c_4 (in other words, c_4 is hosted by c_1) and c_{10} is not hosting components. The HC matrix for Figure 5-4 is.

$$HC = \begin{bmatrix} HC_1 \\ HC_2 \\ HC_3 \\ HC_4 \\ HC_5 \\ HC_6 \\ HC_7 \\ HC_8 \\ HC_9 \\ HC_{10} \end{bmatrix} = \begin{bmatrix} c_4 \\ c_5 \\ c_6 \\ c_7 \\ c_7, c_8 \\ c_8 \\ c_9, c_{10} \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad 5\text{-}6$$

A liaison constraint matrix for components (LC) records the fasteners that physically attach the hosted components to the hosting component under analysis. For a 2D product with n_c components, the LC matrix has n_c rows and one column. For Fig. 4, $LC_1 = [f_1]$ and $LC_7 = [f_8, f_9]$. The LC matrix for Figure 5-4 is.

$$LC = \begin{bmatrix} LC_1 \\ LC_2 \\ LC_3 \\ LC_4 \\ LC_5 \\ LC_6 \\ LC_7 \\ LC_8 \\ LC_9 \\ LC_{10} \end{bmatrix} = \begin{bmatrix} f_1 \\ f_4 \\ f_7 \\ f_2 \\ f_3, f_5 \\ f_6 \\ f_8, f_9 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{5-7}$$

In the next step, with the information of the *HC* and *LC* matrices, the *MF* matrix has to be completed. The *MF* matrix contains the components that physically impede the extraction movement of the fasteners. However, for building components, sometimes the fasteners do not have extraction movement constraints, but without them the assembly would be unstable. Therefore, it is necessary to add the components located in the next levels of the hierarchical liaison graph into a combined constraint matrix (*MF-HC*). The *MF-HC* matrix for Figure 5-4 is.

$$MF - HC = \begin{bmatrix} MF_1 - HC \\ MF_2 - HC \\ MF_3 - HC \\ MF_4 - HC \\ MF_5 - HC \\ MF_6 - HC \\ MF_7 - HC \\ MF_8 - HC \\ MF_9 - HC \end{bmatrix} = \begin{bmatrix} c_7 \\ c_9, c_{10} \\ c_9, c_{10} \\ c_7, c_8 \\ 0 \\ 0 \\ c_8 \\ c_{10} \\ 0 \end{bmatrix} \tag{5-8}$$

An environmental constraint matrix for components *(EnvC)* contains the information related to the environmental impacts associated with the components in terms of their individual life-cycle. Each value contained in the *EnvC* matrix is the result of an LCA for each component meant to be part of the same assemblage. The LCA phases included are production, construction, and EoL. The LCA system boundaries and limitations were settled according to the most common current practices for buildings and in accordance with a full cradle-to-grave life-cycle analysis. EoL treatment is based on average US construction and demolition waste treatment methods and rates, including an avoided burden approach for recycling processing, credit for average energy recovery rates on materials' incineration, and impacts associated with landfilling of materials (KT Innovations et al., 2018). In this respect, further investigations should be done in order to include an EoL scenario considering the residual useful life of reclaimed components for their future reuse. The environmental impacts were calculated per component using the commercial 6D BIM software Revit® and Tally®. Tally® is a specialized software plug-in to perform LCA, for buildings and building components, aligned to ISO 14040-14044 which are the most widely accepted and well-known standards for LCA. The calculated environmental impacts were Global Warming Potential (GWP) in equivalent carbon dioxide kilograms (kg CO_2 eq) and Primary Energy Demand (PED) in Mega Joules (MJ). The *EnvC* matrix for Figure 5-4 is.

$$EnvC = \begin{bmatrix} EnvC_1 \\ EnvC_2 \\ EnvC_3 \\ EnvC_4 \\ EnvC_5 \\ EnvC_6 \\ EnvC_7 \\ EnvC_8 \\ EnvC_9 \\ EnvC_{10} \end{bmatrix} = \begin{array}{c} \begin{array}{cc} \textbf{GWP} & \textbf{PED} \end{array} \\ \begin{bmatrix} 805.43 & 6{,}416.06 \\ 805.43 & 6{,}416.06 \\ 805.43 & 6{,}416.06 \\ 228.94 & 3{,}124.31 \\ 202.74 & 1{,}568.91 \\ 202.74 & 1{,}568.91 \\ 174.34 & 2{,}516.24 \\ 485.25 & 3{,}733.11 \\ 12.47 & 185.29 \\ 21.93 & 301.00 \end{bmatrix} \end{array} \quad (5\text{-}9)$$

An economic constraint matrix for components (*EC*) contains the budgeting information associated with the work for selective demolition or disassembly of each component. The matrix records in each row the individual demolition/disassembly cost for each component meant to be part of the same assemblage. The component cost for these work was retrieved from the US database RSMeans (2015). The data recovered from this database is considered representative for the scope of this study which is the building market in North America. Nevertheless, further investigations should be done in order to adjust the fluctuations of the suggested prices due to particularities of the local economies of the building being adapted. The *EC* matrix for Figure 5-4 is.

$$EC = \begin{bmatrix} EC_1 \\ EC_2 \\ EC_3 \\ EC_4 \\ EC_5 \\ EC_6 \\ EC_7 \\ EC_8 \\ EC_9 \\ EC_{10} \end{bmatrix} = \begin{bmatrix} \$438.25 \\ \$438.25 \\ \$438.25 \\ \$86.75 \\ \$71.61 \\ \$71.61 \\ \$86.75 \\ \$174.73 \\ \$67.29 \\ \$40.12 \end{bmatrix} \begin{array}{l} S.Demolition \\ S.Demolition \\ S.Demolition \\ S.Disassembly \\ S.Disassembly \\ S.Disassembly \\ S.Disassembly \\ S.Demolition \\ S.Disassembly \\ S.Disassembly \end{array} \quad (5\text{-}10)$$

5.4.3 Optimized part disassembly directions

As a generality, a target component can only be removed in one disassembly direction, and it cannot change directions during disassembly. In buildings, the fasteners can be reached from different directions. In addition, the building components are subject to hosting constraints to keep the physical integrity of the whole structure. Therefore, for this study approach, the best extraction direction for a component is the one that contains the highest number of hosted components and then minimizes one of the objectives of interest (net environmental impacts of the discarded components or the cost of the building work). Avoiding disassembling other components that are not related to the physical stability of the target component reduces the number of removed parts, while the best disassembly sequence plan reduces the net environmental impacts or reduces the total cost of the building work, depending on preferences. The approach in this study chooses optimized part disassembly directions before searching for global solutions. According to Smith et al. (2012) choosing directions before searching reduces model complexity and searching time.

In the manufacturing industry, some prior studies have utilized advanced searching algorithms to enumerate and evaluate all possible solutions for selective disassembly and to find optimal solutions; however, these methods typically require a tremendous amount of computational resources, even for simple assemblages (S. Smith & Hung, 2015; S. Smith et al., 2012; S. Smith et al., 2016; S. S. Smith & Chen, 2011). Other studies used stochastic random search methods to simplify the searching process and to find near-optimal solutions; nevertheless, these methods might generate solutions, which are uncommon or unrealistic (S. Smith & Hung, 2015; S. Smith et al., 2012; S. Smith et al., 2016; S. S. Smith & Chen, 2011). This paper presents a rule-based recursive method for obtaining near-optimal heuristic selective disassembly sequences for buildings' dismantling. The method uses certain disassembly rules to eliminate uncommon or unrealistic solutions based upon physical, environmental and economic constraints. Additionally, rather than considering the whole geometry of the building's assemblage, the developed method only considers the geometric relationship and interdependence between a part and its neighboring parts. If a part can be disassembled, its geometric relationships, as well as its interdependence, with the neighboring parts will be dynamically updated. The constraint information of the assemblage parts is examined from the inside out. As a result, the developed method can effectively find near-optimal heuristic solutions while reducing computational time and complexity. The evaluation criteria include number of removed components, as well as amount of environmental or building cost for selective disassembly/demolition work.

5.4.4 The disassembly sequence plan model

The proposed model in this study is an inverted tree where the root node represents a target component and the leaf nodes represent the parts that constrain the target component. The approach for creating a single-target sequence disassembly plan gets parts from the DG, then it arranges and orders them part-by-part in levels.

5.4.4.1 Expert rules

Instead of generating all possible paths for the disassembly sequence planning of a component target, expert rules are used to find an optimized sequential disassembly plan that removes all parts, based upon motion, hosting, environmental, and economic constraints. The approach in this study uses expert rules to improve solution quality, minimize graph complexity, and reduce searching time (S. Smith et al., 2012). Similar to previous studies for manufacturing products' disassembly (S. Smith & Hung, 2015; S. Smith et al., 2012;

S. Smith et al., 2016; S. S. Smith & Chen, 2011), the rules for this study were derived from case studies for buildings. The rules use the *LC, HC, PC, EnvC,* and *EC* matrices to choose part disassembly directions. The following are the expert rules which define the recursive selective disassembly planning process.

- Rule 1: The best disassembly direction for removing the target component *t* is the direction *EXTRACTION_DIRECTION(c)* which contains the most number of hosted components MF_t-*HC* in the MC_t direction.
- Rule 2: If the target component *t* is not hosting any other components, then the best disassembly direction for removing *t* is *EXTRACTION_DIRECTION(c)* for which the sum of the environmental impacts or building cost of the blocking components is the lowest.
- Rule 3: All *f'* that physically constrain *c* must be removed before *c*.
- Rule 4: All *c'* that constrain *p* in *EXTRACTION_DIRECTION(p)* must be removed before *p*.
- Rule 5: The best direction for removing all *p'* is *EXTRACTION_DIRECTION(p),* unless the *p'* have pre-assigned disassembly directions.
- Rule 6: The least convenient disassembly direction option would be the one that overlaps their working space with the ground.

The searching process first checks if the target component *t* is hosting secondary components. If so, the direction for the extraction in MC_t has to include most of them, according to the Rule 1. According to the Rule 2, if the target component *t* is not hosting any other components, then the best disassembly direction for removing *t* is the one in which the sum of the environmental impacts or building cost of the blocking components, is the lowest. The user has to specify whether the objective is to minimize a specific environmental impact from the Environmental Matrix (*EnvC*) or the building cost associated with the disassembling work. In this way, different disassembly plans could be generated according to the user settings and needs of the building project. Then, the searching process checks if component under study, c_n, is fixed by any fastener. If so, all of the fasteners need to be disassembled before retrieving the component c_n, according to Rule 3. If a part *p* is not fixed or occluded by other parts, it can be disassembled and it can be placed in the final disassembly path. Otherwise, all of the fasteners and components in its way need to be disassembled first, according to Rule 4. The process retrieves the parts (*p'=c' or f')* that constraint other parts under analysis in the given direction, puts the constraining parts in a queue, and moves one-part p_n at a time from the queue to the sequence disassembly plan. For the next iterations, new constraining parts of an old constraining part under analysis are added to the queue avoiding the duplication of any of them. The process repeats to each part *p*, until all parts *p'* are added to the sequence disassembly plan. In order to make the approach more realistic, it is possible to pre-assign disassembly directions to any part *p* that has to be performed in that way due to construction procedures, according to Rule 5. Similarly, according to Rule 6, the overlapping of the working space path with the ground is the least practical option to disassemble a component. Expert rule 6 is a recursive rule that is used with all of the other expert rules. Figure 5-6 shows a flowchart of the searching process. The selective disassembly planning method is iterative since Rules 3 and 4 add new constraining parts to the queue under analysis. Part by part is analyzed until the entire disassembly planning is complete for a target component.

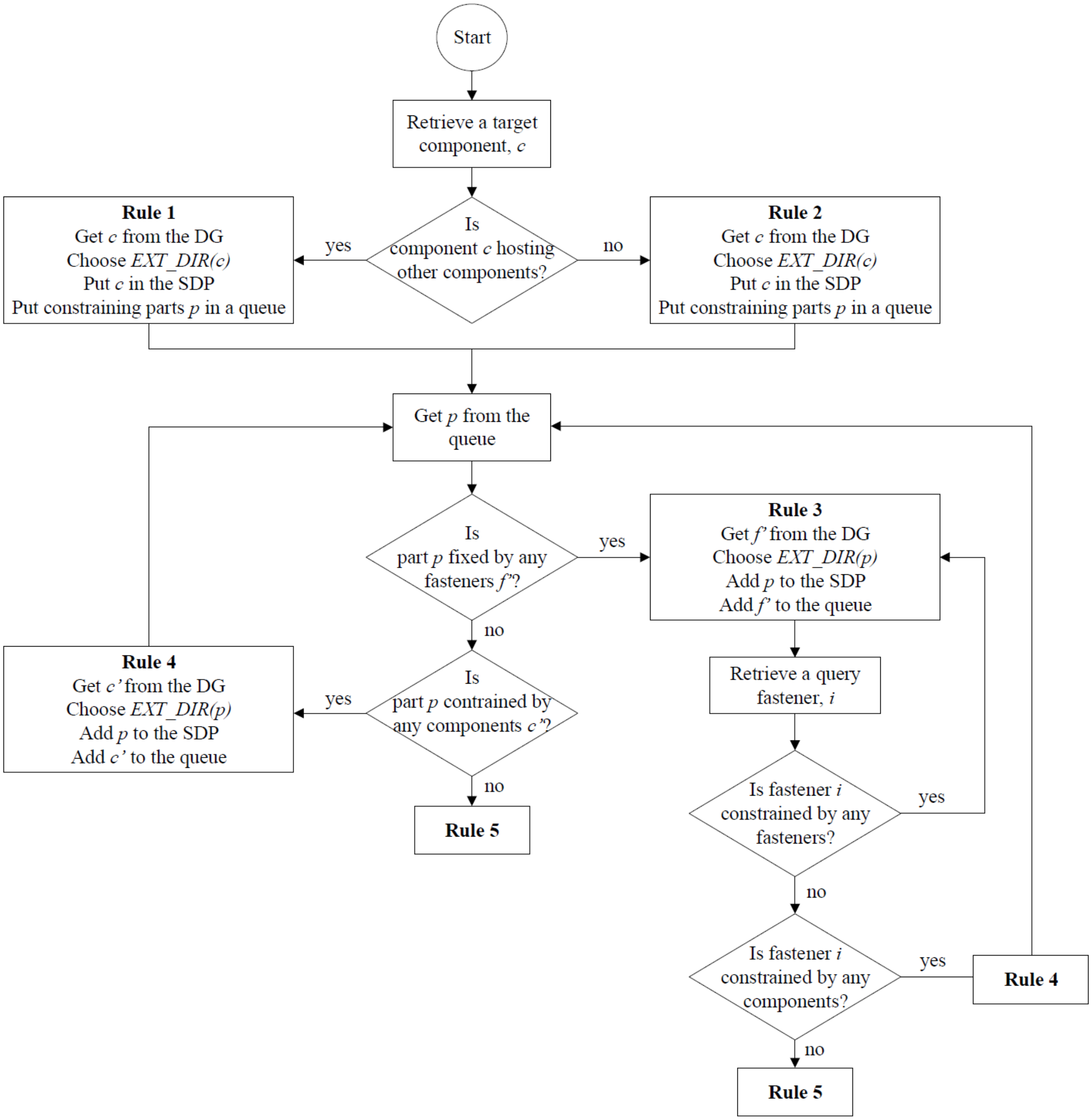


Figure 5-6: An Approach for Sequential Disassembly Planning for Buildings (SDPB)

5.4.4.2 Disassembly sequence planning algorithms

Algorithm 5-1 in Table 5-1 shows the steps for creating the concatenation of the hosted components in a second level of nesting, that are linked to a given fastener under study. The objective is to automatically create the combined matrix *MF-HC* in the disassembly graph model section. With the information contained in the *MC*, *PC*, *EnvC* and *EC* matrices, an algorithm was created that automatically merges them into an Environmental Cost Matrix (*EVM)* or a Building Cost Matrix *(BCM)* necessary for applying the expert rule number 2. The type of cost to minimize have to be established by the user. Algorithm 5-2 in Table 5-2 shows the steps for creating the *EVM* matrix. This matrix contains the numerical quantification of the accumulated cost associated with all of the components that intersect with the projection of a given component to extract, in every extraction direction inside their working space for extraction. With the initial matrices ready as well as the secondary matrices necessary for applying the expert rules, a third algorithm was developed for creating selective disassembly plans for single-targets. Algorithm 5-3 in Table 5-3 shows the detailed steps for creating disassembly sequence planning for building assemblages. Finally, an algorithm was created to plot the inverted tree graph of the final disassembly plan. The algorithm uses a specialized plot tool from Matlab® libraries called digraph. The algorithm generates the source and target vectors that the plot tool needs in order to display the final inverted tree graph properly. The scripts of Algorithms 5-1, 5-2, and 5-3 can be found on Appendix D.

Table 5-1: Algorithm for creating a combined matrix MF-HC for the first expert rule

```
Step   Algorithm 5-1: Combined Matrix $MF_{HC}$
1      Creating an empty $MF_{HC}$ matrix with the MF matrix size
2      FOR (each row of the MF matrix) DO
3          Assign the hosting component of the fastener under study using the LC matrix
4          IF (the hosting component have first-level hosted components assigned, record them in a vector) THEN
5              Add the second-level hosted components of each first-level hosted component to the MF matrix cell under study
               in the respective row position in the $MF_{HC}$ matrix
6          ELSE Add the components of the MF matrix cell under study in the respective row position in the $MF_{HC}$ matrix
7      END
```

Table 5-2: Algorithm for creating an EVM matrix for the second expert rule

```
Step   Algorithm 5-2: EVM Matrix
1      Selecting the environmental impact of interest and creating a vector with the associated values;
       EVM_VALUES ← environmental impact values per component;
2      Extract the components from MC to create PC and create an empty EVM matrix with the same size as PC;
3          FOR (each cell of PC matrix) DO
4                Assign the environmental value of every component $c_n$;
5                FOR (each cell of the EVM matrix) DO
6                      Calculate the sum of the environmental impact of the corresponding PC cell;
7      END
```

Table 5-3: Algorithm for creating an optimized disassembly sequence planning for building assemblages

```
Step  Algorithm 5-3: Disassembly Sequence Planning
1     Select a target component $c_n$ to be disassembled;
2     Creating an empty FINAL_EXTRACTION_VECTOR (fev);
3     Select a disassembly direction for the target component $c_n$, using Rule 1
      EXTRACTION_DIRECTION (d) ← disassembly direction;
      EXTRACTION_VECTOR_UNDER_STUDY (evus) ← parts to be disassemble in the disassembly direction $d$;
4     FOR (all parts which can be disassembled in direction $d$) DO
5         IF (the part is a fastener) THEN
6             Add the fastener under study to the fev vector;
7             Create a queue vector with the parts that constrain the fastener under study according to $MF_{HC}$ matrix;
              QUEUE_VECTOR (qv) ← parts that constrain the fastener under study;
8             FOR (all parts in the qv vector) DO
9                 IF (the part is a component) THEN
10                    Make the current component under study the new target component $c_n$;
11                    Go to step 3;
12                ELSE add the fastener under study to the fev vector
13        ELSE add the component under study to the fev vector
14            Make the current component under study the new target component $c_n$;
15            Go to step 3;
16    END
```

5.4.5 Case study

Two examples are used to demonstrate the single-target selective disassembly method for buildings.

5.4.5.1 Example 1

To clearly demonstrate the feasibility of the proposed method, the developed algorithms were tested in the two-dimensional representation of the assembly prototype (see Figure 5-4 and 5-7). The software used for this purpose was Matlab®. The new method demonstrates that it is possible to create selective disassembly plans that optimize a given objective function. The method is able to create an individual disassembly plan for each target component using the default removal method. Selection of target components requires engineering judgment based on structural system understanding and project goals. The method is able to create realistic and feasible disassembly plans. Figure 5-7 shows the 19-part assembly prototype under study. If an enumeration method is used, there are $19! = 1.22\cdot10^{17}$ possible disassembly sequences. If a stochastic searching method is used, many unrealistic solutions might be generated. However, the new method approach in this study eliminates many unrealistic solutions and finds near-optimal selective disassembly sequences effectively.

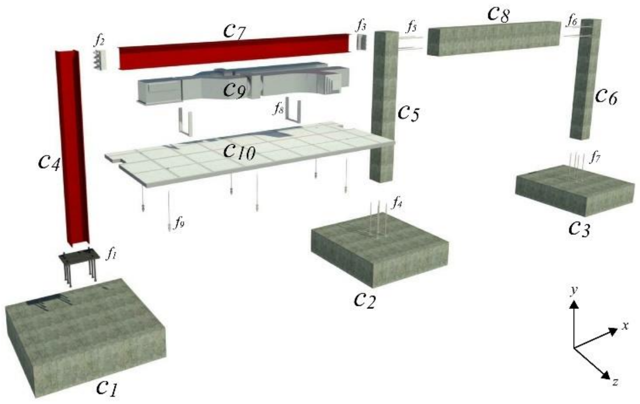


Figure 5-7: Assembly prototype

In this study, the method chooses the best direction for removing a given target component and it creates one single-target disassembly sequence plan. For Figure 5-4, the best directions for removing components c_7 and c_5 are $-y$ and $+x$ directions respectively. Figure 5-8 show the final single-target disassembly plan graphs for components c_7 and c_5 generated by the proposed model approach. In this study, the new approach found optimized solutions for number of parts, part order, and amount of environmental impact in an LCA perspective. The environmental impact selected for illustrative purposes was GWP. The approach also considers motion and fastener constraints. The approach found a solution $S_1 = (c_7\ f_2\ f_3\ c_9\ f_8\ c_{10}\ f_9)$ for c_7, and $S_2 = (c_5\ f_3\ f_4\ f_5\ c_7\ f_2\ c_9\ f_8\ c_{10}\ f_9\ c_8\ f_6)$ for c_5. The associated GWP environmental impact for each disassembly plan is 208.74 kg CO_2 eq and 896.73 kg CO_2 eq respectively. The associated building cost for each disassembly plan is \$194.16 and \$440.50 respectively.

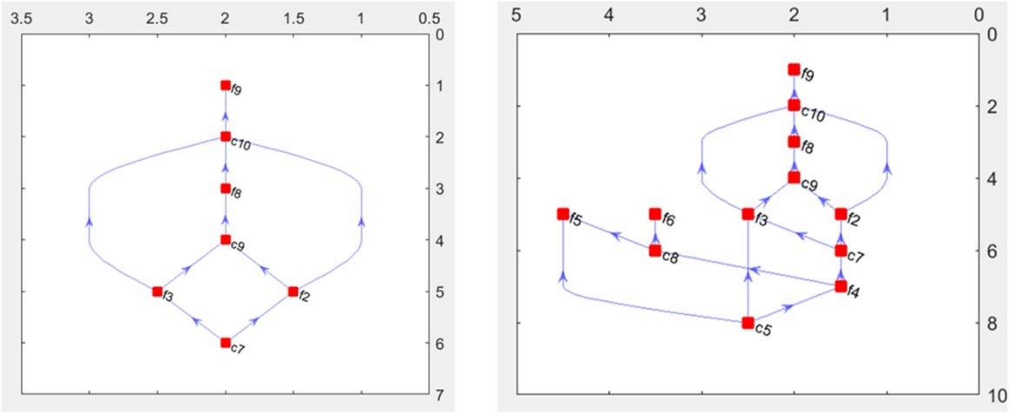


Figure 5-8: Automated graph generation of the single-target disassembly plans for components c_7 and c_5

5.4.5.2 Example 2

Figure 5-9 and 5-10 shows a 3D example of a hypothetical assembly that may be repeated in a large building. In this example, component 19 is the target component that is a K-Series bar open-web steel joist bay span. A selective disassembly sequence planning for disassembling component 19 is found as shown in Figure 5-11, and it is $S_1 = (c_{19}\ f_{19}\ f_{20}\ c_{20}\ f_{21}\ c_{21}\ f_{22})$. The environmental impact selected for illustrative purposes was GWP. The associated GWP environmental impact for the disassembly plan is 451.54 kg CO$_2$ eq. The associated building cost for the disassembly plan is $280.91.

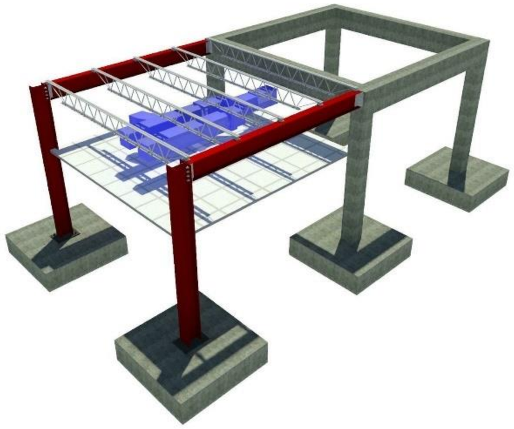


Figure 5-9: Example building assembly 2

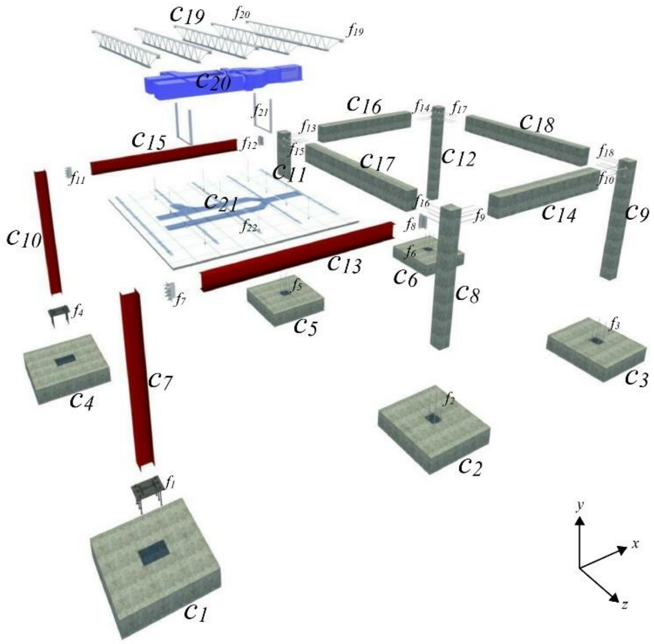


Figure 5-10: Exploded view of example building assembly 2

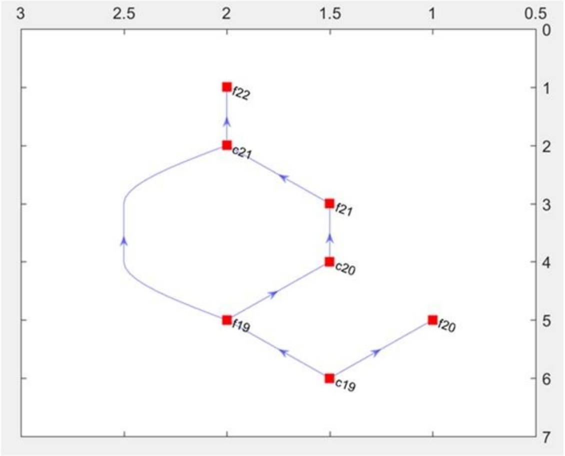


Figure 5-11: Automated graph generation of the single-target disassembly plan for components c_{19}

5.5 Summary of findings on selective disassembly sequence planning method for adaptive reuse of buildings

The study presented in this chapter establishes the reference framework of the key role that adaptive reuse of buildings has inside the CE value chain in construction. Also, this study describes the principles for improving the process of adaptive reuse with a technical approach, as well as the importance of disassembly planning inside this process. In the end, a novel single-target selective disassembly sequence planning method for buildings is developed and validated as a contribution for improving the inefficiencies of adaptive reuse of existing buildings. As discussed in this chapter, the importance of adaptive reuse relies on the fact that there is an enormous built environment nowadays. Therefore, by improving the inefficiencies in the adaptive reuse process, it is possible to fully exploit the residual life-cycle expectancy of the current building stock.

During the process of adaptive reuse of an existing building, specific targeted components must be selectively disassembled for repair, reuse, recycle, or refurbishment. Implicitly, the building subsystem containing the targeted components will thus be disassembled as well. Prior studies describe methods for removing single or multiple targets from a manufactured product. These studies have thoroughly considered solution quality, model complexity, and searching time. However, none of these prior studies have been applied to building disassembly or adaptive reuse. The goal of this study is to improve solution quality and minimize model complexity in the selective disassembly planning process for buildings. Through case studies, this research developed and validated a new selective disassembly sequence planning model approach for retrieving targeted components from buildings. The new model approach is based on the disassembly sequence structure graph (DSSG) model theory for manufactured products. Also, this approach involves an environmental-impact, building-cost, and rule-based analysis for finding optimized disassembly sequence plans.

The new model approach contains the set of parts that must be removed in order to remove the target parts. Aside from this, the model approach is able to optimize the environmental-impact or the building cost performance for the disassembly process depending on the setting preferences. The approach uses expert rules to choose parts, part order, and part disassembly directions, based upon physical constraints. The approach finds practical, realistic, and physically feasible solutions for selective disassembly of buildings. The solutions remove parts in a practical order and with realistic part motions for the building components. The solutions remove obstructed parts in subassemblies. Thus, whole subassemblies are removed optimally. Even though the disassembly planning method approach developed in this study can be implemented in a generic way to any kind of building assemblages, the case studies showed that finding repetitive patterns or repetitive subassemblies is an excellent way to reduce the complexity of the model and to make it more practical. It is obvious that due to the high standardization of certain types of residential and commercial buildings, it is possible to find the patterns of repetition of the subassemblies and then to segment and study them separately in order to simplify the complexity of the analysis. In the end, the objective is to find a generic solution for the set of repetitive elements in a repetitive subassembly. The proposed method has the flexibility of being adapted to include other constraint matrices aside from the economic and environmental cost. For example, for disassembly time, the method could retrieve the productivity rates from the BIM model to be included in a new constraint matrix.

More investigation related to the environmental impacts and building costs of selective disassembly, selective demolition, and building refurbishment could be desirable, with the aim of making the results of this study more accurate and practical. In the same way, there could be parallel research, to delve into the topic of generating the initial constraint matrices in an automatic way, for instance by retrieving data and constraints directly from the BIM model or through point cloud processing.

Chapter 6: Deconstruction planning and scheduling for adaptive reuse of buildings[5]

6.1 Abstract

Adaptive reuse is a way of maximizing the residual utility of existing assets. Adaptive reuse makes it possible to retrieve components from an obsolete building through deconstruction programming. Unfortunately, current deconstruction programming practice relies on conventional intuitive planning procedures by professionals, leading to suboptimal results. The study presented in this chapter describes and validates a semi-automated selective deconstruction programming approach for adaptive reuse that can support quantitative analysis. First, a new method is defined for multiple-target selective disassembly sequence planning, using a rule-based recursive approach for obtaining near-optimal heuristic solutions. Then, a method is demonstrated for programming the deconstruction work based on the disassembly sequences. Validation is further achieved through a case study, in which high-quality, practical, and feasible solutions are found by using the new method. The approach helps improve project performance through process automation that supports quantitative analysis, low cost exploration of alternatives, and an iterative design process for meeting project constraints.

6.2 Introduction

Adaptive reuse of buildings is considered a superior alternative for new construction in terms of sustainability and Circular Economy (CE) (Conejos et al., 2015; Douglas, 2006; Kibert, 2007; Langston et al., 2008; Sanchez & Haas, 2018a; E. A. L. Teo & Lin, 2011). However, the current implementations of adaptive reuse rely on descriptive approaches with little objective measurement that depends on the intuition and experience of practitioners (Mohamed et al., 2017; Sanchez & Haas, 2018a; Volk et al., 2018). Intuitive planning procedures are easy to apply but often lead to suboptimal plans. Therefore, increasing the efficiency of the adaptive reuse of buildings through automation and optimization is fundamental to fully exploit the residual life-cycle of buildings, and with it, avoid wasting the embedded resources. In the study presented in this chapter, adaptive reuse of buildings formed of recurring subsystems has been identified as a potentially efficacious application of deconstruction programming because the programming effort can be paid off through application to multiple identical or similar subsystems.

In the same way that project planning for green-field construction has significant impact on a project's outcome (Camacho, Cañizares, Estévez, & Núñez, 2018; Gibson & Gebken, 2003; Kang, Kim, Son, Lee,

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& Limsawasd, 2013), project planning for deconstruction has the potential of improving the performance of an adaptive reuse project. Deconstruction project planning involves the choice of technology, the definition of work tasks, the estimation of the required resources and durations for individual tasks, and the identification of any interactions among the different work tasks. In contrast to the vast literature on construction project planning, the literature on planning of deconstruction projects is limited and scarce (Hübner et al., 2017). Therefore, the development of project planning methods for deconstruction is required to increase the efficacy of the process of adaptive reuse. The goal of this study is to describe and validate a semi-automated selective deconstruction programming approach for adaptive reuse of buildings. The proposed approach is able to support efficient programming of the deconstruction work based on realistic and optimized selective disassembly planning. Although the proposed approach can be applied to any kind of adaptive reuse project, this study is directed to buildings formed of recurring subsystems.

Disassembly sequence planning is one of the most efficient methods to increase the reuse rate of components and reduce environmental impacts (S. S. Smith & Chen, 2011). In this study, first a multiple-target selective disassembly sequence planning model for buildings is described. This is an extension of a previous model for single-target selective disassembly sequence planning for buildings (Sanchez & Haas, 2018b), thus a rule-based recursive approach is used for obtaining near-optimal heuristic selective disassembly sequences. The disassembly planning is performed one component at a time and by considering environmental impacts, building cost, as well as physical constraints. The approach finds high quality, practical, realistic, and physically feasible solutions. The solutions seek to optimize for number of removed parts, part disassembly directions, and environmental/economic cost. The solutions disassemble parts in practical order and in directions that are practical from a deconstruction standpoint.

Next, the study describes an algorithm for programming the deconstruction work based on the disassembly sequences generated. This includes but is not limited to the activity network, critical path, critical activities, and duration of the project. With access to more Project Management (PM) data, the deconstruction project planning stage can be extended to other dimensions, such as the Program Evaluation and Review Technique (PERT), Critical Path Method (CPM) optimization, resource leveling, resource allocation, construction budget control, and deconstruction optimization methods. This last part opens the possibilities for customizing the approach described in this study according to the needs of each kind of deconstruction project, thereby, taking advantage of the benefits of other PM tools. For adaptive reuse of buildings, the approach described here may be used to improve the performance of projects by enhancing the deconstruction planning process.

6.3 Problem statement

The project planning process of a building is an integral part of the larger and more complex building procurement process. Project planning is the single most important process in a project life-cycle and has been studied extensively (Bingham & Gibson, 2017; Cho, 2000; CII, 1994; Dumont & Gibson, 1996; Gibson & Gebken, 2003). As widely reported, the development of an appropriate project planning process leads to improved performance on building projects in the areas of cost, schedule, resources, quality, and operational characteristics (Ballard, 2000a; Camacho et al., 2018; Cho, 2000; CII 1994; Dumont & Gibson, 1996; Edkins et al., 2013; Morris, 2011). Therefore, numerous construction project planning methods and studies have been developed for either conventional or green buildings.

The contemporary definition of green building is an integrated whole building approach, which considers life-cycle at all levels (Keeler & Vaidya, 2016). According to the US Environmental Protection Agency (USEPA): "Green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort." (USEPA, 2016b). Consequently, in the last three decades there has been a growing research interest in improving building projects' performance over all of the life-cycle stages (production, construction, operation, and End-of-Life [EoL]) in order to move towards true sustainability in the construction industry (Asdrubali et al., 2013; Aye et al., 2012; Cabeza et al., 2014; Fay et al., 2000; Gustavsson & Joelsson, 2010; Kneifel, 2010; Ramesh et al., 2010; Ramesh et al., 2012; Zabalza Bribian et al., 2011). Several studies have recognized the importance of the EoL stage (Cong, Zhao, & Sutherland, 2017; Sandin et al., 2014; Silvestre et al., 2014) due to the opportunity for fully exploiting the residual life-cycle value of buildings, and buildings' components/materials.

A shift of thinking in the perception of sustainability in construction has arisen in the last two decades, switching from a creative and innovative approach to a restorative and regenerative one. This change of perception is founded in the needed transformation of the current linear economic model, that is reaching its physical limits, to a circular one (Geissdoerfer et al., 2017; Pomponi & Moncaster, 2017). Therefore, CE building principles and green design methods are becoming an important part of the green building project planning process. Some examples of these principles and methods are design for assembly, supply chain management, Product Recovery Management (PRM), Life Cycle Assessment (LCA), design for disassembly, design for manufacture, disassembly sequence planning, design for adaptability, design for the environment, design for deconstruction, closed materials loops, dematerialization, and closed-loop cycle construction (Kibert, 2007; Sassi, 2008; S. Smith & Hung, 2015; Volk et al., 2014). These principles and methods have the purpose of reducing environmental impacts and increasing economic benefits in a life-cycle perspective (S. Smith & Hung, 2015). The implementation of CE building principles and green design methods in the construction industry are considered a disruptive innovation which is currently transforming the fundamentals of the natural resources value chain worldwide (Lacy & Rutqvist, 2015; Sanchez & Haas, 2018a). In this regard, adaptive reuse of buildings is considered by most as a superior alternative to new construction in terms of sustainability (Conejos et al., 2015; Douglas, 2006; Langston, 2008; Sanchez & Haas, 2018b). Adaptive reuse takes advantage of many of the CE building principles and green design methods, in order to restore and redevelop existing buildings (Bullen, 2007; Langston et al., 2008).

6.3.1 Construction planning inside a circular value chain

The construction planning inside a circular value chain has gained a lot of importance in the last decade due to the huge benefits that can be achieved in terms of sustainability. Some studies have approached this topic from a holistic perspective by analyzing the resources supply chain networks in a local economy, the urban material flows and waste streams, and the resource management for building stocks (Anderson, Wulfhorst, & Lang, 2015; Mastrucci, Marvuglia, Leopold, & Benetto, 2017; Ortlepp et al., 2016; Stephan & Athanassiadis, 2017). On the other hand, several studies have focused on improving the buildings' materials/components flow stream of individual construction projects (Hübner et al., 2017; Jaillon & Poon, 2014; Sassi, 2008; Won & Cheng, 2017). Among the different approaches in the research field of CE in the construction industry, shared founding principles lie in the optimization of resources use and waste management by closing material and energy loops (Geissdoerfer et al., 2017; Pomponi & Moncaster, 2017). Similarly, for all of the approaches, the communication and information technologies, such as highly specialized software for complex simulations, real-time up-to-date databases, and interconnectivity of infrastructure systems, plays a fundamental role.

In their work, Sanchez and Haas (2018a) point out the importance of the pre-project planning for closed-loop cycle building construction, as well as the main differences in comparison to the front-end planning for green-field construction. At the end, they propose the reference framework for: (1) defining the role that adaptive reuse of buildings has inside the construction value chain in the CE and (2) developing a Project Definition Rating Index (PDRI) for adaptive reuse of buildings. Due to the importance in the field of buildings retrofit and renovation of the building stock, in 2009 the Construction Industry Institute (CII) (CII, 2009) developed the Front End Planning for Renovation and Revamp (R&R) Projects. The investigations concluded that an appropriate front-end planning has the potential of improving the performance of R&R projects. As part of this work, the existing PDRI tools for buildings were revised to reflect unique issues related to R&R projects. Other studies have focused on developing sophisticated modelling tools for quantifying and mapping construction material flows and waste streams in a urban scale, in order to improve the management of building stock in terms of CE (Langston, 2013; Mastrucci et al., 2017; Ortlepp et al., 2016; Stephan & Athanassiadis, 2017).

On a smaller scale, there has been a growing interest in recent years in the field of planning methods for closed loop cycle of buildings' materials and components. Won and Cheng (2017) did an extensive review of construction and demolition (C&D) waste management and minimization studies in order to identify the inefficiencies and to improve them through implementing appropriate technology, such as Building Information Modeling (BIM) and 3D coordination, control and planning. Similarly, Huber et. al. (2017) provided a comprehensive overview of methods for deconstruction project planning of buildings as well as research gaps in the field. Other studies have delved into the field of potential of reusable building materials/components towards a CE, such as reclaiming and reusing structural steel (Gorgolewski, 2006; Gorgolewski, 2008; Yeung et al., 2015), and urban mining from old existing assets (Lacy & Rutqvist, 2015; Luscuere, 2017).

6.3.2 Deconstruction programming for adaptive reuse

The design and planning process of an adaptive reuse project is arguably more complex than the design and planning of green-field construction projects. The extra complexity lies in the initial existing conditions that represent initial design constraints and restrictions. If the initial evaluation of the existing conditions is incorrect or underestimated, the impacts for the project's outcome could be disastrous (Conejos et al., 2016). Also, the adaptive reuse process first includes an intensive planning stage associated with the selective deconstruction of the existing building asset, followed by the planning of the construction work for the redevelopment, adaptation, and in some cases the expansion of the building asset. This study is focused on the selective deconstruction planning stage. In the selective deconstruction planning stage, the designers decide which building components, or subsystems, should be retrieved and the deconstruction methods to apply. Although, the field of deconstruction project planning of buildings has been studied for years, there is no evidence of studies developed for the selective deconstruction planning for buildings (Hübner et al., 2017; Sanchez & Haas, 2018b). All of the previous studies presented in the last section have focused on the total or partial deconstruction of building assets with an assumed fixed programming of work activities and work packages. For adaptive reuse projects, the programming of the work activities and work packages can change according to the design decisions of the building components to retrieve. For adaptive reuse projects, the selective deconstruction planning is an iterative process where the different design options could be driven by financial, technical, functional, and/or aesthetic needs, among others (Conejos et al., 2014; Langston et al., 2008).

The process of deconstruction programming, also known as deconstruction scheduling, in adaptive reuse projects is a cornerstone to influence the project's outcome. Through appropriate programming the designers can estimate project’s parameters such as total duration, critical path(s), activity precedence, and resource allocation. Then, planners can apply methods in the literature of PM in order to improve the project’s performance, such as resource leveling, schedule compression techniques, and optimization methods (Bakry, Moselhi, & Zayed, 2014). In this matter, the adaptive reuse process has the challenge that there could be numerous selective deconstruction plans based on the designer’s decisions and project needs. Every plan can lead to a distinctly different programming of the activities which has a profound impact on deconstruction planning. These have been some of the technical limitations perhaps explaining why the current implementations of adaptive reuse planning rely on descriptive approaches with little objective measurements that depend on the intuition and experience of practitioners (Sanchez & Haas, 2018a; Volk et al., 2018). Due to the importance of adaptive reuse inside the CE, there is a need for improving the selective deconstruction programming process thorough automation and optimization in order to maximize the benefits of the building stock renovation.

This study is directed at adaptive reuse projects in general. However, the importance and relevance for adaptive reuse projects that are repetitive should be highlighted because of recurring building subsystems. Due to the need of increasing the efficiency of the building projects' outcome, prefabrication and modularization are construction processes that the industry has used and mastered for centuries (Bakry et al., 2014; Isaac, Bock, & Stoliar, 2016). Construction projects take advantage of prefabrication and modularization for creating recurring building subsystems and modules, with the same group of sequential activities. Today's built environment contains repetitive building subsystems and modules in almost all construction sectors, and the evidence suggests that this trend will continue in the future (Isaac et al., 2016; McGraw Hill Construction, 2011). In this matter, existing assets formed of recurring building subsystems represent a good opportunity to take advantage of the benefits of the intensive and rigorous design process for adaptive reuse described in this paper, including the selective deconstruction programming. Once the deconstruction scheduling is developed for a single subsystem, the programming can be mass implemented on all other repetitive modules, generating profound efficiencies and cost/schedule savings over deconstruction planning for a single (unique) construction assembly. Possible use cases for selective deconstruction programming in adaptive reuse projects, that are repetitive because of recurring subsystems, include layout changes for unitary apartments in high-rise buildings, reconditioning repetitive rooms in low-rise buildings, and redeveloping recurrent spaces in existing residential buildings (see Figure 6-1).

According to Hübner et. al. (2017), applying deconstruction planning methods can only calculate up to a specific level of detail due to computational and practical constraints, limiting their implementation in construction projects. However, a deep level of detail for the selective deconstruction programming of repetitive building subsystems is affordable and worthwhile due to the amount of project's outcome benefits in the large scale, such as the crew work continuity (Bakry et al., 2014), and the learning phenomenon (Hassanein & Moselhi, 2005). Additionally, with the appropriate level of detail and the use of the 4D BIM, the deconstruction programming could become a powerful communication and training tool for the workforce. This being said, there are certain levels of detail which should not be considered due to practical implications. An example of this would be modelling the exact location of nails in wood framing. While it is possible to model and reuse each nail in a wood frame assembly, the cost savings of harvesting each individual nail is not practical. As such, it is not necessary to model the exact spatial configuration of certain components. While this study does not explore or propose the required levels of detail for certain deconstruction planning methods, it is simply suggested that increased detail is proportionately favorable for analysis as the repetitive nature of an adaptive reuse project increases. In the next sections the proposed approach and its application in an adaptive reuse project case study is presented.

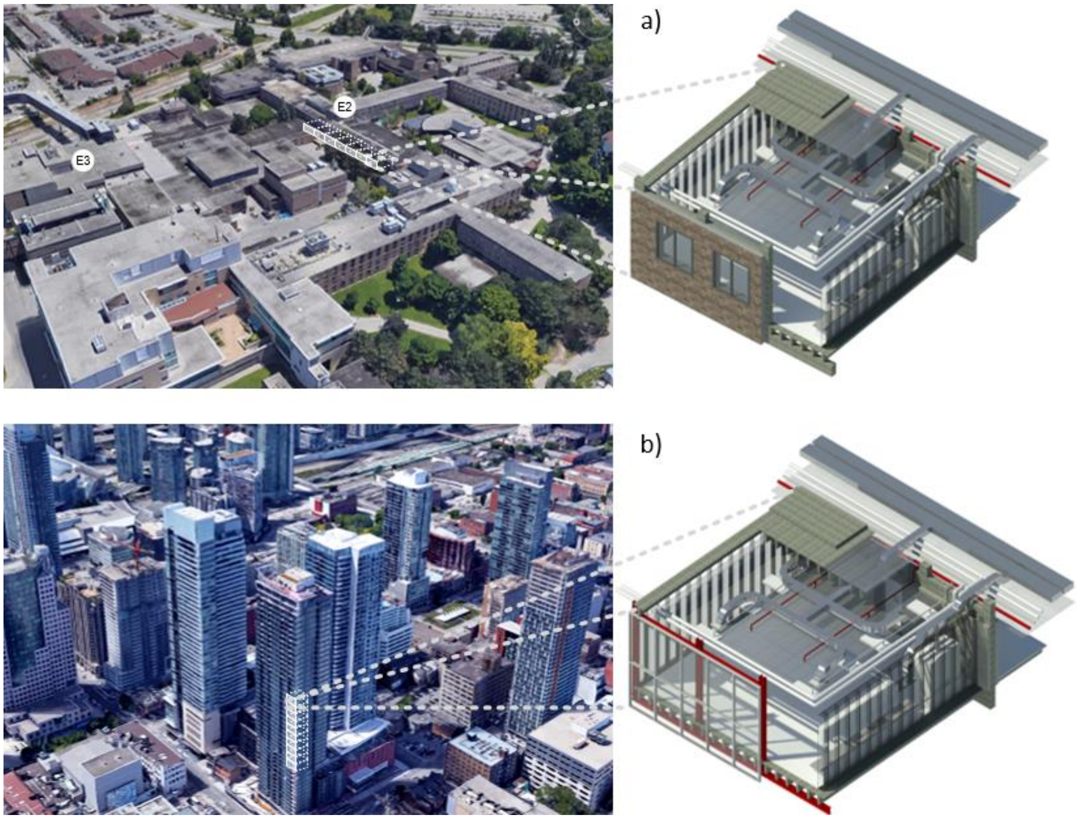


Figure 6-1: Examples of repetitive modular units in the built environment: a) set of lab rooms with a recurrent layout, and b) repetitive apartment rooms on a high-rise building.

6.3.3 The knowledge gap

Adaptive reuse of buildings plays a key role in the construction value chain of a Circular Economy (CE). In order to improve the outcomes of adaptive reuse building projects, it is necessary to implement an appropriate project planning. This includes the development of a correct, quantitative, analytical, and objective selective deconstruction programming. According to the literature review, there is a lack of methods for deconstruction programming for adaptive reuse projects. To the authors' knowledge, this is the first study that describes and validates a method for selective deconstruction programming for adaptive reuse of buildings. This study provides a better understanding of the parameters involved in the process of deconstruction programming for adaptive reuse projects, in order to improve the project performance.

6.4 Deconstruction project planning for adaptive reuse of buildings

Planning for disassembly plays a fundamental role within deconstruction project planning for adaptive reuse, where the disassembly planning sequences for recovering targeted components have to be performed efficiently according to the building project objectives. The targeted components to recover depend directly on the adaptive reuse design of the building. In this regard, the adaptive reuse design could be directed by multiple design criteria that have been defined in several previous studies (Bullen, 2007; Conejos, 2013; Conejos et al., 2014; Wilson, 2010). Some of these design criteria are mandatory (e.g. physical integrity, legal requirements, and functional service) while others ones optional (e.g. technological retrofits, social aspects, architectural vision and programming, and political context). In the end, the designers are responsible for making the final decisions of a functional and affordable adaptive reuse design. Because of the multiple possible designs for adaptive reuse of a fixed asset, the planning for disassembly of targeted components will also change from design to design. Based on a proposed disassembly plan, it is possible to continue the deconstruction planning in detail through the programming of the deconstruction work, estimation of resource allocation, and computing the associated budget, among others. In the end, this becomes an iterative design process, much of it intuitive, where the best design will be the one that fulfills the projects needs and limitations.

However, intuitive planning has inevitably led to poor project outcomes and in some cases has even led to project failures. This is due to the technical limitations and complexities that the entire process requires, such as the large amount of required project data to gather and compute, the multiple criteria for different possible designs, and the lack of user-friendly standardized procedures for optimizing the outcomes. In this study framework for deconstruction project planning by using BIM-based phase planning is proposed (see Figure 6-2), in order to improve the inefficiencies inside the process of adaptive reuse of buildings. Inside this framework, a deconstruction programming method for adaptive reuse of buildings based on a multiple-target selective disassembly sequence planning model for buildings is developed. In addition, the basis for retrieving data from the BIM model is established in order to fully automate the process for deconstruction project planning.

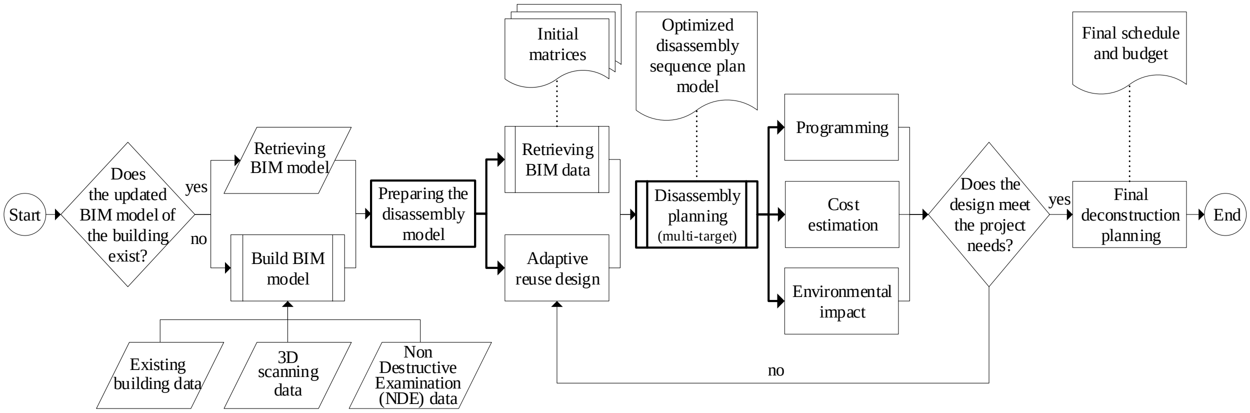


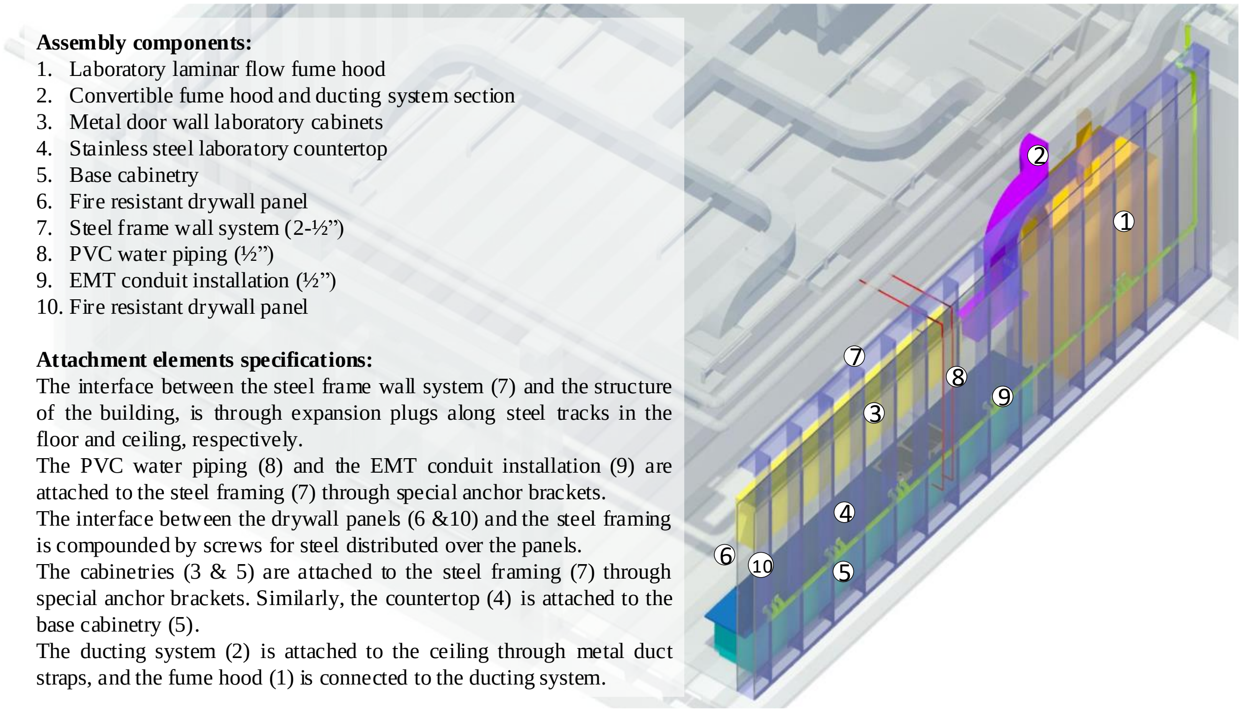
Figure 6-2: Process map for selective deconstruction project planning by using BIM-based phase planning

6.4.1 The disassembly sequence plan model for adaptive reuse of buildings

This study is an extension of the previous work related to single-target selective disassembly planning for adaptive reuse (Sanchez & Haas, 2018b). The single-target disassembly sequence plan model for buildings is an inverted tree that contains a minimum set of parts that must be removed before retrieving a target component. A part can be a component (building component) or a fastener (building connection), and they are represented as a square and a circle, respectively. Root nodes represent target components, leaf nodes represent parts that constrain the target components, and the links between them represent constraints. A building's assembly model is represented by constraint matrices where each cell position contains constraints for a part under study. The rows of the constraint matrices represent the assembly parts, and the columns represent the extraction direction under analysis ($+x$, $-x$, $+y$, $-y$, $+z$ and $-z$). A constraint can be physical, functional, environmental, or economical. The approach for creating a single-target selective disassembly model for buildings gets parts from the Disassembly Graph (DG) model, arranges and orders the parts in levels, and adds the parts to the inverted tree (Sanchez & Haas, 2018b; S. Smith et al., 2012). Finally, the approach uses expert rules to improve solution quality, minimize graph complexity, and reduce searching time for finding optimized disassembly sequence plans (Sanchez & Haas, 2018b; S. Smith et al., 2012; S. Smith et al., 2016).

6.4.2 The 6D BIM disassembly model

BIM offers designers the ability to assess different design alternatives at the conceptual stage of the project, through the virtual simulation of the performance of the final product (Jalaei & Jrade, 2014). The potential of BIM tools to correct mistakes at the early stages, aid in accurately scheduling and sequencing the construction, identifying conflicts, advocating design alternatives, and facilitating the selection of appropriate solutions for complex project has been proven for the past ten years (Gan et al., 2018; Jalaei & Jrade, 2014). A 6D BIM model of a building integrates the three-dimensional geometry, topology, and physical properties of the model (3D), time of building activities (4D), building work cost estimating (5D), and environmental impact assessment (6D). For the process described in Figure 6-2, BIM is used as the main digital platform in the iterative process of adaptive reuse design, including the deconstruction project planning. Figure 6-1a, shows a schematic view of an adaptive reuse project of the "Engineering 2" (E2) building at the University of Waterloo campus, as well as the 6D BIM model of one of the rooms. In 2017, an entire corridor of office rooms, located on the second floor of the E2 building, was redeveloped, reconditioned, and repurposed as part of an adaptive reuse project at the University of Waterloo. The office rooms where converted into laboratories of the Department of Civil and Environmental Engineering. The renovated rooms had a similar recurrent layout with the same construction systems. Figure 6-3 shows the details of a specific assembly subset of the original existing building just as an example for this study.



Assembly components:

1. Laboratory laminar flow fume hood
2. Convertible fume hood and ducting system section
3. Metal door wall laboratory cabinets
4. Stainless steel laboratory countertop
5. Base cabinetry
6. Fire resistant drywall panel
7. Steel frame wall system (2-½")
8. PVC water piping (½")
9. EMT conduit installation (½")
10. Fire resistant drywall panel

Attachment elements specifications:

The interface between the steel frame wall system (7) and the structure of the building, is through expansion plugs along steel tracks in the floor and ceiling, respectively.

The PVC water piping (8) and the EMT conduit installation (9) are attached to the steel framing (7) through special anchor brackets.

The interface between the drywall panels (6 &10) and the steel framing is compounded by screws for steel distributed over the panels.

The cabinetries (3 & 5) are attached to the steel framing (7) through special anchor brackets. Similarly, the countertop (4) is attached to the base cabinetry (5).

The ducting system (2) is attached to the ceiling through metal duct straps, and the fume hood (1) is connected to the ducting system.

Figure 6-3: 6D BIM disassembly model - Cluster 1: Isolated assembly under study

It is well known that the quality and complexity of disassembly models affect the solution quality and complexity of the calculations (S. Smith et al., 2012). In Chapter 5, the simplification of multiple fasteners in one single connection as just one analytical fastener in the disassembly model is established, in order to keep the model in a reasonable complexity range and in realistic terms for buildings (Sanchez & Haas, 2018b). Similarly, in this study the concept of "limits of design" for disassembly models applied for buildings is defined. In the process of adaptive reuse design some building parts, subsystems, and/or entire systems do not have to be modified at all. Therefore, their inclusion as part of the disassembly model is unnecessary. In this study the unmodified elements are considered as the limits of design. A BIM model is a powerful and highly organized graphical interface that brings the designers the flexibility to decide and visualize what parts of the building would be part of the limits of design and what parts would be include in the disassembly model. Figure 6-3 shows in colors the disassembly model, cluster 1. On the contrary, all of the elements of the building that are part of the limits of design are displayed in white. In a well-structured BIM model, the determination of the limits of design as well as the assembly components is straightforward just by selecting either isolated components, subsystems, or entire systems, and then clustering them. This simplification reduces the complexity of the model and the computational requirements. Also, this graphical interface feature of BIM models, gives extraordinary freedom for the designers to explore different design solutions according to different criteria. Figure 6-4 shows the hierarchical liaison graph for the disassembly model (cluster 1) where components c_x, c_y, c_z and c_w represent the limits of design. The concept of hierarchical liaison graph for the disassembly model is explained in Chapter 5 and is used for improving the process of finding disassembly sequences for targeted components (Sanchez & Haas, 2018b).

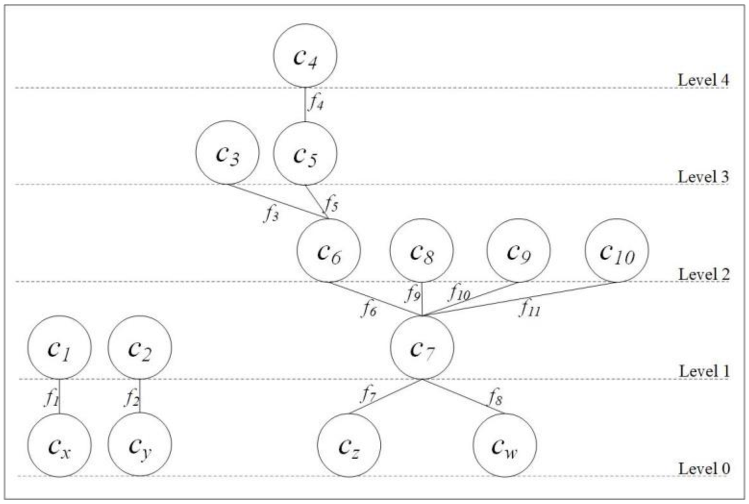


Figure 6-4: Hierarchical liaison graph of the disassembly model: Cluster 1

Since many buildings being evaluated for adaptive reuse do not have up-to-date BIM models, it may be necessary to obtain an as-built model through manual or automated methods. A growing area of research is expanding the capabilities of automated as-built model creation; which is cheaper, faster and more accurate than manual methods (Laefer & Truong-Hong, 2017; Patraucean et al., 2015). These automated methods often utilize as-built data from laser scanning (dense 3D point clouds), which has a rapid, accurate and agile workflow. Geometric algorithms are continually being developed to classify 3D point clouds for modelling building interfaces (e.g., steel frames, doorways, façade penetrations, etc.) (Hélène Macher, Tania Landes, & Pierre Grussenmeyer, 2017). Derivation of algorithms for detection of architectural and structural building elements is made possible using many common computer vision concepts (Kobyshev, Riemenschneider, Bódis-Szomorú, & Van Gool, 2017). However, current automated methods are limited to either geometrically simple features (planar, cylindrical, etc.) or very specific primitives that are extracted through means of machine learning, neural networks or other advanced means. The challenge with these methods is that shape descriptors need to be created for each unique component or part. This can be very tedious especially considering that many objects in buildings undergoing adaptive reuse have geometric characteristics that vary even between similar components (e.g., free-formed concrete elements, geometric distortions in pipes, stick-built steel framing). To address these challenges, this study recommends focusing on repeating (or modular) assemblies so that an automated as-built modelling workflow can be developed in detail on a single assembly and then carried out on all like assemblies, thus achieving economies of scale for as-built model extraction.

6.4.3 Retrieving BIM data from the model

The proposed method relies on rich data in order to compute economically viable solutions that take into account the practical limitations of deconstructing a construction assembly as well as LCA benefits. The authors demonstrate how all data required can be extracted from a detailed BIM model. Specifically, the following types of data are retrieved from a BIM model:

- Geometric data (areas, volumes, linear lengths of components)
- Spatial constraints (the direction that each component is allowed to move for dissasembly)
- Dissassembly constraints (the precedent relationships between components which dictate how dissasembly takes place)
- LCA data (embodied environmental impact of building materials)

In addition to the data being extracted from a BIM model, data pertaining to resource and project management is utilized, which comprises of construction resources (materials, labor, and machinery), scheduling, and deconstruction costs. While some of this data might be obtained directly from a BIM model (depending on the level of detail), it can also be readily collected from any project management software package.

While some BIM models contain purely surface-based data (e.g., a 2D rectangle to represent a window), it is preferable to have solid-based data (3D rectangular prism to represent a window), since this improves the accuracy of component interaction within an assembly. While the proposed selective dissasembly method ultimately requires that a user create several matrices to define the information retrieved from the BIM model, the authors are currently investigating methods to automatically conduct selective disassembly through computational algorithms. Figure 6-5 shows the exploded view of the disassembly model (cluster 1) under study.

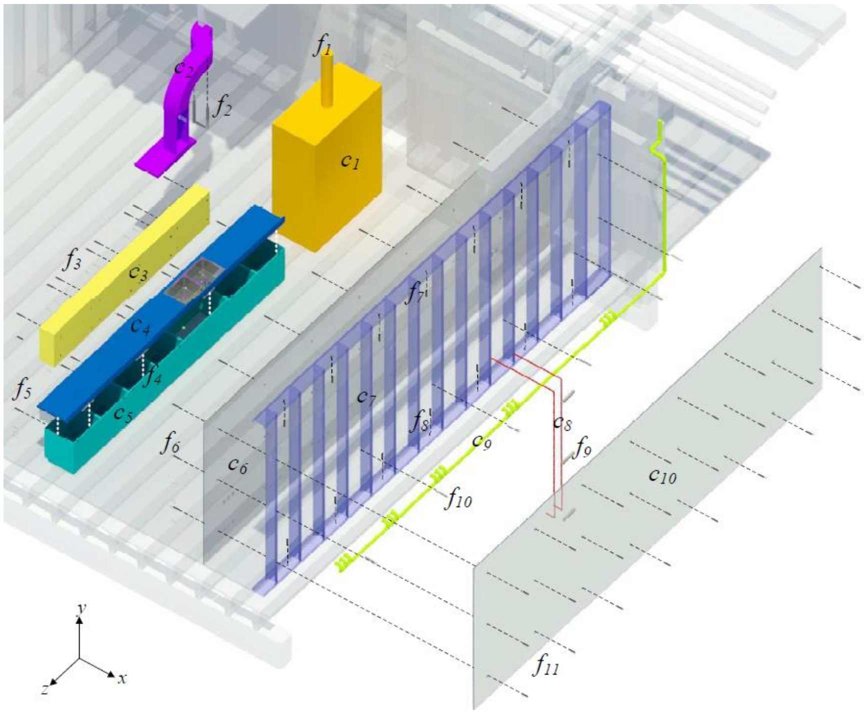


Figure 6-5: Exploded view of the disassembly model: Cluster 1

6.4.4 An approach for creating a multiple-target disassembly sequence planning for buildings

The approach for creating a multiple-target disassembly sequence plan model merges single-target plan models to create one with multiple targets. If the single-target plan models have identical nodes, including the extraction direction, then the approach merges them in one plan model with multiple targets. Otherwise, the plan models will remain disjoint. In this study, the method chooses the best direction for removing each target component and creates one single-target plan model for each target component. Then the method looks for the identical nodes in between the single-target plan models. If there are identical nodes between two plan models, the method merges them to create one plan model with multiple-targets. The method compares plan models one by one, starting from the plan model with more number of parts. If there is more than one extraction direction for a target component, the method can create more single-target plan models and select and merge the best one in the multiple-target plan model. The best single-target plan model is defined as the one with a maximum number of target components and a minimum number of parts. The final multiple-target disassembly sequence plan model represents a high quality, realistic, practical, and physically feasible solution that is optimized for the number of removed parts. Figure 6-6 shows the workflow for the proposed method for buildings disassembly. This kind of model approach for multiple-target disassembly sequence planning has been proven successful in the manufacturing industry. According to Smith et al. (2012) this approach improves solution quality and reduces model complexity, compared to prior approaches. The scripts of the algorithm described in Figure 6-6 can be found on Appendix E.

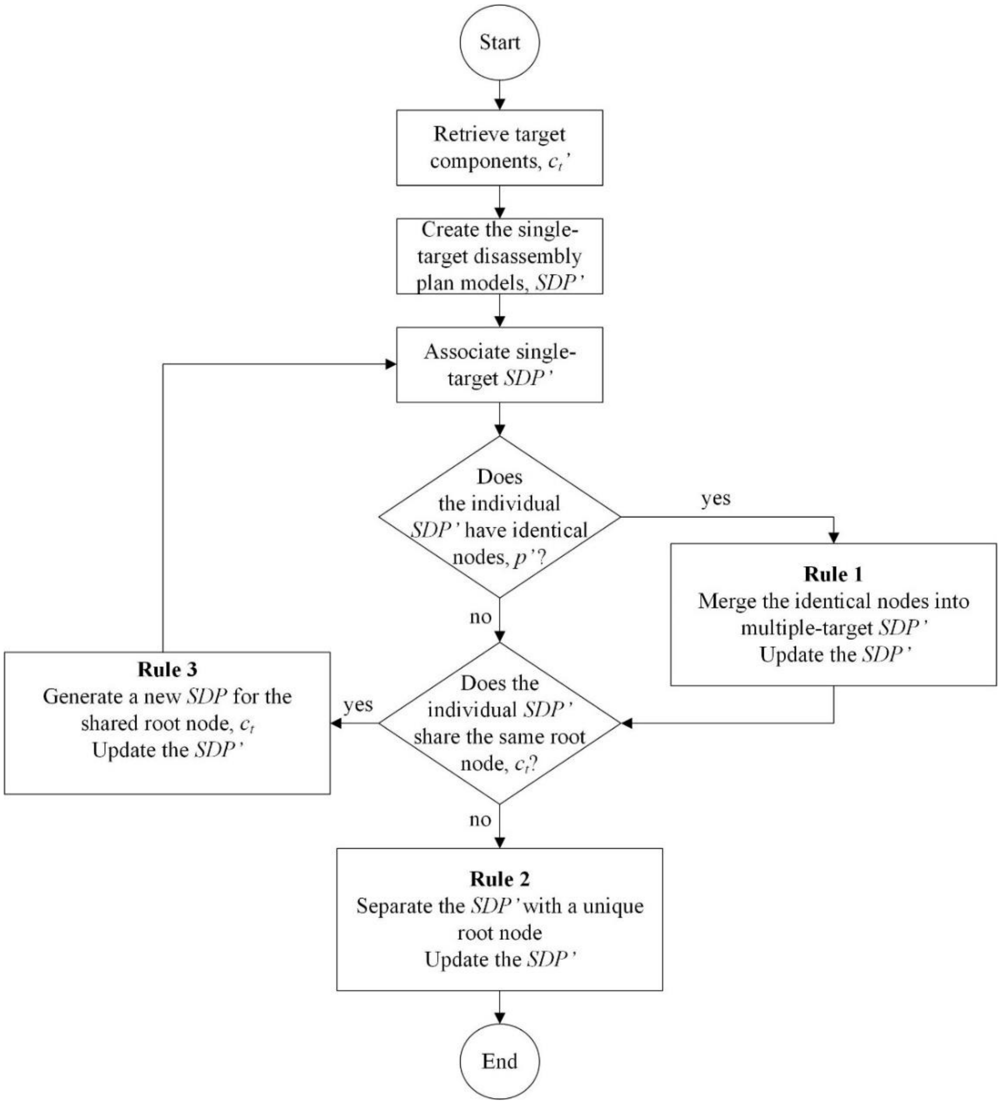


Figure 6-6: An algorithm for creating a multiple-target sequential disassembly planning (SDP) model for buildings

6.4.5 Expert rules

The single-target disassembly sequence plan model approach for buildings uses expert rules to improve solution quality, minimize graph complexity, reduce searching time, and reduce computational requirements (Sanchez & Haas, 2018b). The multiple-target disassembly sequence plan model approach for buildings uses expert rules to choose the best single-target plan models of different target components that are meant to be part of the same disassembly plan model. Different rules can be used for different applications, and in this study the rules were derived from disassembly planning case studies for buildings and literature review in the topic. The following are the expert rules which define the recursive multi-target selective disassembly planning process.

- Rule 1: If the individual *SDP'* have identical nodes, *p',* including their extraction direction, then merge the identical nodes, *p'*, of the single-target *SDP'* to create multiple-target *SDP'*.
- Rule 2: If the individual *SDP'* do not have identical nodes, *p'*, and they do not share the same root node, c_t, then keep separated the *SDP'* with a unique root node.
- Rule 3: If the individual *SDP'* do not have identical nodes, *p'*, but they share the same root node, c_t, then generate a new *SDP* for the shared root node, c_t, with a different extraction direction.

For Figure 6-5, the best direction for removing components c_2, c_5, and c_6 are $-y$, $-x$, and $-x$, respectively. Figure 6-7 shows the single-target disassembly sequence plan model for components c_2, c_5, and c_6. The plan model for component c_6 contains the plan model for component c_2 and c_5. Therefore, the approach merges the plan models for components c_2 and c_5 to create one multiple-target disassembly sequence plan model for three components.

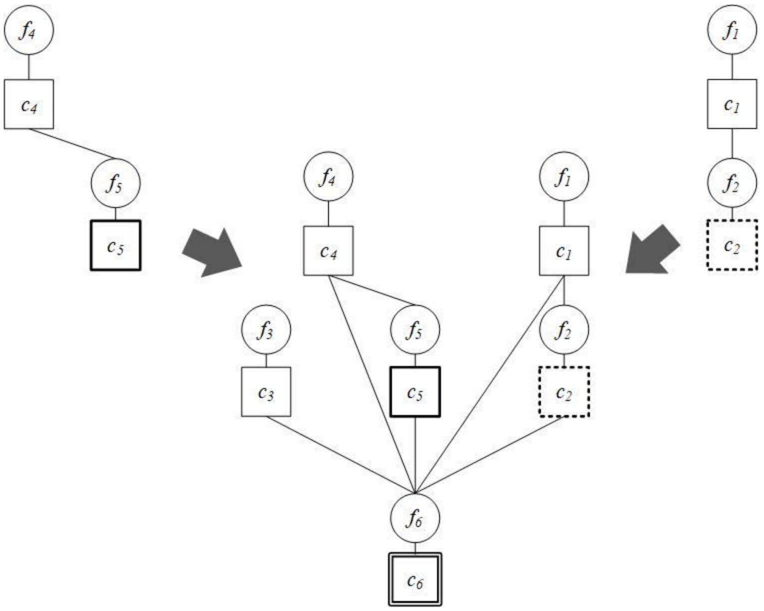


Figure 6-7: Multiple-target disassembly sequence plan model for components c_2, c_5, and c_6

6.5 Selective deconstruction programming

As pointed out in the literature review section, this is the first study in the field of selective deconstruction programming for buildings. In this matter, similar studies have been developed and validated in the manufacturing industry principally, showing extraordinary results since the last decade. For manufacturing products, the selective disassembly time estimation has been focused on sequential planning, dismantling one part at a time. This makes sense since typically only one worker can be involved in the process of dismantling a product. In contrast, buildings can be deconstructed by numerous workers operating in parallel. This study describes an approach to generate the programming of deconstruction work based on a selective disassembly sequence plan model. The approach builds and stores individual source and target vectors with the precedent information for the building's parts to deconstruct, along the execution of the subroutine. The source and target vectors represent nodes. Then, the individual vectors are merged into a main deconstruction plan. In the end, the main deconstruction plan is used to create the activity project network of the deconstruction work.

In first instance, the deconstruction work consists of non-destructive disassembly of the building's parts. The information related to the construction resources (materials, labor, and machinery), labor productivity rates, duration, and the associated direct cost of the deconstruction work is retrieved from the 6D BIM model. Then, all this information is exported to a PM software package in order to complete the selective deconstruction programming. The objective is to determine essential deconstruction project planning information such as project duration, critical activities, resource allocation, and total project cost. Also, other project parameters could be estimated, such as, work assignment, cashflow, and material inventory management. In a deeper analysis, this stage of the deconstruction project planning can be improved by using other PM methods like resource leveling, schedule crashing, and resource allocation. Also, it could be possible to apply any of the optimization methods covered in the literature review section. These optimization methods brings the opportunity of expanding the scope of the deconstruction planning to other fields such as minimizing the environmental impact and maximizing the life-cycle of the building components.

After a preliminary deconstruction planning has been calculated, the stakeholders can decide if the planning satisfies the needs of the adaptive reuse project. If the objectives of the project are not fulfilled, then the designers can go back to modify the adaptive reuse design. This becomes an iterative process where the decision makers can learn from the old designs and move forward in order to improve the final adaptive reuse design. The automation of the selective deconstruction project programming is the cornerstone to make this process feasible and affordable.

6.6 Case study

The following case study is used to demonstrate the present approach for deconstruction programming for adaptive reuse of buildings, which includes multiple-target selective disassembly. The software used for this purpose were Matlab® and MsProject®. A 6D BIM assembly model was prepared for the University of Waterloo adaptive reuse case study displayed in Figures 6-1a, 6-3 and 6-5. The new method demonstrates that it is possible to create an optimized multi-objective selective disassembly plan for the building assembly. The method is able to create an individual disassembly plan for each target component, and then to merge them all in a multi-objective disassembly plan. The method is able to create realistic and feasible disassembly plans for buildings. Based on the final disassembly plan, the method builds up the deconstruction plan with the information of the deconstruction activities and their interdependence. The deconstruction plan is used to create the activity project network of the deconstruction work. Figure 6-5 shows the 21-part assembly model under study.

This study uses a previously described algorithm (Sanchez & Haas, 2018b) to create optimized single-target disassembly sequences for the targeted components. For Figure 6-5, the best directions for removing components c_6 and c_7 are $-x$ and $+x$ directions respectively. Figure 6-8 shows a multiple-target disassembly plan for components c_6 and c_7. The approach found a solution $S1 = (c_6\ f_6\ c_2\ f_2\ c_1\ f_1\ c_5\ f_5\ c_4\ f_4\ c_3\ f_3)$ for c_6, and $S2 = (c_7\ f_7\ f_8\ c_6\ f_6\ c_9\ f_{10}\ c_8\ f_9\ c_{10}\ f_{11}\ c_2\ f_2\ c_1\ f_1\ c_5\ f_5\ c_4\ f_4\ c_3\ f_3)$ for c_7. Then the approach merged the single plans into one with multiple objectives. The final solution was $S3 = (c_7\ f_7\ f_8\ c_6\ f_6\ c_9\ f_{10}\ c_8\ f_9\ c_{10}\ f_{11}\ c_2\ f_2\ c_1\ f_1\ c_5\ f_5\ c_4\ f_4\ c_3\ f_3)$. The associated life-cycle environmental impact for the final disassembly plan is 1,434 kg CO_2 eq and 22,611 MJ. The associated building cost is $1,703.67 USD. In the final step, the approach builds up the deconstruction plan with the information of the deconstruction activities and their interdependence. Figure 6-8 shows the deconstruction programming for components c_6 and c_7. In Figure 6-9, the CPM is displayed, showing the critical activities in red. The final duration of the dismantling work is 20 working hours.

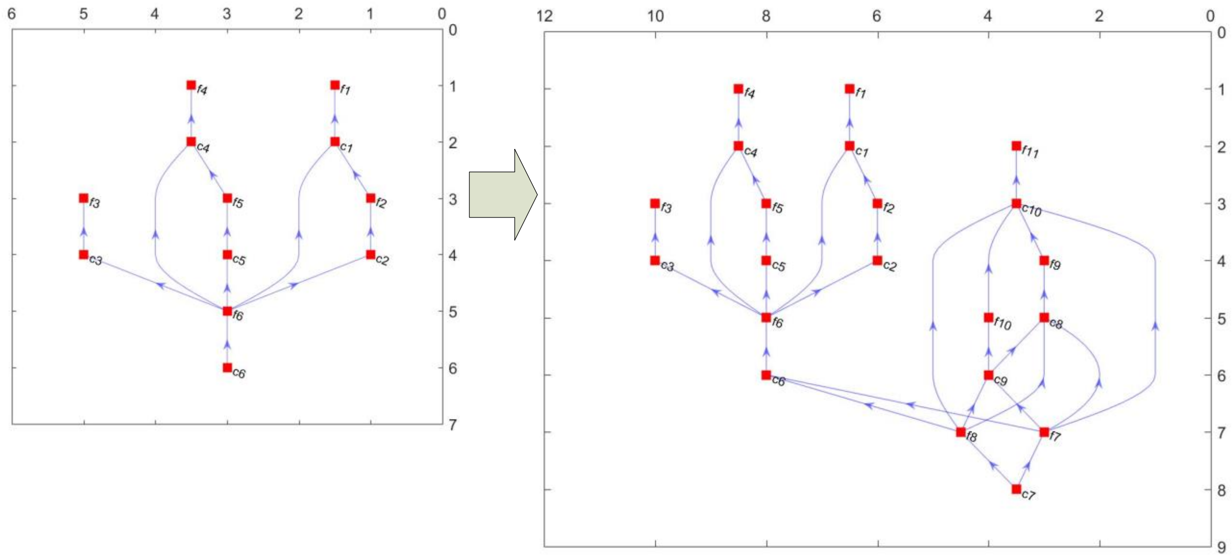
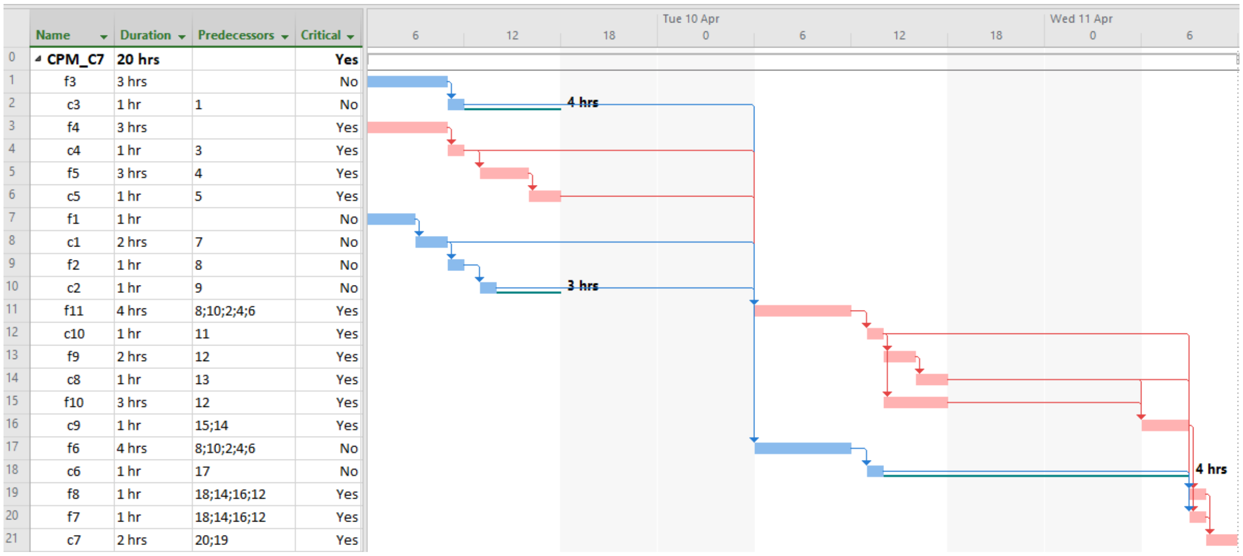


Figure 6-8: Automated generation of the multiple-target disassembly plan for components c_6 and c_7



	Name	Duration	Predecessors	Critical
0	CPM_C7	20 hrs		Yes
1	f3	3 hrs		No
2	c3	1 hr	1	No
3	f4	3 hrs		Yes
4	c4	1 hr	3	Yes
5	f5	3 hrs	4	Yes
6	c5	1 hr	5	Yes
7	f1	1 hr		No
8	c1	2 hrs	7	No
9	f2	1 hr	8	No
10	c2	1 hr	9	No
11	f11	4 hrs	8;10;2;4;6	Yes
12	c10	1 hr	11	Yes
13	f9	2 hrs	12	Yes
14	c8	1 hr	13	Yes
15	f10	3 hrs	12	Yes
16	c9	1 hr	15;14	Yes
17	f6	4 hrs	8;10;2;4;6	No
18	c6	1 hr	17	No
19	f8	1 hr	18;14;16;12	Yes
20	f7	1 hr	18;14;16;12	Yes
21	c7	2 hrs	20;19	Yes

Figure 6-9: Automated generation of the deconstruction programming for components c_6 and c_7

6.7 Summary of findings on deconstruction planning and scheduling for adaptive reuse of buildings

Adaptive reuse of buildings has demonstrated to be a superior alternative for new construction in terms of sustainability and CE, when it is applied properly. The study presented in this chapter establishes the reference framework about the importance of developing an appropriate deconstruction project planning for improving adaptive reuse projects' outcomes. In order to remedy the current inefficiencies in the deconstruction planning phase for adaptive reuse projects, this study describes the critical processes and sub processes associated to the BIM-based deconstruction project planning. A semi-automated selective deconstruction programming method for buildings is developed and validated as a contribution for improving the deconstruction project planning for adaptive reuse projects. As discussed in the paper, there is a lack of technical methods to assist in the decision making inside the selective deconstruction planning of a building. Therefore, by developing user-friendly standardized procedures and tools, it is possible to fully exploit the benefits in adaptive reuse projects.

The design process for adaptive reuse is an iterative process where the design decisions could be driven by diverse criteria, such as financial, technical, functional, and aesthetic needs. During this iterative process, it is necessary to evaluate the different design options in an objective way, in order to improve the project's outcome. The first phase involved in the evaluation process is through deconstruction planning. In this matter, prior studies have developed methods for deconstruction planning of buildings. These studies have thoroughly considered practicality of the methods, areas of opportunity for optimization, and technical affordability. However, none of these prior studies have been applied to deconstruction for adaptive reuse. The fundamental difference is that those previous studies are based on a fixed programming of the deconstruction work, and the deconstruction planning for adaptive reuse projects involves a deconstruction programming based on selective deconstruction of building components. The goal of this study is to describe and validate a semi-automated selective deconstruction programming approach for adaptive reuse of buildings. The proposed approach is able to create an efficient programming of the deconstruction work based on realistic and optimized selective disassembly planning. The new approach builds on a previous work related to single-target selective disassembly sequence planning algorithm for adaptive reuse of buildings. The approach is able to create the programming of deconstruction work for recovery multiple components of a building assembly, in an automated way. The automatization of this complex process is a critical feature in order to make the iterative process of adaptive reuse affordable, measurable, and comparable for real adaptive reuse projects.

The deconstruction programming approach developed in this study aims to improve adaptive reuse projects' outcomes in terms if sustainability and CE. This method is a user-friendly tool that helps during the iterative process of evaluating different design options for repurposing an existing building asset. Disassembly planning and deconstruction time estimation has been the focus of many research efforts in different industries including the manufacturing and construction industry. In comparison to the manufacturing industry, the construction industry has more limited research in this field. The manufacturing industry has developed studies in all of the levels of product disassembly, including 1) destructive vs non-destructive, 2) complete vs selective, and 3) sequential vs parallel. Because of the particularities and specific objectives of these kind of studies, the level of detail for the analysis has been very comprehensive and complete. For example, the disassembly time estimation analysis for products include reorientations, change of extraction directions, hardness of joint elements, selecting working tools, postural requirements, and material handling requirements. Contrasting, there is no evidence of studies in the field of selective deconstruction programming for buildings. The approach developed in this paper is the first one in its class and it represents an opportunity for closing the knowledge gap in this matter.

This study demonstrates the affordability and practicality for applying selective deconstruction programming for adaptive reuse projects by using current technologies such as 6D BIM, disassembly planning optimization models, and PM software. This study can be broadly used with different objectives and purposes, for example the reduction of waste stream in the construction industry through the recovery of building components for reuse and recycle. Some degree of waste may still result if not all components in the existing assembly are fully reused. While these components could be recycled, an alternative approach could be the creation of facilities that house construction components while they await reuse in other projects. A great example of this could be facilities that house old steel frame components. Rather than recycling or melting down old steel members, components could be kept in a warehouse until needed for future projects. This is similar to warehouses which house parts for manufacturing that await reuse in like assemblies.

One of the limitations for the application of the proposed approach for existing assets, is the need of a representative and accurate BIM model. However, there is a strong push and development in the field of generating BIM models from existing buildings by using 3D scanning and Non-Destructive Testing explorations. Developing an accurate BIM model of existing buildings could be used for many other purposes aside the repurposing of the asset, such as maintenance scheduling, building system analysis, asset management, and disaster planning. On the other hand, since the last decade BIM has become a required feature for planning new buildings and infrastructure. Therefore, the proposed study could be applied straightforward for the selective deconstruction planning of these kind of assets. Finally, the development of deconstruction planning by using BIM has other benefits such is the highly organized graphic interface for the designers, and the possibility to make BIM a powerful communication and training tool for the workforce involved in the deconstruction work.

As future research, the method approach has to incorporate more deconstruction techniques aside disassembly such as selective and partial demolition. Depending on the building components, more deconstruction techniques should be added in order to create alternative dismantling plans. These alternative dismantling plans would affect the interdependence of the activity network for the deconstruction work and therefore the deconstruction programming and planning would change. In other topics, more investigations related to the labor rates, deconstruction timing, direct cost, and environmental impact of the deconstruction work could be desirable with the aim of making the results of this study more accurate and representative. In the same way, there could be parallel research, to delve into the topic of retrieving the BIM data from the disassembly model in an automatic way, in order to make the planning process more efficient.

Chapter 7: Multi-objective analysis for selective disassembly of buildings[6]

7.1 Abstract

Adaptive reuse has the potential to maximize the residual utility and value of existing assets through green design methods such as selective disassembly planning. Studies in the field of selective disassembly for adaptive reuse of buildings are scarce and there is no evidence of established methodologies and/or analysis for the optimization of the environmental and financial benefits. A multi-objective analysis is key to obtaining several effective selective disassembly plans for the adaptive reuse of an existing asset through the combination of different deconstruction methods. The analysis is carried out in terms of the physical, environmental, and economic constraints of the deconstruction methods per building component. The Sequential Disassembly Planning for Buildings (SDPB) method, presented in previous studies, is used in order to generate the optimized disassembly plans for retrieving target components. At the end, a weighted multi-objective optimization analysis is incorporated to generate the set of noninferior solutions that minimizes environmental impacts and building cost. The results show that different complete disassembly plans exist for all of the possible combinations. The possible combinations are driven by the deconstruction methods per component, as well as the dismantling interdependence. For adaptive reuse of buildings, the methods described in this study can be used to improve the project outcomes according to specific goals and constraints (e.g. environmental, economic, technical).

7.2 Introduction

Adaptive reuse of buildings plays a key role in the transition from a resource-based economy and towards a Circular Economy (CE) in the construction industry. Adaptive reuse has the potential to maximize the residual utility and value of existing assets by "giving them new life" through green design methods, such as selective disassembly planning. Green design methods are used to reduce environmental impacts and to increase economic benefits over the entire product or service lifecycle. Adaptive reuse is considered a disruptive practice in the current capital project delivery model for the renewal of today’s built environment (Geissdoerfer et al., 2017; Sanchez & Haas, 2018a). Therefore, the field of green design methods for buildings is still underdeveloped in comparison to other industries such as automotive, textile, and manufacturing. In particular, the studies in the field of selective disassembly for adaptive reuse of buildings are scarce and, to the knowledge of the authors, there is no evidence of established methodologies and/or

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[6] The contents of this section of the chapter have been incorporated within a paper that will be submitted for publication. B. Sanchez, C. Rausch, C. Haas, and R. Saari, “Multiobjective optimization analysis for adaptive reuse of buildings” Submitted to the Journal of Building and Environment. Planned submission date February 2019. Only minor editorial changes are applied for being consistent with the University of Waterloo thesis format.

analyses for the optimization of environmental and financial benefits. The aim of the study presented in this chapter is to develop a multi-objective optimization analysis for the selective disassembly planning of an existing asset through the combination of different deconstruction methods. The analysis is carried out in terms of the physical, environmental, and economic constraints of the deconstruction methods per building component. The Sequential Disassembly Planning for Buildings (SDPB) method, presented in previous studies (Sanchez & Haas, 2018b; Sanchez et al., 2019), is used in order to generate the optimized disassembly plans for retrieving single or multiple targeted components. The SDPB method is extended with the purpose of including more than one deconstruction method per component. Finally, a weighted multi-objective optimization analysis is incorporated to generate the set of noninferior solutions that minimizes environmental impacts and building costs.

The results show that different complete disassembly plans exist for all of the possible combinations. The possible combinations are driven by the deconstruction methods per component, as well as the dismantling interdependence. For adaptive reuse of buildings, the proposed study can be used to improve the project outcomes according to specific goals and constraints (e.g. environmental, economic, technical). The results of this study improve the decision-making process for adaptive reuse building projects by adding comprehensive quantitative analysis towards resource optimization. This study provides a better understanding of the management of the multiple variables involved in the process of selective disassembly for adaptive reuse in order to improve the project performance.

7.3 Problem statement

Over the last two decades, environmental concerns have driven the research of construction projects' life cycle performance towards a holistic approach to sustainability (Anderson et al., 2015; Blengini & Di Carlo, 2010; Chastas et al., 2016; Ortiz et al., 2009). As a result, circular building concepts, such as a CE for infrastructure, closed-loop cycle construction, and Cradle-to-Cradle construction, have been identified as feasible and effective alternatives towards a more sustainable development in the construction industry. These alternatives imply a radical change in the conceptualization of new building projects, in comparison to the traditional way for greenfield construction, where circular building principles become a fundamental part of capital project delivery, including the building project definition process. In this matter, several studies have recognized the importance of the End of Life (EoL) stage in existing buildings, and the opportunity of their adaptive reuse as a superior alternative in terms of CE (Langston et al., 2008; Sanchez & Haas, 2018b; E. A. L. Teo & Lin, 2011). However, for the capital project delivery in a CE framework, there is a lack of science-based, user-friendly, and generic methods to: 1) improve adaptive reuse project outcomes, 2) develop appropriate planning for closed-loop cycle construction, and 3) plan for the optimization of the benefits of adaptive reuse.

7.3.1 Capital project delivery for a Circular Economy

The development of the closed-loop cycle capital project delivery for buildings is the pursuit of a business strategy of an enterprise in principle and the kickoff of a project in practice. Until now, the traditional business strategy in project delivery for buildings has been based on the premises of increasing productivity, profitability, and efficiency in the construction and operational phases (Cho & Gibson Jr., 2001). This is simply the response of the building market to the challenges of an increasing demand for buildings, accelerated competition, increased economic pressures, and rapid technological change. However, it has been demonstrated that the traditional emphasis on meeting time, budget, and project performance goals is no longer sufficient to guarantee the achievement of sustainable development objectives in the construction industry (Asdrubali et al., 2013; Sanchez & Haas, 2018a).

The understanding of the challenge of sustainable development, as well as the implementation of strategies to tackle this global concern, has continuously changed due to technological advances and interdisciplinary applied research all around the globe. It is claimed that the world today is facing immense social, economic and environmental challenges like never before (UN, 2015). Therefore, it is necessary to expand the business strategy planning of building projects into the dimensions of sustainability. A business strategy planning for a CE in construction is a means to effectively tackle the aforementioned challenges. This new business strategic planning should not disregard the traditional mindset; instead, it should expand it.

7.3.2 Green design methods for adaptive reuse of buildings

In previous work, the important role of green design methods and deconstruction planning methods in the adaptive reuse process of buildings has been discussed (Sanchez & Haas, 2018b). Green design methods are intended to reduce environmental cost and increase economic benefits over the entire product or service lifecycle (S. Smith et al., 2016). Examples of green design methods are design for assembly, supply chain management, Product Recovery Management (PRM), Life Cycle Assessment (LCA), design for disassembly, design for remanufacture, and disassembly sequence planning.

In the field of design for disassembly and deconstruction for buildings, improvements can be achieved by considering future disassembly of building elements at the planning stage of new buildings (Gorgolewski, 2008). For example, researchers studied the cost-effectiveness of deconstruction compared with traditional demolition of residential construction (Guy & McLendon, 2000). Akbarnezhad, Ong and Chandra (2014) demonstrated the efficiency of using BIM-based economic and environmental assessments in construction strategies to quantify the affordable benefits accurately. This study included the effect of prices and energy embodiment of the materials and components, transportation, energy use and costs associated with the recycling processes, inflation rate, costs of designing the components for reusability, and costs of disassembly and re-assembly. In his work, Kokkos (2014) developed a sophisticated parametric and associative toolbox that exposes the environmental and financial impacts of the concept of design for deconstruction. Shultmann and Sunke (2007) delved into the energy savings, in terms of embodied energy, that could be achieved through using different recovery techniques on deconstruction projects. Other studies have investigated the optimization of the economic performance of the deconstruction and recovery processes of EoL buildings by using mixed-integer and binary linear programming (Aidonis, Xanthopoulos, Vlachos, & Iakovou, 2008; Xanthopoulos, Aidonis, Vlachos, & Iakovou, 2012).

Despite the advances in the area of building deconstruction planning, only a few studies have developed deconstruction planning methods for the adaptive reuse of existing assets. Sanchez and Haas (2018b) developed the first-in-its-class selective disassembly sequence planning method for adaptive reuse of buildings. The method seeks to minimize disassembling cost of retrieving a single selected component from a building assembly, based upon physical constraints. As an extension of this work, Sanchez, Rausch, and Haas (2019) developed a multiple-target sequential disassembly planning model for buildings, as well as a novel approach for deconstruction programming for adaptive reuse of buildings.

7.3.3 Multi-objective optimization analysis for selective disassembly

The field of selective disassembly planning of manufacturing products have been explored during the last 30 years. In their work Smith et al. (2012) demonstrated that their Disassembly Structure Sequence Graph (DSSG) model approach improves solution quality and search time for disassembly models in comparison to prior techniques. The DSSG model approach has been developed and successfully tested in several case studies for the manufacturing industry (S. Smith & Hung, 2015; S. Smith et al., 2012; S. Smith et al., 2016). The DSSG model approach has been adapted in each study to optimize single or multiple objectives such as minimizing the search time, minimizing the number of removed parts, minimizing the number of changes on the reorientation for extracting parts, minimizing the amount of labor for disassembly based on the difficulty of dismantling parts or modules, minimizing the disassembly cost, maximizing the Recycle Value (RV), and optimizing the cost-benefit of partial disassembly planning with a life cycle impact assessment approach (S. Smith & Hung, 2015; S. Smith et al., 2012; S. Smith et al., 2016). These studies have implemented different methods for developing single and multi-objective optimization analysis.

According to Revelle & Whitlach (1996), the goal of multi-objective optimization analysis is to quantify the degree of conflict among objectives. The conflict between objectives originates when a strategy that is optimal with respect to one objective may be nonoptimal for another. Therefore, the concept of optimality may be inappropriate for a multi-objective analysis. Instead of searching for an optimal or the best overall solution, the goal of a multi-objective analysis is to define the set of solutions for which no other better solutions exist for the objectives of interest. This set of solutions is well known with the name of noninferior solutions or Pareto frontier. The concept of noninferiority is defined as: “A solution to a problem having multiple and conflicting objectives is noninferior if there exists no other feasible solution with better performance with respect to any one objective, without having worse performance in at least one other objective” (Revelle & Whitlach, 1996). An important characteristic when dealing with a multi-objective analysis is that each objective is measured in different units. In other words, the units are incommensurable. At the end of the analysis, the decision makers have the responsibility of choosing the appropriate solution from the set of noninferior solutions.

The multi-objective optimization analysis for this study deals with managing environmental and economic resources in the process of selective dismantling of an existing asset. This study might seek to evaluate environmental quality and economic efficiency trade-offs throughout the deconstruction process. For this study, one of the objective functions seeks to minimize the amount of environmental impacts due to the discarded parts during the selective dismantling process of a building, that might involve the total or partial disassembly of multiple buildings’ subsystems. Depending on the approach of the overall analysis, the user can select a specific environmental impact of interest, such as Global Warming Potential (GWP), Primary Energy Demand (PED), and Water Consumption (WC). The second objective function seeks to minimize the overall cost of deconstruction work. Justification for such an analysis exists if the deconstruction process is repeated across many similar or identical building subsystems such as repetitive lab or living layouts. The conflict or trade-off between these objectives is found in the incommensurable differences between the environmental value and removal cost of different selective disassembly plans for components.

7.3.4 The knowledge gap

Adaptive reuse of buildings plays a key role in moving the value chain of the construction industry towards a more sustainable development and CE. Adaptive reuse is considered a disruptive practice in the current capital project delivery model for the renewal of today’s built environment. Therefore, the field for improving the inefficiencies inside the process of adaptive reuse of buildings through the implementation of green design methods, such as selective disassembly planning and PRM, is still underdeveloped in comparison to other industries (e.g. automotive, textile, and manufacturing). The purpose of this study is to describe and validate a methodology for optimizing the environmental and financial performance of the selective disassembly planning process for adaptive reuse of buildings. A multi-objective optimization analysis is key to finding several effective selective disassembly plans for the adaptive reuse of an existing asset or building subsystem class through the combination of different deconstruction methods.

7.4 Methodology

The proposed methodology for a multiple objective optimization analysis is incorporated into the framework of selective deconstruction project planning by using the BIM-based phased planning presented in a previous work (Sanchez et al., 2019). First, the Sequential Disassembly Planning for Buildings (SDPB) method is used to generate the optimized disassembly plans for retrieving single or multiple target components from a given building's assembly, and according to the adaptive reuse design. The SDPB method optimizes disassembly plans in terms of the physical constraints per building component and by using just one deconstruction method per building component, which is "destructive disassembly". Once the disassembly plans are ready, more deconstruction methods per component are included in the next stage of the analysis. The other deconstruction methods included are "selective demolition" and "perfect disassembly". At the end, a weighted multi-objective optimization analysis is implemented to generate the set of noninferior solutions that minimizes a specific environmental impact and the building cost (see Figure 7-1). After finding the set of noninferior solutions for a given disassembly plan, the decision makers can select the alternative that is more aligned to the objectives of the overall project, and they can continue with the next stages of the deconstruction planning, in order to estimate the final cost and total duration. As shown on Figure 7-1, this becomes an iterative process whereby if the project needs are not fulfilled, the adaptive reuse design should be changed by the designers.

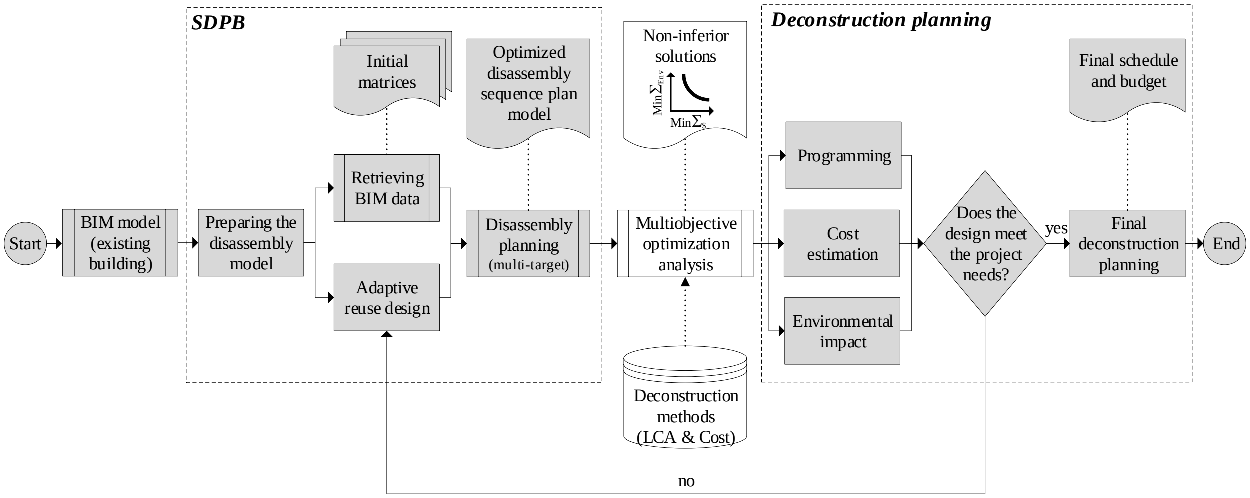


Figure 7-1: Multiple objective optimization analysis for selective deconstruction project planning

7.4.1 The disassembly sequence plan model for adaptive reuse of buildings

This study is built on previous work related to selective disassembly planning for adaptive reuse (Sanchez & Haas, 2018b; Sanchez et al., 2019). First, the authors developed the SDPB single-target disassembly sequence plan model which is an inverted tree that contains a minimum set of parts that must be removed before retrieving a target component. A part, in this case, can be a component (building component) or a fastener (building connection). Root nodes in the inverted tree represent target components, leaf nodes represent parts that constrain the target components, and the links between them represent constraints. A constraint can be physical, functional, environmental, or economical. The SDPB method for creating a single-target selective disassembly model for buildings gets parts from the Disassembly Graph (DG) model, arranges and orders the parts in levels, and adds the parts to the inverted tree (Sanchez & Haas, 2018b; S. Smith et al., 2012). Finally, the approach uses expert rules to improve solution quality, minimize graph complexity, and reduce searching time for finding optimized disassembly sequence plans (Sanchez & Haas, 2018b; S. Smith et al., 2012; S. Smith et al., 2016). In a subsequent study, the authors extended the SDPB method to multiple-target selective disassembly of building components, and also provide the programming of deconstruction work.

Both previously developed disassembly sequence plan models rely on a set of initial matrices, which are derived from geometric and spatial properties of components from a BIM model. The function of these matrices is to define how components and fasteners are related to each other in terms of direct contact, primary movement constraints for disassembly, and overall spatial constraints within a predefined working space parameter. Currently, derivation of these matrices is a manual process that is very tedious and time consuming for large assemblies. In addition, human input is required since most BIM models do not contain the granularity for establishing matrix data such as fastener motion constraints. Most BIM models in construction are simply not detailed enough to include all fastener details (as compared with 3D models used in manufacturing applications). To address these challenges, the authors are exploring methods for deriving initial matrices automatically through use of heuristics (to address modelling discrepancies in BIM models such as lack of fastener data and geometric inconsistencies) and spatial parametrization algorithms (to automatically build constraint matrices once components and fasteners are properly detailed). This work is important in the context of this paper since the overall quality of the multi-objective optimization relies on having accurate and on-demand data for selective demolition, selective disassembly, and complete disassembly methods.

7.4.2 Deconstruction methods per building component

For the proposed approach in this study, it was necessary to estimate the environmental and economic information related to the deconstruction methods included for the multi-objective optimization analysis. The environmental data for building components includes the LCA of selected environmental impacts for each component *j* ($j=1,\dots,J$) meant to be part of the same assembly. The LCA system boundaries and limitations were determined according to the most common current practices for buildings and in accordance with a full cradle-to-grave life cycle analysis as in previous studies (Sanchez & Haas, 2018b). The calculated Environmental Impacts EI^a, *where* $a \in A$, were: 1) Global Warming Potential (GWP) in kilograms of carbon dioxide equivalent (kg CO_2 eq) and 2) Primary Energy Demand (PED) in Mega Joules (MJ). The phases included in the LCA were production stage, construction stage, and End-of-Life (EoL). According to Schultmann & Sunke (2007) the operational stage of an LCA cannot be assigned to a building component or material separately. Fortunately, the sustainability of disassembly plans should theoretically not differ based on the building use phase, assuming they support the same functions. Three different deconstruction methods *m* ($m=1,\dots,M_j$) were analysed for the EoL stage per building component: 1) selective demolition, 2) destructive disassembly, and 3) perfect disassembly. Therefore, the LCA, LCA^a_{jm}, of a specified environmental impact *a* of a building component *j* in deconstruction method *m* is calculated according to Equations 7-1 to 7-3.

$$LCA^a_{jm} = EI^{a,production}_{jm} + EI^{a,construction}_{j} + EI^{a,EoL}_{jm} \qquad 7\text{-}1$$

$$EI^{a,production}_{jm} = EI^{a,raw\ materials\ supply}_{jm} + EI^{a,transport}_{j} + EI^{a,manufacturing}_{jm} \qquad 7\text{-}2$$

$$EI^{a,construction}_{j} = EI^{a,transport}_{j} + EI^{a,installation\ process}_{j} \qquad 7\text{-}3$$

Selective demolition is defined in this methodology as being synonymous with the destruction of components and connections. The EoL treatment for selective demolition is based on average US construction and demolition waste treatment methods and rates, including an avoided burden approach for recycling processes, credit for average energy recovery rates on materials' incineration, and impacts associated with landfilling of materials (KT Innovations et al., 2018). The LCA for selective demolition was calculated per component using the commercial 6D BIM software Revit® and Tally®. Tally® is a specialized software consistent with LCA standards ISO 14040-14044 and EN 15978, which are the most widely accepted and well-known standards for LCA for buildings (KT Innovations et al., 2018). The LCA modeling principles are aligned to the characterization scheme and methodology TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) developed by the United States Environmental Protection Agency (US EPA), commonly used for LCA work in North America (US EPA, 2016). The organization of building life-cycle stages as described in EN 15978 and the processes included in Tally® modeling scope for the purposes of this study are as follows: product stage (A1. raw material supply, A2. transport, and A3. manufacturing), construction stage (A4. transport and A5. construction installation process), and EoL stage (C2. Transport, C3. Waste processing, C4 disposal, and D. reuse, recovery, and recycling potential).

Destructive disassembly is defined in this methodology as the disassembly of components and connections in a manner which preserves their physical integrity. As a simplification for the LCA of destructive disassembly, the results of selective demolition were used with a reduction of 80% of the production stage for raw materials supply and manufacturing, assuming that disassembled components could be reused with only minor refurbishments being made. This is an important simplification in order to have a reasonable approximation of the LCA for destructive disassembly per building component for several key reasons. First, there is a lack of research in the field of estimating the environmental cost for deconstruction activities and refurbishment of building components (Ghisellini, Ripa, & Ulgiati, 2018). Second, the complexity of defining the LCA system boundaries of the different EoL options per building component may become too tedious for low building component quantities (Thormark, 2000). Finally, this simplification is required due to the scarcity of reliable technical information of deconstruction methods and procedures per building component. Some studies have demonstrated that the rate for recovering reusable building components could vary from 70% to 100% depending on the type of component's material, the type of connections (how difficult is to disassembly a component), and the product losses during the deconstruction processes (Sára, Antonini, & Tarantini, 2001). In light of this information, an 80% reduction of raw material supply and manufacturing LCA is used for characterizing selective demolition in this work.

For estimating the LCA for destructive disassembly, the avoided environmental burden of the recycling processing was neglected from the selective demolition LCA calculations since destructive disassembly does not presume the recycling of the recovered components. Perfect disassembly in this approach is defined as the disassembly of building parts with extreme care in order to warrant their direct reuse (i.e., complete physical and functional utility). The LCA for perfect disassembly assumes 100% reduction of the production stage for raw materials supply and manufacturing from the selective demolition LCA. These simplifications were made to accelerate the process of calculating LCA per building component and also due to technical limitations of the LCA software Tally® employed in this research. Further investigations are required in order to make these calculations more accurate and representative. Therefore, the environmental impact EI^a of the LCA production stage for a building component j with an associated deconstruction method m (*m=selective demolition, destructive disassembly, perfect disassembly*) is calculated according to Equations 7-4 to 7-6:

$$EI_{j,sel.demolition}^{a,production} = EI_{j,sel.demolition}^{a,raw\ materials\ supply} + EI_{j}^{a,transport} + EI_{j,sel.demolition}^{a,manufacturing} \qquad 7\text{-}4$$

$$EI_{j,destr.disassembly}^{a,production} = EI_{j,destr.disassembly}^{a,raw\ materials\ supply} + EI_{j}^{a,transport} + EI_{j,destr.disassembly}^{a,manufacturing} \qquad 7\text{-}5$$

$$EI_{j,perfect\ disassembly}^{a,production} = EI_{j}^{a,transport} \qquad 7\text{-}6$$

Where:

$$EI_{j,destr.disassembly}^{a,raw\ materials\ supply} = \left(EI_{j,sel.demolition}^{a,raw\ materials\ supply}\right)0.2 \qquad 7\text{-}7$$

$$EI_{j,destr.disassembly}^{a,manufacturing} = \left(EI_{j,sel.demolition}^{a,manufacturing}\right)0.2 \qquad 7\text{-}8$$

Similarly, the environmental impact EI^a of the LCA EoL stage is calculated according to Equations 7-9 to 7-11:

$$EI_{sel.\ demolition}^{a,EoL} = EI^{a,demolition} + EI^{a,transport} + EI^{a,waste\ processing} + EI^{a,disposal} + EI^{a,recovery\ and\ recycling\ potential} \qquad 7\text{-}9$$

$$EI_{destr.dissasembly}^{a,EoL} = EI^{a,deconstruction} + EI^{a,transport} \qquad 7\text{-}10$$

$$EI_{perfect\ \ dissasembly}^{a,EoL} = EI^{a,deconstruction} + EI^{a,transport} \qquad 7\text{-}11$$

The economic data for building components *j'* includes the information related to the budgeting (bare cost) *C* associated with the three deconstruction methods *m* described above. The cost information for destructive disassembly was retrieved from the national database RSMeans®. The data recovered from this database is considered representative for the scope of this study (i.e., the building market in North America). Nevertheless, further investigations should be done in order to adjust for the fluctuations of the suggested prices due to particularities of the local economies of the building location. Even though RSMeans® contains the prices for a wide variety of construction activities, in the matter of deconstruction activities such as selective deconstruction, selective demolition, and building refurbishment, the estimations are limited to only a few options according to the most common trends in the construction industry. RSMeans® was therefore used for estimating the building cost for the destructive disassembly per building component, and adjustment factors of 0.65 and 1.35 for estimating the selective demolition and the perfect disassembly costs, were used respectively. This is just a rough approximation of the cost variation between conventional demolition and deconstruction/disassembly of building components. This assumption is built in the fact that some studies have reported an increment of 70% on the overall operation costs of a building removal project, if the building is deconstructed instead of being traditionally demolished (Coelho & de Brito, 2011). Certainly, the adjusting factors proposed in this study should be calibrated as desired in the future for a more detailed and specific analysis. Furthermore, future research development in the field of estimating economic and environmental cost for deconstruction activities is expected to increase (Ghisellini et al., 2018). Consequently, it will be possible to use more accurate and realistic data of the selective demolition, destructive disassembly, and perfect disassembly per building component.

The cost estimations in this study do not include salvaged material resale value for simplification purposes. As part of future research, the assumptions used for estimating of the LCA and deconstruction cost should be refined. Therefore, the cost *C* associated with each deconstruction method *m* for a building component *j* is defined as:

$$C_{j,m} = c_{j,m}^{materials} + c_{j,m}^{labor} + c_{j,m}^{equipment} \tag{7-12}$$

The developed form of Equation 7-12 for the deconstruction methods *m* are:

$$C_{j,destr.disassembly} = c_{j,destr.disassembly}^{materials} + c_{j,destr.disassembly}^{labor} + c_{j,destr.disassembly}^{equipment} \tag{7-13}$$

$$C_{j,sel.demolition} = (C_{j,destr.disassembly})0.65 \tag{7-14}$$

$$C_{j,perfect\ disassembly} = (C_{j,destr.disassembly})1.35 \tag{7-15}$$

7.4.3 Multi-objective optimization analysis for selective disassembly

Several methodologies have been devised to portray a multi-objective optimization analysis. For the purposes of this study, it is used the weighted method of multi-objective optimization that boasts widespread use among engineers and is acknowledged as the oldest multi-objective solution technique (Revelle & Whitlach, 1996). The multi-objective optimization problem in this study is to minimize the environmental impact LCA^a, as well as the total cost *C* for the selective deconstruction of a building assembly. Depending on the approach of the overall analysis, the user can select a specific environmental impact of interest. For each building component *j* ($j=1,\ldots,J$) that is part of the final disassembly sequence plan calculated by the SDPB, one of the three different deconstruction methods *m* ($m=1,\ldots,M_j$) established in the previous section could be applied. Each deconstruction method has an associated environmental impact EI^a and building cost *C*. Therefore, the two objective functions have been formulated as follows.

$$Minimize\ Z_1 = \sum_{j=1}^{J}\sum_{m=1}^{M_j} LCA_{jm}^{a} \tag{7-16}$$

$$Minimize\ Z_2 = \sum_{j=1}^{J}\sum_{m=1}^{M_j} C_{jm} \tag{7-17}$$

According to the multi-objective weighted method, the objective functions must be combined into a single-objective function, or grand objective function, by multiplying each objective function by a weight w_n and adding them together. For minimization objectives the grand objective function is multiplied by -1 to change its sense to a maximization. The weight is a variable whose value will change systematically during the solution process. The resulting grand objective function is:

$$Maximize\ Z^G = -w_1 \sum_{j=1}^{J} \sum_{m=1}^{M_j} LCA_{jm}^{a} - w_2 \sum_{j=1}^{J} \sum_{m=1}^{M_j} C_{jm} \tag{7-18}$$

Subject to:

$$\sum_{j=1}^{J} \sum_{m=1}^{M_j} x_{jm} = 1 \qquad j = 1, \dots, J \tag{7-19}$$

$$\sum_{k=1}^{K} w_k = 1 \qquad k = 1, \dots, K \tag{7-20}$$

$$x_{jm} \in (0,1) \qquad j = 1, \dots, J; m = 1, \dots, M_j \tag{7-21}$$

Where:

j	building component of a building assembly, $j=1,\dots,J$,
m	deconstruction method for a building component, $m=1,\dots,M_j$,
a	type of environmental impact, $a=1,\dots,A_{jm}$,
k	associated weighting factor, $k=1,\dots,K$,
LCA_{jm}^{a}	LCA for an environmental impact a of a building component j in deconstruction method m
C_{jm}	total cost for deconstruction of a building component j in deconstruction method m
w_k	value of the associated weighting factor k
x_{jm}	decision variable

$$x_{jm} = \begin{cases} 1, & \text{if building component } j \text{ ends in deconstruction method } m \\ 0, & else \end{cases}$$

The grand objective function 7-18 will generate the set of noninferior solutions for the multi-objective optimization problem. Constraints 7-19 ensure that every deconstruction method is processed once. Constraints 7-20 ensure that every weighting factor is processed once. Constraints 7-21 define the decision variable $x_{jm} \in \{0,1\}$ as binary.

7.5 Case Study

For the process described in Figure 7-1, BIM was used as the main digital platform for the case study. Figure 7-2 shows the 6D BIM model of an adaptive reuse project of the "Engineering 2" (E2) building at the University of Waterloo campus. In 2017, an entire corridor of office rooms and old labs, located on the second floor of the E2 building, was redeveloped, reconditioned, and repurposed as part of an adaptive reuse project at the University of Waterloo. The office rooms and old labs where converted into modern flexible laboratories of the Department of Civil and Environmental Engineering. Figure 2-2 shows the details of a specific assembly subset of the original existing building as an example for this study. Table 7-1 shows the LCA results with an EoL of selective demolition per building component for GWP and PED, respectively. As alluded to in the previous sections, the LCA for building components were calculated with the software Tally®. Even though the plugin Tally® is not able to calculate the LCA of mechanical and electrical equipment for buildings (MEEB), such as the fume hoods and lamps, auxiliary data were employed from other LCA studies. LCA studies for specific MEEB are scarce and their characteristics are specific. Here, LCA results from similar mechanical and electrical equipment were used, such that the technical considerations were consistent with those proposed in the study. For example, even though it was possible to align appropriately the organization of life-cycle stages and the modeling scope processes, it was not possible to find LCA studies referring to the same life-cycle inventory (Castorani, Rossi, Germani, Mandolini, & Vita, 2018; KT Innovations®, Thinkstep®, & Autodesk®, 2018). Regardless, the differences between inventory datasets are not significant, since they refer to generic processes applicable in several geographic areas of the world. Consequently, the LCA for these MEEB are approximations with a reasonable degree of accuracy. For the scope of this study, only a few MEEB are included (laboratory laminar flow fume hood and the convertible fume hood); therefore, improving the accuracy of their impacts would not significantly change the reported results. However, this approach could make use of new data as LCA software for buildings improve their representation of mechanical and electrical components in the future.

Assembly components:

1. Laboratory laminar flow fume hood
2. Convertible fume hood and ducting system section
3. Metal door wall laboratory cabinets
4. Stainless steel laboratory countertop
5. Base cabinetry
6. Fire resistant drywall panel
7. Steel frame wall system (2-½”)
8. PVC water piping (½”)
9. EMT conduit installation (½”)
10. Fire resistant drywall panel

11-14 & 19 Air duct system
15. Fire water piping
16 & 22. EMT conduit installation (½”)
17,18,20 & 21. PVC water piping (3”)
23-26 Ceilindrop ceiling systemg fixed lamps
27 & 28 Drop ceiling system

Attachment elements specifications:

The steel frame wall system (7) is attached to the structure of the building in the floor and ceiling.
The PVC water piping (8) and the EMT conduit installation (9) are attached to the steel framing (7).
Drywall panels (6&10)attached to the steel framing (7).
Cabinetries (3&5) are attached to the steel framing (7) and the countertop (4) is attached to the cabinetry (5).
The ducting system (2) is attached to the ceiling and the fume hood (1) is connected to the ducting system.
Components (11,13,15-28) are attached to the structural ceiling through hangers and fasteners.
The air ducts (12&14) are attached to air ducts (11&13), respectively.

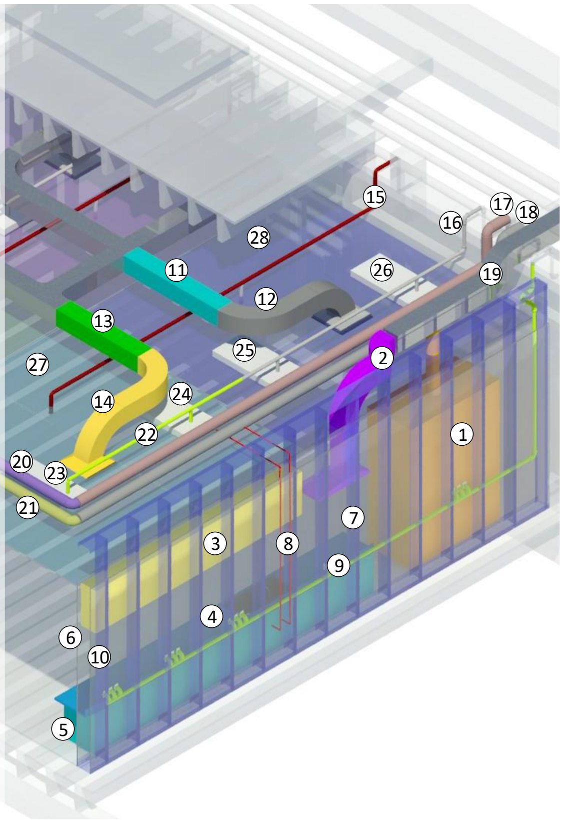


Figure 7-2: 6D BIM disassembly model - Cluster 1: Isolated assembly under study

Table 7-1: LCA results with an EoL of selective demolition per building component for GWP and PED

Building component	**Product stage [A1-A3]**		**Construction stage [A4-A5]**		**EoL stage [C2-C4,D]**		**Source**
	GWP (Kg CO_2 eq)	PED (MJ)	GWP (Kg CO_2 eq	PED (MJ)	GWP (Kg CO_2 eq)	PED (MJ)	
c_1	270.5	4,030.3	10.8	154.7	0.0	0.0	(Castorani, et al., 2018)
c_2	181.9	2,550.4	3.6	51.6	-26.4	-233.0	(Castorani, et al., 2018)
c_3	127.3	3,597.0	4.6	65.2	35.9	-934.0	(KT Innovations et al., 2018)
c_4	311.9	4,500.0	4.9	70.6	-62.4	-722.0	(KT Innovations et al., 2018)
c_5	127.3	3,597.0	4.6	65.2	35.9	-934.0	(KT Innovations et al., 2018)
c_6	117.0	2,066.0	4.6	66.1	7.4	125.0	(KT Innovations et al., 2018)
c_7	202.4	2,663.0	2.7	37.9	-58.3	-514.0	(KT Innovations et al., 2018)
c_8	6.9	146.0	0.1	1.8	0.1	1.0	(KT Innovations et al., 2018)
c_9	31.7	416.6	0.4	5.9	-9.1	-80.4	(KT Innovations et al., 2018)
c_{10}	117.0	2,066.0	4.6	66.1	7.4	125.0	(KT Innovations et al., 2018)
c_{11}	91.7	1,207.0	1.2	17.2	-26.4	-233.0	(KT Innovations et al., 2018)
c_{12}	137.6	1,810.5	1.8	25.8	-39.6	-349.5	(KT Innovations et al., 2018)
c_{13}	91.7	1,207.0	1.2	17.2	-26.4	-233.0	(KT Innovations et al., 2018)
c_{14}	137.6	1,810.5	1.8	25.8	-39.6	-349.5	(KT Innovations et al., 2018)
c_{15}	20.8	438.0	0.4	5.4	0.2	2.9	(KT Innovations et al., 2018)
c_{16}	15.8	208.3	0.2	3.0	-4.6	-40.2	(KT Innovations et al., 2018)
c_{17}	62.4	1,314.0	1.1	16.3	0.5	8.6	(KT Innovations et al., 2018)
c_{18}	62.4	1,314.0	1.1	16.3	0.5	8.6	(KT Innovations et al., 2018)
c_{19}	210.9	2,776.1	2.8	39.5	-60.7	-535.9	(KT Innovations et al., 2018)
c_{20}	62.4	1,314.0	1.1	16.3	0.5	8.6	(KT Innovations et al., 2018)
c_{21}	62.4	1,314.0	1.1	16.3	0.5	8.6	(KT Innovations et al., 2018)

c_{22}	15.8	208.3	0.2	3.0	-4.6	-40.2	(KT Innovations et al., 2018)
c_{23}	91.7	1,207.0	3.6	51.6	-26.4	-233.0	(KT Innovations et al., 2018)*
c_{24}	91.7	1,207.0	3.6	51.6	-26.4	-233.0	(KT Innovations et al., 2018)*
c_{25}	91.7	1,207.0	3.6	51.6	-26.4	-233.0	(KT Innovations et al., 2018)*
c_{26}	91.7	1,207.0	3.6	51.6	-26.4	-233.0	(KT Innovations et al., 2018)*
c_{27}	389.1	4,314.0	4.4	63.0	-184.0	-1,624.0	(KT Innovations et al., 2018)
c_{28}	389.1	4,314.0	4.4	63.0	-184.0	-1,624.0	(KT Innovations et al., 2018)

* excluding electronic components

The E2 case study is used to demonstrate the presented approach for a multi-objective optimization analysis for selective disassembly planning for buildings. The software used for this purpose was Matlab®. Figure 7-3 shows the 57-part assembly model under study. This study uses a previously described algorithm (Sanchez & Haas, 2018b) to create optimized single-target disassembly sequences, SDPB, for the targeted components c_7 and c_{13}. For Figure 2, the best direction for removing components c_7 and c_{13} is $+x$ direction. Figure 7-4 shows a multiple-target disassembly plan for components c_7 and c_{13}. The approach found a solution $S1 = (c_7\ f_7\ f_8\ c_6\ f_6\ c_9\ f_{10}\ c_8\ f_9\ c_{10}\ f_{11}\ c_2\ f_2\ c_1\ f_1\ c_5\ f_5\ c_4\ f_4\ c_3\ f_3)$ for c_7, and $S2 = (c_{13}\ f_{14}\ c_{14}\ f_{15}\ c_{24}\ f_{25}\ c_{22}\ f_{23}\ c_{23}\ f_{24}\ c_{27}\ \ f_{28})$ for c_{13}. Then the approach merges the single SDPB into one with multiple objectives. Because the single plans do not share nodes in common, the final multi-target plan has two root nodes.

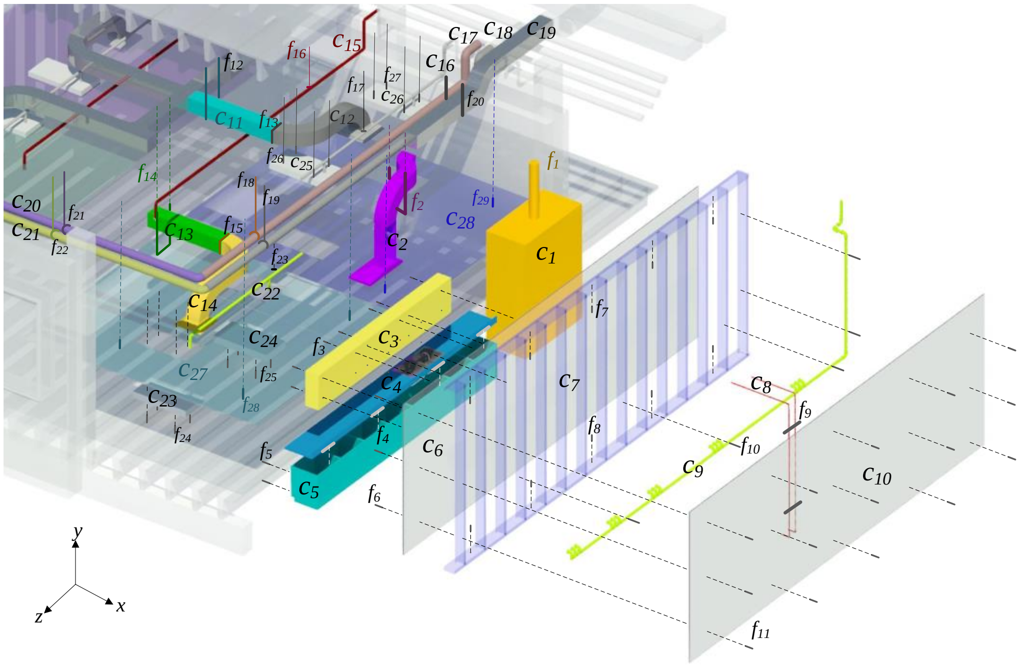


Figure 7-3: Exploded view of the disassembly model: Cluster 1

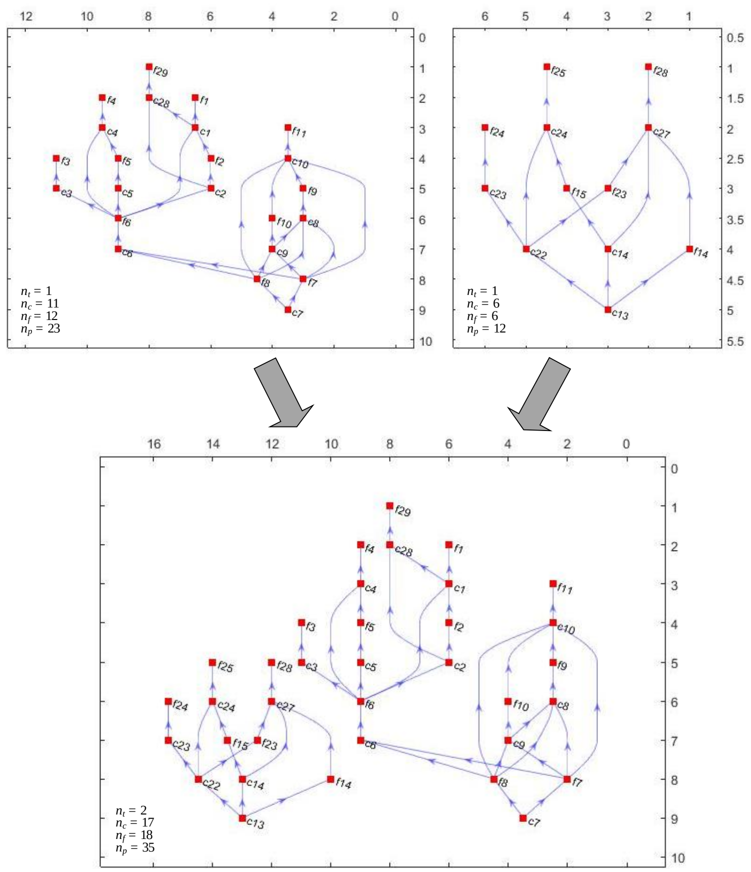


Figure 7-4: Automated generation of the multiple-target SDPB for components c_7 and c_{13}

Once the disassembly plan DSPB is ready, the weighted multi-objective optimization analysis for deconstruction methods is implemented to generate the set of noninferior solutions that minimizes a specific environmental impact (GWP) and the building cost. Table 7-2 summarizes the result of the calculations, and Figures 7-5 and 7-6 displays in a graphical way the noninferior solutions founded with the proposed approach.

Table 7-2: Case Study - Set of noninferior solutions for the SDPB of components c_7 and c_{13}

k	w_1	w_2	Solution	GWP (Kg CO_2 eq)	Deconstruction Cost ($USD 2018)
1	1.0	0.0	A	120.24	$2,955.76
2	0.9	0.1	B	121.56	$2,930.15
3	0.8	0.2	C	135.98	$2,856.87
4	0.7	0.3	D	144.10	$2,833.03
5	0.6	0.4	E	330.42	$2,507.99
6	0.5	0.5	F	640.59	$2,117.37
7	0.4	0.6	G	844.87	$1,900.10
8	0.3	0.7	H	981.64	$1,876.64
9	0.2	0.8	I	1,930.50	$1,462.24
10	0.1	0.9	J	2,080.67	$1,430.96
11	0.0	1.0	K	2,199.75	$1,423.14

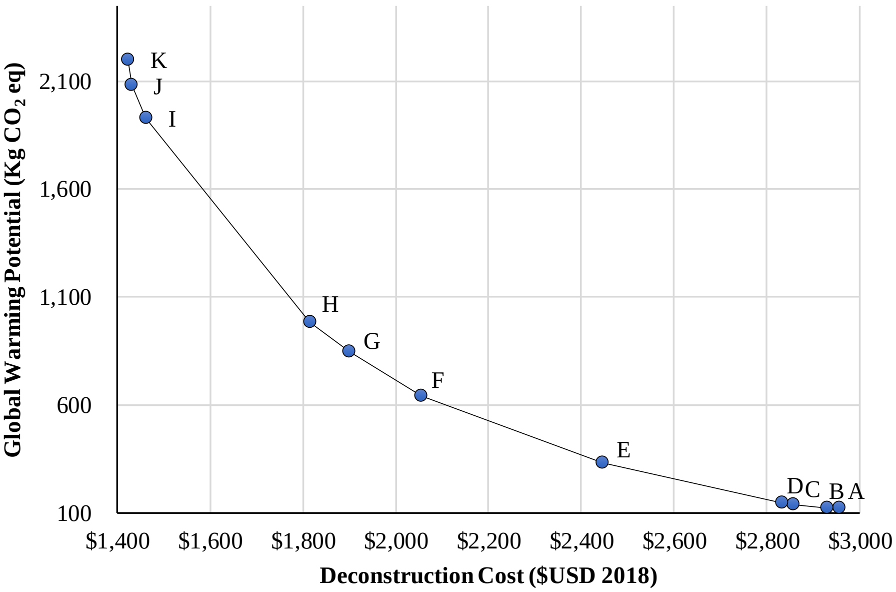


Figure 7-5: Pareto frontier for minimizing the Global Warming Potential and deconstruction cost of the SDPB for components c_7 and c_{13} by using different deconstruction methods

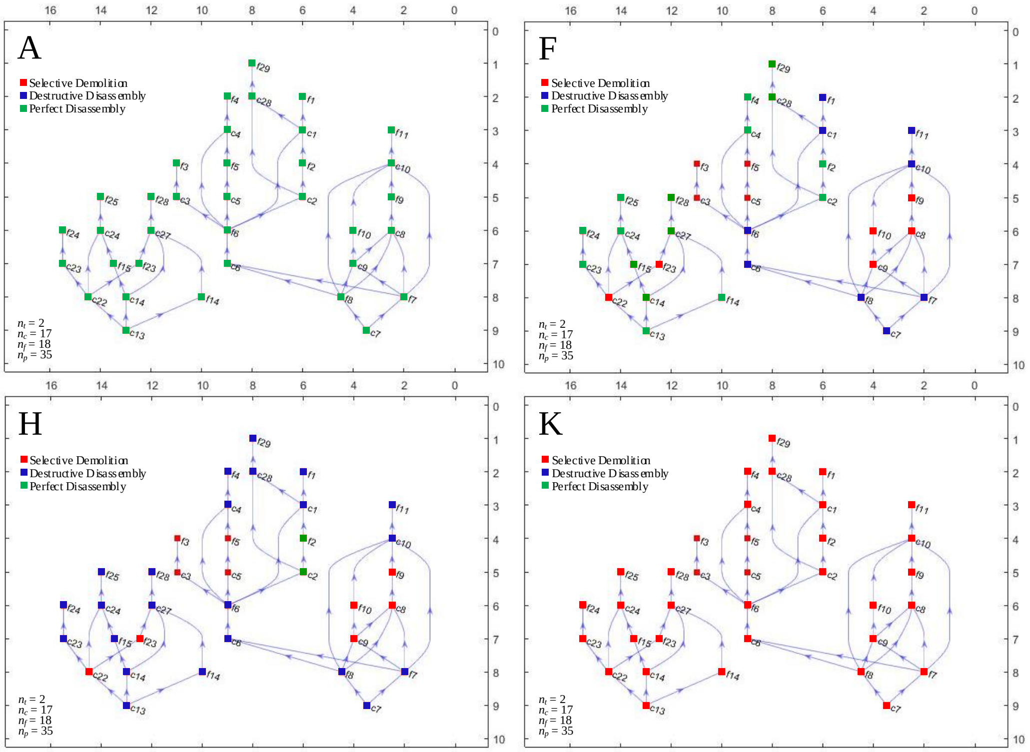


Figure 7-6: Set of noninferior solutions for the SDPB of components c_7 and c_{13}

The result of the case study shows that the different deconstruction methods per building component influence the environmental and economic cost of the selective deconstruction process. The solution A represents the eco-friendlier option because it is the one which reduces its negative environmental loads as represented by GWP. In contrast, the solution K represents the most cost-effective option because it minimizes the cost for the deconstruction of the building assembly. The points in-between are intermediate points that balance the negative environmental load and building cost according to the weighting factors defined by the user. Potential weighting factors determine solutions that are part of the Pareto frontier. This method is thus an effective approach to generate a set of non-inferior solutions for multiple objectives in the selective deconstruction planning of buildings. In the end, the decision makers have the responsibility of choosing the most appropriate solution from the set of non-inferior solutions, according to the specific adaptive reuse building project goals. The methodology described in this study is an effective and user-friendly tool for practitioners and decision makers to perform a multi-objective analysis based on scientific and holistic life-cycle techniques.

With the set of non-inferior solutions, decision makers can focus on the interpretation of the results in terms of sustainability and CE. For example, in this particular case study the solution A costs $1,534 USD more but avoids over 2,000 Kg CO_2 eq. This represents the best option for decreasing the environmental burden for the deconstruction process. However, the intermediate points give alternatives to acknowledge the components with the highest environmental value to recover the net environmental burden of the different deconstruction plans. The economic value associated with CO_2 eq emissions can be estimated using the Social Cost of Carbon (SCC). It is intended to represent the full economic damages associated with emitting one ton of CO_2 (or CO_2 eq). Impacts include agricultural productivity, human health, property damage, flood risk, and ecosystem services, among others (Shindell, 2015). The SCC has been estimated through a wide variety of studies (see, e.g., (Nordhaus, 2017)) including for the purpose of U.S. regulatory analysis (Greenstone, Kopits, & Wolverton, 2013), and applied to evaluate damages (Shindell, 2015; Yeung, Walbridge, Haas, & Saari, 2017b). The recommended regulatory SCC for emissions in 2020 range from $12 to $123/ton (in 2007 USD), with a value of $42/ton discounted at 3% (Sheet, 2013). Therefore, the monetization of the avoided carbon emissions for the solution A of the case study is around $84 USD which is the 5% of the deconstruction over cost. Economically speaking, solution A does not represent an attractive alternative with this estimate of the social cost of carbon emissions. However, regulatory carbon prices vary, and the theoretical cost of carbon is uncertain in the mid and long term (Shindell, 2015). Therefore, finding the solutions on the Pareto frontier for the environmental and economic cost, as proposed in this study, can help decision makers select the best option under the regulatory and epistemic uncertainty associated with carbon emissions price, and also with other environmental impacts of interest, such as PED, water consumption, etc.

The results of the case study show that the proposed methodology is able to efficiently find different deconstruction plans that optimize multiple objectives for the selective deconstruction of a building asset class. The proposed methodology creates high quality, practical, and realistic selective deconstruction plans that are part of the Pareto frontier of the multi-objective optimization analysis. Some of the main strengths of the proposed methodology is that it is user friendly for analysts and practitioners, and it is easily customizable according to the specific objectives pursued in an adaptive reuse building project. Some of the set ups that could be customized are: 1) the number of objectives to optimize (2 or more), 2) the environmental impact to minimize, 3) the number of deconstruction methods per building component, and 4) the amount of solutions to include in the Pareto frontier. This characteristic of the methodology brings to the user flexibility and a full range of options to test along the compound process of adaptive reuse design, and everything under a practical level of complexity. Even the simplifications proposed in this study related to the approximate estimation of the LCA and building cost for selective deconstruction processes represent a feasible alternative with a reasonable amount of precision, considering that the investigations in this field are scarce and sometimes null.

As discussed in the literature review, the complexity of adaptive reuse projects is due to the different constraints for a specific building project in context. The constraints range from technical, economic, and even social needs. Therefore, the proposed methodology helps in improving the performance of adaptive reuse projects through optimizing the selective deconstruction process according to the specific needs (objectives) of the project. Furthermore, this methodology is an advance in the semi-automation of the complex process of adaptive reuse design that involves complex subprocesses in the fields of LCA for buildings, selective disassembly planning for buildings, and BIM modeling.

7.6 Summary of findings on multi-objective analysis for selective disassembly of buildings

Adaptive reuse has the potential to maximize the residual utility and value of existing assets through green design methods, such as selective disassembly planning. Green design methods are used to reduce environmental impacts and to increase economic benefits over the entire product or service lifecycle. However, the field of green design methods for buildings is still underdeveloped in comparison to other industries such as automotive, textile, and manufacturing. Attending to the aforementioned need, the aim of the study presented in this chapter is to develop a multi-objective optimization analysis for the selective disassembly planning of an existing asset through the combination of different deconstruction methods. The analysis is carried out in terms of the physical, environmental, and economic constraints of the deconstruction methods per building component. The SDPB method presented in previous studies is used in order to generate the optimized disassembly plans for retrieving target components. The SDPB method was extended with the purpose of including more than one deconstruction method per component. At the end, a weighted multi-objective optimization analysis is incorporated to generate the set of noninferior solutions that minimizes environmental impacts and building cost.

This study demonstrates that there is a considerable environmental and economic savings potential along the selective deconstruction planning for adaptive reuse of existing assets. During the process of selective deconstruction planning, the designers have to wisely evaluate the environmental and economic cost of the building components to deconstruct and the deconstruction methods to apply. In this way, it is possible to maximize the net benefits of the selective deconstruction of a building. Even though the main objective of this study is focused on the optimization of selective disassembly planning for adaptive reuse of buildings, emphasis is placed on the potential for reusing the recovered building components through the proposed selective disassembly methods. It is well known that reuse of components is the best EoL alternative in terms of sustainability due to the amount of environmental benefits embedded. As demonstrated in the case study, the recovery of building components through selective disassembly increases the building cost, but it decreases considerably the negative net environmental loads (emissions to the atmosphere, energy demand, water depletion, etc.). Other potential environmental benefits of deconstruction are: decreased disturbance to the site (its soil, ground cover, and vegetation), conserved landfill space, reduction in material mass sent to landfill, conservation of natural resources by reused materials replacing new building materials (this allows the regeneration rate of natural resources to be faster than the depletion rate), and decreased air-borne lead, asbestos, and nuisance dust at and around the job site (Coelho & de Brito, 2011; Lund & Yost, 1997; Pun, Liu, Langston, Treloar, & Itoh, 2006).

The proposed study represents an advance in the field of understanding the economic and social benefits of recovered building components towards a CE in the construction industry. Specifically, it provides a means for quantifying the value of reuse across multiple dimensions that may be neglected in traditional analysis. Conventionally, the economic value of a building component or material reaches its peak after construction and drops to zero after demolition and disposal (Pun et al., 2006; Sára, Antonini, & Tarantini, 2000). Nonetheless, reutilisation of recovered building components in other construction projects enables the economic value of building components to be boosted to another peak level after the recovery process through selective deconstruction. The reuse of building components also provides steady supply for regional construction activities and stimulates the creation of new employment opportunities for the construction industry. There is societal benefit to any operation that increases the employment of people in the region. The deconstruction methods, such as selective demolition and destructive disassembly, involved in the partial deconstruction of an adaptive reuse building project are highly labor demanding (Coelho & de Brito, 2011), which is translated as the generation of new sources of employments. Also, because the field of jobs related to deconstruction work is relatively new, and it has been scarcely explored, there are interesting opportunities for the creation of new kinds of job. For example, the different range of methods to deconstruct a building component such as selective demolition, destructive disassembly, and a perfect disassembly. Job creation can be an important policy consideration for federal agencies or communities engaged in building removal. This topic should be deeply researched in the future in order to fully understand the dynamics and synergy between the different agents inside the CE value chain.

The major contribution of this work is the development of an integrated decision-making methodological framework for the adaptive reuse design process, encompassing the optimization of the environmental impacts as well as the building cost along the deconstruction processes. In contrast, the past research efforts focused mainly on suggesting qualitative and quantitative approaches for the entire deconstruction of a building asset with a fixed deconstruction programming of activities that do not capture the issues of customized selective deconstruction processes.

A number of methodologies have been devised to portray the noninferior set among conflicting objectives in engineering problems. For the purposes of this study, the weighted method of multi-objective optimization was used that has widespread use among engineers. The final goal is to generate the set of noninferior solutions by the appropriate technique. Based in previous studies in the field of selective disassembly planning for buildings, the proposed approach has been demonstrated to be a strong and efficient way to generate comprehensive information about the best available choices for the selective deconstruction of a building asset. This method represents an affordable tool for the decision makers along the deconstruction process for the adaptive reuse of an existing building.

This study has demonstrated the technical affordability of applying the proposed methodology with a reasonably level of complexity and accuracy. The tools and methods that are part of the workflow in the proposed approach, such as the SDPB method, 6D BIM modeling, RSMeans® databases, and Tally® LCA analysis, are available in the market and they are specialized tools for buildings with simplified procedures in order to keep the overall analysis in a reasonable range of complexity. The evidence suggests that in the future all of these tools and methods will be continuously developed in order to make them more efficient, simple, and reliable. The proposed study represents an advance on the integration of diverse technologies in the fields of deconstruction building planning, virtual building modeling, environmental assessment, and cost performance of adaptive reuse building projects.

Chapter 8: Summary, Conclusions and Recommendations for Future Work

8.1 Thesis summary

Buildings contribute significantly to the global environmental load caused by human activities. As such, in the last decades there has been a growing interest in improving a building's performance over its life-cycle stages (production, construction, operation, and End-of-Life [EoL]). Several studies have recognized the importance of the EoL stage in buildings, and the opportunity of their adaptive reuse as a superior alternative to new buildings in terms of sustainability and Circular Economy (CE). Adaptive reuse, identified as a process to improve the financial, environmental, and social performance of buildings, involves restoring and in some cases changing the use of existing buildings that are obsolete or are nearing their disuse stage. The aim of this research is to add a life-cycle perspective to the decision-making for adaptive reuse building project planning to improve environmental and economic performance outcomes.

In a first stage of this study, the framework of capital project planning for a CE is defined, as well as the fundamental role of adaptive reuse of buildings inside the circular construction value chain. It is argued that the early capital projects delivery phases for a CE should have distinct stages, decision gates, and more appropriate planning methods, such as selective disassembly, Life Cycle Assessment (LCA) monetization protocols, and optimization methods. An investigation of related studies underpins the capital project planning framework proposed and the research that must still be accomplished to enable a more CE in the capital projects sector. Aside, a life-cycle based decision-making methodology for evaluating adaptive reuse of buildings is developed with the purpose of understanding and unveiling the environmental and economic implications. This methodology is used for the analysis of the net environmental impacts and buildings cost performance of an adaptive reuse case study in the city of Waterloo, Ontario, Canada. A detailed consequential substitution LCA and a building cost analysis are performed in order to quantitatively demonstrate the relevance of each building component, as well as their influence on the net environmental impact and building cost due to adaptive reuse.

In a second stage, semi-automated optimization approaches to assist in maximizing the environmental and economic benefits in the process of adaptive reuse through selective disassembly planning are developed and validated. These optimization approaches are performed employing advanced Building Information Modeling (BIM), Product Recovery Management (PRM), and LCA technologies which have recently opened up a wide range of solutions in the field of sustainability in the construction industry. To the authors' knowledge, these are the first methods developed for selective disassembly planning of buildings. Although the proposed methods can be applied in any types of construction assembly, this thesis mainly focuses on buildings assemblages. Contributions of developing the described framework include developing (1) an efficient single-target selective disassembly sequence planning method approach for buildings, (2) an efficient approach for the selective deconstruction programming of buildings, and (3) a multi-objective optimization analysis approach for selective disassembly planning of buildings. Validation of all of the proposed methods is achieved through functional demonstration with adaptive reuse case studies, in which high quality, practical, and physically feasible solutions for selective disassembly of building components are found.

The overall proposed framework in this research have demonstrated to be effective to improve sustainability in the construction industry by proving the life-cycle net environmental and economic potential benefits of buildings' adaptive reuse. Also, this research marks a referent for the development of user-friendly methods and tools applicable for improving inefficiencies in the process of adaptive reuse through optimization of the selective disassembly planning, with a life-cycle perspective.

8.1.1 Capital project planning for a Circular Economy in the construction industry

Adaptive reuse synthesizes many of the CE principles and methods in order to restore, reconfigure and repurpose existing buildings. An urgent need exists to develop and validate effective planning principles, methods and tools for adaptive reuse building projects. In particular, while the PDRI for buildings is known to be an effective planning tool for green-field building projects, it has limited applicability to the circular model. Complementary tools are also required such as selective disassembly planning methods, LCA analysis procedures, and methods to justify development incentives offered by government. Thus, in Chapter 3 it is proposed a capital project planning framework and related research that must be accomplished to enable a more CE in the capital projects sector. Chapter 3 provides a short introduction to the main concepts addressed in this study, the CE in construction, CE for the built environment, and the implications of circular building principles in capital project delivery.

8.1.2 Analysis of the net environmental impacts and buildings cost performance for adaptive reuse of buildings

Adaptive reuse of buildings is considered a superior alternative for the renewal of today’s built environment. However, little research has been done for assessing adaptive reuse building projects in terms of life-cycle and CE. Because of the great impact that the building industry has on the environment, failing to optimize buildings’ useful life can result in their residual life-cycle expectancy not being fully exploited, and with it, wasting the resources embedded therein, such as Primary Energy Demand. The aim of the study presented in Chapter 4 is to develop a life-cycle analysis of the net environmental impacts as well as the building’s cost performance of an adaptive reuse project. This study focuses on the analysis of the structural system. Results show that the adaptive reuse of the building structure produces a considerable decrease on the environmental impacts and the construction building cost. Distribution of cost among materials, labor, and equipment is different than those for a new building. This study objectively demonstrates the considerable benefits of the adaptive reuse of the structure of an existing asset. In contrast, the non-structural building subsystems have been identified as an area with high potential for improving the existing inefficiencies during the adaptive reuse process.

8.1.3 Selective disassembly sequence planning for adaptive reuse of buildings

Adaptive reuse of buildings can be an attractive alternative to new construction in terms of sustainability and a CE. Achieving net benefits with adaptive reuse partly relies on efficiently planning building disassembly. The aim of the study presented in Chapter 5 is to describe a new efficient single-target selective disassembly sequence planning method developed for adaptive reuse of buildings. Finding a global optimum disassembly planning solution for buildings can be time consuming and physically impractical due to the high number of possible solutions. The method developed seeks to minimize environmental impact and removal costs using rule-based recursive analyses for planning recovery of target components from multi-instance building subsystems based upon physical, environmental, and economic constraints. Rule-based recursive methods have been demonstrated to be an efficient alternative to find near-optimal disassembly sequences by eliminating uncommon or unrealistic solutions. Validation is achieved through functional demonstration with case studies, where high quality, practical, realistic, and physically feasible solutions for single-target selective disassembly of buildings are found by using the new method. For adaptive reuse of buildings, the new method can be used to reduce the costs of disassembly and demolition and improve the planning process.

8.1.4 Deconstruction planning and scheduling for adaptive reuse of buildings

Adaptive reuse is a way of maximizing the residual utility of existing assets. Adaptive reuse makes it possible to retrieve components from an obsolete building through deconstruction programming. Unfortunately, current deconstruction programming practice relies on conventional intuitive planning procedures by professionals, leading to suboptimal results. The study presented in Chapter 6 describes and validates a semi-automated selective deconstruction programming approach for adaptive reuse that can support quantitative analysis. First, a new method is defined for multiple-target selective disassembly sequence planning, using a rule-based recursive approach for obtaining near-optimal heuristic solutions. Then, a method is demonstrated for programming the deconstruction work based on the disassembly sequences. Validation is further achieved through a case study, in which high-quality, practical, and feasible solutions are found by using the new method. The approach helps improve project performance through process automation that supports quantitative analysis, low cost exploration of alternatives, and an iterative design process for meeting project constraints.

8.1.5 Multi-objective analysis for selective disassembly of buildings

Adaptive reuse has the potential to maximize the residual utility and value of existing assets through green design methods such as selective disassembly planning. Studies in the field of selective disassembly for adaptive reuse of buildings are scarce and there is no evidence of established methodologies and/or analysis for the optimization of the environmental and financial benefits. A multi-objective analysis is key to obtaining several effective selective disassembly plans for the adaptive reuse of an existing asset through the combination of different deconstruction methods. The analysis is carried out in terms of the physical, environmental, and economic constraints of the deconstruction methods per building component. The Sequential Disassembly Planning for Buildings (SDPB) method, presented in previous studies, is used in order to generate the optimized disassembly plans for retrieving target components. At the end, a weighted multi-objective optimization analysis is incorporated to generate the set of noninferior solutions that minimizes environmental impacts and building cost. The results show that different complete disassembly plans exist for all of the possible combinations. The possible combinations are driven by the deconstruction methods per component, as well as the dismantling interdependence. For adaptive reuse of buildings, the methods described in this study can be used to improve the project outcomes according to specific goals and constraints (e.g. environmental, economic, technical).

8.2 Discussion

The field of barriers to adaptive reuse has been studied and documented deeply, due to the importance of the topic (Conejos et al., 2016). The framework and the methods developed in this thesis helps to tackle some technical barriers, such as, physical restrictions, technical difficulties, and inaccuracy of information and drawings, as well as other barriers related to the resource-based business model in the construction industry, such as, inertia of production, commercial risk, and financial perceptions. This thesis marks a referent for the development of user-friendly methods and tools for improving inefficiencies in the process of adaptive reuse through the optimization of the selective disassembly planning and with a life-cycle perspective.

The methodologies described in this thesis use BIM as the main technological platform to assist in the planning, and design stages for adaptive reuse building projects. However, it has been pointed out that current BIM approaches are insufficient to efficiently support adaptive reuse projects. BIM is insufficient when adaptive reuse is conceptualized as a flow of building materials and components through a circular value chain. While recognizing the role of 6D BIM within project and asset management that assumes a single use cycle for parts, materials and systems, current BIM models do not support important project activities of adaptive reuse projects, such as, disassembly planning, product recovery management, or parametric design and simulation to integrate recovered products. In the presented methods it has been identified some needs and requirements for BIM models that support these activities. The requirements are focused on how to effectively represent parts, materials and systems, as well as, interfaces between them. Also, additional properties need to be defined such as adaptable geometry, life cycle cradle-to-cradle characteristics, functional state, usage history, as well as, the building elements' membership and the role within the overall building system.

The functionality of the methodologies presented in this thesis has been demonstrated for isolated clusters of building components meant to be part of a whole building. This has been in order to keep the complexity of the models and the computational requirements for the calculations in a reasonable range. Once, we have tested and validated the models in a small scale, in the next stage more investigations have to be done in order to extend the application of the methods to entire buildings or infrastructure systems. Although, this should be a straightforward scaling step, there are some technical implications that might be considered such as, the elevated amount of data and meta-data to manually extract from the BIM models, the missing adaptive reuse characteristics in current BIM models, and the integration of performance analysis of buildings' subsystems. (e.g. energy performance analysis, structural analysis, building's LCA, etc.). These are some of the main technical barriers that have to be solved in order to be able to scale the application of the presented methodologies in this thesis in an effective way. Fortunately, advancements in the fields of: 1) automation in construction (e.g. computer-aided workflows automation, machine learning tools for construction, process simulation modeling) (Chen, García de Soto, & Adey, 2018), 2) digitization of the built environment (e.g. scan-to-BIM, digital twins, IoT) (Bosché, Ahmed, Turkan, Haas, & Haas, 2015; Whyte & Hartmann, 2017), and 3) information modeling for buildings (e.g. BIM, CIM, building information systems, integration of specialized modeling software for buildings) (ASCE, 2015; US GSA, 2007; Volk et al., 2014) are helping towards getting over these technical barriers and the evidence suggests that this trend will continue in the coming years.

The practical implications of implementing the methods presented in this thesis towards moving to a CE can be discussed in terms of the benefits either for particular sustainable building projects or for the whole circular value chain in the construction industry. The direct benefits for particular building projects are improvement on the management of resources and waste by minimizing (or closing) material and energy loops, minimizing the negative environmental impacts, and adding quantitative analysis to the decision-making process during the process of building dismantling. It is well known the fact that project planning has the potential of improving projects outcomes (Bingham & Gibson, 2017; Cho & Gibson Jr., 2001; Collins, Parrish, & Gibson, 2017; Edkins et al., 2013), therefore the methods and tools presented in this thesis aims to improve adaptive reuse projects outcomes through appropriate project planning during the phase of buildings dismantling and adaptation planning. Also, the quantitative methods approach presented here, represent a stepping stone to overcome the technical barriers (e.g. physical restrictions, complexity and technical difficulties, and inaccuracy of information and drawings (Conejos et al., 2016)) that impede, and sometimes underestimate, the implementation of closed-loop construction such as, adaptive reuse of buildings (Sanchez & Haas, 2018a; Sanchez & Haas, 2018b), design for future adaptability (Conejos, Chew, & Yung, 2017; Douglas, 2006; Kibert, 2007), designing with reused building components (Gorgolewski, 2008; Sassi, 2008), cradle-to-cradle building design (Bastein et al., 2016; Lacy & Rutqvist, 2015), and designing buildings as future raw material banks (Turntoo®, 2019).

The direct benefits for the whole circular value chain in the construction industry are the reduction of waste streams to the landfills, the appreciation on the value of reusable building components, a better management of building stocks and raw materials for construction, and the stability on the inflationary prices of building materials/components over the increasing scarcity of raw materials. The global building sector, as its demand for raw materials, is growing at unprecedented rates and it will continue to do so in the coming decades (UN, 2017). For instance, it is expected that by 2050 the building floor area by world region will at least double its size. As discussed in the background and motivation section of this thesis, it will be physically, economically, and environmentally impossible to reach the projected building development without taking advantage of the current building stock. In one hand, the building industry is responsible for 40% of waste to landfill and 32% of world resource depletion (Intergovernmental Panel on Climate Change (IPCC), 2015; IPCC, Langston et al., 2008). On the other hand, the scarcity of raw materials in the construction industry is a concept presently high on the agenda of resource policies all over the world due to the increasing trend in the raw materials' prices and the volatility showed during the last decade (Mancini, De Camillis, & Pennington, 2013; Sieffert, Huygen, & Daudon, 2014). Even though, the vast global endowment of raw materials may not be exhausted soon, the extraction and production are becoming more challenging due to an increasing dependence on ever more dilute and distant stocks of ores and other resources and the parallel increase in waste from extraction of materials and the disposal of an ever-growing built environment (Kibert, 2007; Mancini et al., 2013). As soon as a lower grade of resource banks becomes available, extraction implies increasing negative environmental impacts such as, energy consumption, emissions, water requirements, mining waste, bigger impacts on landscape as well as the exploration of ecologically sensitive areas. Therefore, there is an urgent need to reduce the excessive waste of resources along the entire supply chain in the construction industry by increasing the implementation of CE strategies for the current and future build environment.

The implementation of the CE principles presented in this thesis has the potential of improving sustainability of the infrastructure systems by taking advantage of the inherent redundancy created by the expansion of urban development. The premise is improving infrastructure sustainability and resilience through redundancy. According to Ahern (2013), the sustainability of cities involves resilience, the capacity to recover from disturbances without changing fundamental state to be sustainable over a longer term. Redundancy is achieved when multiple elements or components provide the same, similar, or backup functions, spreading risks across time, geographical areas, and multiple systems. Therefore, through quantifying and mapping the potential environmental benefits embedded in the building stock, such as initial embodied energy, greenhouse gas emissions, water and material stock, it will be possible to generate relevant information for the governments and city councils for better understanding, planning, and managing the infrastructure systems towards sustainable development, resilient systems, and CE by using the existing redundancy of the built environment.

The work presented in this thesis represents an advance of the forefront for the regulation of energy and natural resources in a circular value chain in the construction industry. This study proposes an innovative understanding of the real value of the built environment in terms of sustainability through merging cutting-edge software technology with the most updated and realistic buildings' databases, and the improvement on the monetization of environmental impacts (e.g. primary energy demand and global warming potential). Consequently, consumers and decision-makers will be able to improve the management of energy and natural resources in a CE. For example, policy makers could use these tools to objectively decide how to use taxes, credits, or incentives to influence adaptive reuse and other close loop construction strategies. Finally, the shift towards a CE is transforming the fundamentals of the natural resources value chain worldwide, including the sources of primary energy. The presented study develops technical methodologies for fully exploiting the residual life cycle value of existing assets, and with it, taking advantage of the embedded resources.

8.3 Conclusions and contributions

The key contributions and associated conclusions of the work presented in this thesis are summarized below.

8.3.1 Capital project planning for a Circular Economy in the construction industry

In Chapter 3 it is argued that project planning for capital projects must change as business models shift from a linear to a CE. Thus, a capital project planning framework is proposed for closed-loop cycle construction projects. Also, a reference framework for required revisions to develop a planning tool for adaptive reuse projects is suggested. This framework identifies the project scope elements from the PDRI for buildings that must be modified in order to align them with circular building principles. Finally, it is concluded that in the capital project delivery phase of circular infrastructure, science-based, user-friendly, and fit-for-purpose methods are needed to decide amongst green-field construction versus adaptive reuse, to develop pre-project planning for closed-loop cycle construction, and to plan for the optimization of the benefits of adaptive reuse.

8.3.2 Analysis of the net environmental impacts and buildings cost performance for adaptive reuse of buildings

The main conclusions and contributions of the study presented in Chapter 4 follow. The demolition of a building may be premature, if its residual utility is ignored. Current implementation of adaptive reuse relies on intuitive planning procedures. The structural system of buildings has the highest potential for adaptive reuse. Main inefficiencies for adaptive reuse projects are in non-structural subsystems. Adaptive reuse plays a key role in the transformation towards a CE. The study presented in Chapter 4 is a practical way to determine the desirability of applying adaptive reuse for building projects. With the development of a case study, the technical affordability and practicality of applying the proposed methodology was demonstrated using the current technologies and trends in the construction industry.

8.3.3 Selective disassembly sequence planning for adaptive reuse of buildings

The main conclusions and contributions of the study presented in Chapter 5 follow. Buildings’ disassembly planning can improve adaptive reuse performance. Rule-based building's disassembly methods efficiently find near-optimal solutions. Parts' interdependence analysis is critical for effective disassembly planning. Simplification of the disassembly model reduces computational requirements. Engineering judgment of target components selection reduces the model’s complexity. The selective disassembly sequence planning method for buildings presented, developed, and validated in Chapter 5 represents an advance for improving the technical inefficiencies of adaptive reuse of existing buildings. To the authors’ knowledge, this is the first study that describes and validates an optimization method for sequential disassembly planning for adaptive reuse of buildings (SDPB).

8.3.4 Deconstruction planning and scheduling for adaptive reuse of buildings

The main conclusions and contributions of the study presented in Chapter 6 follow. Deconstruction planning methods for adaptive reuse of buildings have been scarcely investigated. The study presented in this chapter develops and validates a pioneering selective deconstruction programming approach for adaptive reuse of buildings. Correct deconstruction programming has the potential of improving adaptive reuse projects' outcomes performance. A multi-target disassembly planning method for buildings, based on the single-target SDPB method described in the previous chapter, is described and validated through functional case studies. The approach for selective deconstruction programming for building assemblies presented in this chapter improves adaptive reuse projects' performance through process automation.

8.3.5 Multi-objective analysis for selective disassembly of buildings

The main conclusions and contributions of the study presented in Chapter 7 follow. Adaptive reuse has the potential to maximize the residual utility and value of existing assets through the optimization of the deconstruction/disassembly planning. A multi-objective optimization analysis is key to obtaining several effective selective disassembly plans for the adaptive reuse of an existing asset through the combination of different deconstruction methods. The proposed methodology described in this study creates high quality, practical, and realistic selective deconstruction plans that are part of the Pareto frontier of the multi-objective optimization analysis for minimizing the environmental and economic costs. Also, the proposed study represents an advance in the field of understanding the economic and social benefits of recovered building components towards a CE in the construction industry. There is societal benefit to any operation that increases the employment of people in a region, as is the case of implementing and promoting selective deconstruction methods in the building industry. Also, reutilisation of recovered building components in other construction projects enables rescuing the marginal economic value of reusable building components instead of wasting them through demolition and landfill disposal.

8.4 Limitations

One of the limitations of the selective disassembly/deconstruction methods presented in Chapters 5, 6, and 7, is that they require accurate and reliable inputs. All of these inputs come from different sources such as databases of the economic cost of deconstruction work for buildings components, LCA with a specific EoL for the buildings components, and manual generation of the meta-data of the Disassembly Graph (DG) model (Initial constraint matrices) for the SDPB approach. Therefore, the accuracy of the results of the presented methods rely on the quality of the input data. As discussed in each chapter, nowadays the quality of this input data is questionable (and it could be improved) due to the lack of studies in each field related to deconstruction/disassembly of buildings components. However, all the evidence points that these fields are becoming the center of the research towards advancing on sustainable construction, green design methods, and CE in the construction industry.

Another limitation of the work presented in this thesis, is that the usability of the SDPB method approaches is mainly threatened by the amount of data to manually enter (in addition of the actual work of a designer) to use it properly. All of the spatial, topological, and interdependence constraints of a building assembly under study have to be manually organized in DGs for their computational processing. Simplifications and assumptions could facilitate and speed up the process, but they could also decrease the reliability of the output. Therefore, a compromise between these two positions must be determined to ensure a maximization of outcomes and insight with a minimization of additional work. Nevertheless, automation can be developed to help embed intelligence into the data generated in digitization workflows. For example, there could be developed algorithms with the objective of retrieving (or generating) the necessary SDPB data from a BIM model.

Another limitation is that the different methods presented in Chapters 5, 6, and 7 are not fully automated yet. The main reason is that the methods requires different kinds of technological platforms for preprocessing the data at different stages. The main technological platforms used are the BIM software Revit®, the LCA software plugin Tally®, the RSMeans® databases, the spreadsheet software MS Excel®, the programming platform MATLAB®, and the project management software MS Project®. There is no single platform that is able to develop all of the specialized tasks required for the goals of the proposed studies. However, all of them are able to exchange the postprocessed data in a compatible format for the other platforms. The presented methods in this thesis still need manual processing and cognition per platform before exporting the postprocessed data to the next processing step. The evidence shows that the advances into interoperability between technological platforms will continuously being developed with the computational technology improvement.

8.5 Recommendations for future research

In this section, some potential research thrusts for extending the work initiated in this research are discussed.

8.5.1 Development of a pre-project planning tool for adaptive reuse

In Chapter 3 suggest a reference framework for required revisions to develop a pre-project planning tool for adaptive reuse projects. This framework identifies the project scope elements from the PDRI for buildings that must be modified in order to align them with circular building principles. Similarly, it is argued that some project scope elements should be completely modified according to the nature of the value chain in a CE. Finally, another set of project scope elements that should remain without any changes in the approach are defined. However, they should be investigated in order to demonstrate and validate the weight that represents their importance in the performance of a closed-loop cycle construction project. As well, validation is required to examine the hypothesis that the successful completion of a closed-loop cycle building project is positively correlated with the quality of the project definition during the pre-project planning phase. In other words, a well-defined project definition would correspond to a higher probability of project success in terms of sustainability.

8.5.2 Analysis of the net environmental impacts and building cost performance of adaptive reuse of non-structural building subsystems

In Chapter 4 an analysis of the net environmental impacts and building cost performance of an adaptive reuse building project is presented. The analysis focused on the structural building subsystem due to its relative importance to the rest of the building. Part of future work should include the analysis of the other building subsystems, such as, building envelope, mechanical, electrical, and plumbing subsystems. As discussed in Chapter 4, the field of adaptive reuse of non-structural subsystems should be studied in depth in order to solve the inefficiencies during the restoration process. It is worthy to highlight that the analysis of the adaptive reuse of non-structural subsystems faces major challenges due to the lack of data and studies to estimate the life-cycle environmental impact and economic performance of the processes involved, such as, selective deconstruction methods, building restauration work, and refurbishment of retrieved building components. The literature on these topics is very limited, therefore there is a need to develop more accurate investigations on this matter.

8.5.3 Incorporation of complex deconstruction methods for the SDPB approach

As future research, the new selective disassembly planning approach SDPB presented in Chapter 5 has to incorporate more than a single method of disassembly or deconstruction according to the most common practices in this matter. In the study presented in Chapter 5, the default method is the one that creates a complete disassembly sequence plan for a target component. Depending on the component, more methods can be added in order to create alternative disassembly sequence plans. The added methods can involve removal of a component's subset without the need of disassembling them internally. Additionally, in the case of a component replacement, a method could be included where a temporal extra-component is added to the original assembly. Overall, the approach has to be able to create all of the alternative disassembly sequence plans and choose the best option. For multiple targets, the approach presented in this study could be extended to create a whole-subsystem disassembly sequence plan comprised of a combination of single-target plans, with their respective internal optimal directions. The final goal of all of these is to develop a more robust and realistic approach with more deconstruction options according to the trends in the construction industry.

8.5.4 Selective parallel disassembly planning for adaptive reuse of buildings

The studies presented in Chapters 5, 6, and 7 have demonstrated that disassembly sequence planning plays an important role in green design for the adaptive reuse of buildings. Selective sequential disassembly planning removes parts one at time in order to retrieve targeted components in an efficient way. However, several investigators have conducted research on disassembly planning for manufactured products has demonstrated that parallel disassembly planning has the potential to reduce disassembly steps, disassembly time, and environmental impacts (S. Smith & Hung, 2015; Sosa, Eppinger, & Rowles, 2007; Tseng, Chang, & Cheng, 2010). The objective of parallel disassembly planning is to apply modular design theory to group parts into modules to reduce products complexity and, as a result, to simplify the complexity of the disassembly planning. The issue of product modularization responds to the exploration of selective disassembly. In other words, decomposing a product into modules reduces the difficulty in searching for feasible solutions to disassembly planning problems. Also, it is possible to divide modules into specific kind of clusters according to the modular design theory selected. For example, it is meaningful to divide modules into two clusters, one valuable for recycling and the other not worth recycling. This illustrates that different policies can be chosen for different types of modules. To the knowledge of the authors, there is no evidence of studies in the field of selective parallel disassembly planning for buildings. As it has been discussed and demonstrated in Chapter 5, disassembly planning plays a fundamental role for improving the performance of adaptive reuse building projects. Therefore, the development of effective tools for selective parallel disassembly for building assemblies is necessary. The general framework for understanding the fundamental technical differences between the disassembly planning of manufactured products and building assemblies has been established in Chapter 5, 6, and 7. Therefore, the topic of selective parallel disassembly planning for adaptive reuse of buildings is a natural progression of the ideas/methods developed in those chapters.

8.5.5 Analysis across the building stock to determine the potential environmental/economic benefits of adaptive reuse of buildings

Several authors have claimed that as a part of sustainable urban development, adaptive reuse of buildings plays an important role (Bullen, 2007; Conejos, 2013; Conejos et al., 2015; Conejos et al., 2014; Douglas, 2006; Highfield & Gorse, 2009; Langston, 2012; Langston, 2008; Langston et al., 2008; Schultmann & Sunke, 2007; Tan et al., 2014; Wilson, 2010). Beyond isolating the potential benefits of adaptive reuse per building it is necessary to understand their effects in a holistic way. This statement introduces the concept of improving infrastructure sustainability and its resilience through building redundancy and practicing modularization. According to Ahern (2013), sustainability of cities involves resilience, the capacity to recover from disturbance without changing their fundamental state to be sustainable over a longer term. Redundancy and modularization are achieved when multiple elements or components provide the same, similar, or backup functions. Redundancy and modularization spread risks across time, across geographical areas, and across multiple systems. When a major urban function or service is provided by a centralized entity or infrastructure, it is more vulnerable to failure. When the same function is provided by a distributed or decentralized system, it is more resilient to disturbance. Redundancy and modularization are strategies for preparing and pre-planning for when (not if) a system fails. Examples include site or sub-watershed based sewerage or storm-water systems as in the Chicago, Illinois Green Alleys program, or the Augustenborg Housing Project retrofit in Mälmo, Sweden (Ahern, 2013).

Existing buildings approaching the end of their lifespan could become a “mine” of raw materials and resources embedded (e.g. embodied energy, marginal economic value, recycle/reuse potential, etc.), since recovering the components through PRM is often more efficient than extracting raw materials to produce new ones. In an ideal system, whereby EoL building materials/components are maximally reused and recycled in other construction projects (either new construction or adaptive reuse of existing buildings), the overall construction will have a slower natural resources exploitation rate than the rate of regeneration of those natural resources, which will definitely benefit the environment. Therefore, through quantifying the potential net environmental and economic benefits of adaptive reuse of the building stock in urban developments, it could be possible to generate the necessary information for the decision-makers in order to manage natural resources in a sustainable way and to promote sustainable and resilient infrastructure by using the existing redundancy of the built environment. Through this approach, it could be possible to estimate the level of relief on the demand on the current centralized infrastructures on urban settlements.

8.5.6 Research on environmental and construction cost of deconstruction methods

As discussed in Chapter 7, there is a current need of developing research on green design methods for the deconstruction of existing buildings, including selective disassembly planning. The conclusions of the case study presented in Chapter 7 show that different deconstruction methods per building component influence the environmental and economic cost performance of the selective disassembly process, in terms of life-cycle. Unfortunately, the research related to the environmental and cost analysis for deconstruction methods is very limited. What is more, the studies related to reliable technical information of deconstruction methods and procedures per building component are very scarce. This technical information is critical to develop accurate environmental and cost analysis of the different deconstruction methods for building components.

Therefore, there is a need of developing these kinds of studies in order to advance in the field of green design methods for buildings.

8.5.7 Automated meta-data generation from BIM models for buildings' adaptive reuse design

The studies presented in Chapter 5, 6 and 7 are built over the theory of structure Disassembly Graphs (DG) for sequential disassembly. As explained in Chapter 5, the theory of structure DG needs as data inputs the spatial, topological, and interdependence constraints of the disassembly models. These data inputs have to be prepared in forms of matrices (initial matrices) for its computational analysis. The initial matrices are the meta-data that is processed by the structure DG theory in order to create effective disassembly plans for a given disassembly model. If the building assembly under study has a high number of components the amount of meta-data to generate will be substantially large. Even for small assemblies, such as the case studies presented in Chapters 5,6, and 7, the amount of meta-data to generate is considerable. In the first instance, this meta-data is manually generated since is the most easy and recurrent way. However, manual processing of meta-data is slow and it increases the probabilities of incurring through human error. After developing the case studies in the chapters mentioned above, it has been noticed that BIM models could be used for automated meta-data generation. A well-structured BIM model could contain all of the spatial, topological, and interdependence information for the disassembly model. Then by using a plugin software (such as Dynamo® for Revit® for the case studies) it could be possible to develop algorithms to generate the meta-data from the BIM model in an automated way. The benefits of automated digitization workflows far outweigh existing manual approaches. Some of the benefits include better precision in the development of the tasks, reduction of mistakes, faster processing time, saving of time due to rework, efficient protocols to detect and correct mistakes, possibility for the analysis of more complex assembly models, possibility of increasing the level of detail of the assembly models, and taking advantage of the work embedded in BIM models (that nowadays represent the standard for building design and planning).

8.6 Publications

The peer-refereed publications, directly related to the scope of this thesis, and authored by the candidate are listed below:

8.6.1 Peer-refereed journal articles

1. **Sanchez, B.**, & Haas, C. (2018). Capital project planning for a circular economy. *Construction Management and Economics, 36(6)*, 303-312. doi: 10.1080/01446193.2018.1435895

2. **Sanchez, B.**, & Haas, C. (2018). A novel selective disassembly sequence planning method for adaptive reuse of buildings. *Journal of Cleaner Production, 183,* 998-1010. doi: doi.org/10.1016/j.jclepro.2018.02.201
3. **Sanchez, B.**, Rausch, C., & Haas, C. (2019). Deconstruction programming for adaptive reuse of buildings. *Automation in Construction,* Submitted in September 2018, (Under review).
4. **Sanchez, B**., Esnaashary Esfahani, M., & Haas, C. (2018). Analysis of the net environmental impacts and buildings cost performance of an adaptive reuse project - case study: Region of waterloo county courthouse renovations. *Environment Systems and Decisions,* Submitted in December 2018, (Under review).
5. **Sanchez, B**., Rausch, C., Haas, C., & Saari, R. (2019). Multi-objective optimization analysis for adaptive reuse of buildings. *Building and Environment,* Submitted in February 2019, (Under Review).

8.6.2 Peer-refereed conference papers

1. **Sanchez, B.**, & Haas, C. (2017). Methodology for improving the net environmental impacts of new buildings through product recovery management. Paper presented at the *Proceedings of the 6th CSCE/CRC International Construction Specialty Conference,* Vancouver, Canada.
2. **Sanchez, B**., & Haas, C. T. (2018). A novel single-target selective disassembly sequence planning method for adaptive reuse of buildings. Paper presented at the *1st International Conference on New Horizons in Green Civil Engineering,* Victoria, British Columbia, Canada.
3. Eray, E., **Sanchez, B.**, & Kang, S. & Haas, C. (2018). Usage of interface management in adaptive reuse of buildings. Paper presented at the *35th CIB W78 2018 Conference IT in Design, Construction, and Management,* Chicago, Illinois, USA.
4. **Sanchez, B.**, Rausch, C., Haas, C., & Saari, R. (2019). Multi-objective optimization analysis for selective disassembly planning of buildings. Paper presented at the *36th International Symposium on Automation and Robotics in Construction (ISARC),* Banff, AB, Canada.
5. Rausch, C., **Sanchez, B.** & Haas, C. (2019). Spatial parameterization of non-semantic CAD elements for supporting automated disassembly planning. Paper presented at the *2019 Modular and Offsite Construction (MOC),* Banff, AB, Canada.
6. **Sanchez, B.**, & Rausch, C. & Haas, C. (2019). Selective deconstruction programming for adaptive reuse of buildings. Paper presented at the *The 2019 ASCE International Conference on Computing in Civil Engineering-Theme: Future Cities and Resilient Infrastructures,* Georgia Institute of Technology, Atlanta, Georgia, U.S.A.

Bibliography

Adams, W. M. (2006). The future of sustainability: Re-thinking environment and development in the twenty-first century. Paper presented at the *Report of the IUCN Renowned Thinkers Meeting, 29*-31.

Ahern, J. (2013). Urban landscape sustainability and resilience: The promise and challenges of integrating ecology with urban planning and design. *Landscape Ecology, 28*(6), 1203-1212.

Aidonis, D., Xanthopoulos, A., Vlachos, D., & Iakovou, E. (2008). On the optimal deconstruction and recovery processes of end-of-life buildings. Paper presented at the *Proceedings of the 2nd WSEAS/IASME International Conference on Waste Management, Water Pollution, Air Pollution, and Indoor Climate (WWAI'08),*

Akbarnezhad, A., Ong, K. C. G., & Chandra, L. R. (2014). Economic and environmental assessment of deconstruction strategies using building information modeling. *Automation in Construction, 37*, 131-144. doi:10.1016/j.autcon.2013.10.017

American Society of Civil Engineers (ASCE). (2015). In Issa R., Olbina S. (Eds.), *Building information modeling : Applications and practices*. Reston, Virginia: American Society of Civil Engineers.

Anderson, J. E., Wulfhorst, G., & Lang, W. (2015). Expanding the use of life-cycle assessment to capture induced impacts in the built environment. *Building and Environment, 94*, 403-416. doi:https://doi.org/10.1016/j.buildenv.2015.08.008

Asdrubali, F., Baldassarri, C., & Fthenakis, V. (2013). Life cycle analysis in the construction sector: Guiding the optimization of conventional italian buildings. *Energy and Buildings, 64*, 73-89. doi:10.1016/j.enbuild.2013.04.018

Asif, M., Muneer, T., & Kelley, R. (2007). Life cycle assessment: A case study of a dwelling home in scotland. *Building and Environment, 42*(3), 1391-1394. doi:10.1016/j.buildenv.2005.11.023

Assembly, U. G. (2015). Transforming our world: The 2030 agenda for sustainable development. *New York: United Nations,*

Aye, L., Ngo, T., Crawford, R. H., Gammampila, R., & Mendis, P. (2012). Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy and Buildings, 47*, 159-168. doi:10.1016/j.enbuild.2011.11.049

Azari, R., & Abbasabadi, N. (2018). Embodied energy of buildings: A review of data, methods, challenges, and research trends. *Energy and Buildings, 168*, 225-235. doi:10.1016/j.enbuild.2018.03.003

Bakry, I., Moselhi, O., & Zayed, T. (2014). Optimized acceleration of repetitive construction projects. *Automation in Construction, 39*, 145-151. doi:10.1016/j.autcon.2013.07.003

Ballard, G. (2000a). Lean project delivery system. *LCI white paper #8* (pp. 6) Lean Construction Institute.

Ballard, G. (2000b). *The last PlannerTM system of production control.* (Unpublished Doctoral dissertation). School of Civil Engineering, University of Birmingham,

Bastein, A., Verstraeten-Jochemsen, J., Rietveld, E., Hauck, M., Frijters, E., Klijn, O., & Driessen, B. (2016). *Circular amsterdam: A vision and action agenda for the city and metropolitan area*. Amsterdam, Netherlands: TNO.

Beatham, S., Anumba, C., Thorpe, T., & Hedges, I. (2004). KPIs: A critical appraisal of their use in construction. *Benchmarking, 11*(1), 93-117. doi:10.1108/14635770410520320

Beccali, M., Cellura, M., Fontana, M., Longo, S., & Mistretta, M. (2013). Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits. *Renewable & Sustainable Energy Reviews, 27*, 283-293. doi:10.1016/j.rser.2013.05.040

Bingham, E., & Gibson, G. E., Jr. (2017). Infrastructure project scope definition using project definition rating index. *Journal of Management in Engineering, 33*(2), 04016037. doi:10.1061/(ASCE)ME.1943-5479.0000483

Blengini, G. A., & Di Carlo, T. (2010). The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Buildings, 42*(6), 869-880. doi:10.1016/j.enbuild.2009.12.009

Bosché, F., Ahmed, M., Turkan, Y., Haas, C. T., & Haas, R. (2015). The value of integrating scan-to-BIM and scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components. *Automation in Construction, 49*, 201-213. doi:10.1016/j.autcon.2014.05.014

Bullen, P. A. (2007). Adaptive reuse and sustainability of commercial buildings. *Facilities, 25*(1/2), 20-31.

Cabeza, L. F., Rincon, L., Vilarino, V., Perez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable & Sustainable Energy Reviews, 29*, 394-416. doi:10.1016/j.rser.2013.08.037

Camacho, A., Cañizares, P. C., Estévez, S., & Núñez, M. (2018). A tool-supported framework for work planning on construction sites based on constraint programming. *Automation in Construction, 86*, 190-198. doi:https://doi-org.proxy.lib.uwaterloo.ca/10.1016/j.autcon.2017.11.008

Canadian Industrial Energy End-use Data and Analysis Centre (CIEEDAC). (2016). CIEEDAC database on energy, production and intensity indicators for canadian industry. Retrieved from http://naicsdb.rem.sfu.ca/CIEEDACweb/mod.php?mod=NAICSPublic&menu=1602

Cantell, S. F. (2005). *The adaptive reuse of historic industrial buildings: Regulation barriers, best practices and case studies* (Master dissertation). Available from Virginia Polytechnic Institute and State University.

Castorani, V., Rossi, M., Germani, M., Mandolini, M., & Vita, A. (2018). Life cycle assessment of home smart objects: Kitchen hood cases. *Procedia CIRP, 69*(Complete), 499-504. doi:10.1016/j.procir.2017.11.113

Chastas, P., Theodosiou, T., & Bikas, D. (2016). Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. *Building and Environment, 105*, 267-282. doi:10.1016/j.buildenv.2016.05.040

Chen, Q., García de Soto, B., & Adey, B. T. (2018). Construction automation: Research areas, industry concerns and suggestions for advancement. *Automation in Construction, 94*, 22-38. doi:10.1016/j.autcon.2018.05.028

Cho, C. (2000). *Development of the project definition rating index (PDRI) for building projects* (Doctoral dissertation). Available from The University of Texas.

Cho, C., & Gibson Jr., G. E. (2001). Building project scope definition using project definition rating index. *Journal of Architectural Engineering, 7*(4), 115-125. doi:10.1061/(ASCE)1076-0431(2001)7:4(115)

Coelho, A., & de Brito, J. (2011). *Economic analysis of conventional versus selective demolition—A case study* doi:https://doi.org/10.1016/j.resconrec.2010.11.003

Collins, W., Parrish, K., & Gibson, G. E. (2017). Development of a project scope definition and assessment tool for small industrial construction projects. *Journal of Management in Engineering*, *33*(4) doi:10.1061/(ASCE)ME.1943-5479.0000514

Conejos, S. (2013). *Designing for future building adaptive reuse* (Doctoral Dissertation). Available from ePublications@bond. Retrieved from http://epublications.bond.edu.au/theses/72/

Conejos, S., Langston, C., & Smith, J. (2015). Enhancing sustainability through designing for adaptive reuse from the outset: A comparison of adaptstar and adaptive reuse potential (ARP) models. *Facilities*, *33*(9-10), 531-552. doi:10.1108/F-02-2013-0011

Conejos, S., Chew, M. Y. L., & Yung, E. H. K. (2017). The future adaptivity of nineteenth century heritage buildings. *International Journal of Building Pathology and Adaptation*, *35*(4), 332-347. doi:10.1108/IJBPA-03-2017-0012

Conejos, S., Langston, C., Chan, E. H. W., & Chew, M. Y. L. (2016). Governance of heritage buildings: Australian regulatory barriers to adaptive reuse. *Building Research & Information*, *44*(5-6), 507-519. doi:10.1080/09613218.2016.1156951

Conejos, S., Langston, C., & Smith, J. (2014). Designing for better building adaptability: A comparison of adaptSTAR and ARP models. *Habitat International*, *41*, 85-91. doi:10.1016/j.habitatint.2013.07.002

Cong, L., Zhao, F., & Sutherland, J. W. (2017). Integration of dismantling operations into a value recovery plan for circular economy. *Journal of Cleaner Production*, *149*, 378-386. doi:10.1016/j.jclepro.2017.02.115

Construction Industry Institute (CII). (1994). *Pre-project planning: Beginning a project the right way*. Austin, Texas: CII.

Construction Industry Institute (CII). (2009). *RS242-1 - front end planning for renovation and revamp projects: An overview*. Austin, Texas: CII.

Costantino, N. (2006). The contribution of ranko bon to the debate on sustainable construction. *Construction Management and Economics, 24*(7), 705-709. doi:10.1080/01446190500127203

Crosthwaite, D. (2000). The global construction market: A cross-sectional analysis. *Construction Management and Economics, 18*(5), 619-627.

Denis, F., Vandervaeren, C., & Temmerman, N. D. (2018). Using network analysis and BIM to quantify the impact of design for disassembly. *Buildings, 8*(8) doi:10.3390/buildings8080113

Densley Tingley, D., & Davison, B. (2012). Developing an LCA methodology to account for the environmental benefits of design for deconstruction. *Building and Environment, 57*, 387-395. doi:10.1016/j.buildenv.2012.06.005

Department of Housing and Urban Development (DHUD). (2001). *Smart codes in your community: A guide to building rehabilitation codes*. Washington, DC: Building Technology Incorporated.

Douglas, J. (2006). *Building adaptation* (2nd edition ed.). UK: Elsevier Ltd.

Dumont, P. R., & Gibson, G. E. (1996). *Project definition rating index (PDRI).* (Research Rep. No. 113-11). Austin, Texas: The University of Texas.

Dumont, P. R., Gibson Jr., G. E., & Fish, J. R. (1997). Scope management using project definition rating index. *Journal of Management in Engineering, 13*(5), 54-60.

Edkins, A., Geraldi, J., Morris, P., & Smith, A. (2013). Exploring the front-end of project management. *Engineering Project Organization Journal, 3*(2), 71-85. doi:10.1080/21573727.2013.775942

Egan, J. (1998). *Rethinking construction: The report of the construction task force to the deputy prime minister*. Norwich: Department of the Environment, Transport and the Regions.

Fay, R., Treloar, G., & Iyer-Raniga, U. (2000). Life-cycle energy analysis of buildings: A case study. *Building Research and Information, 28*(1), 31-41.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., . . . Suh, S. (2009). Recent developments in life cycle assessment. *Journal of Environmental Management, 91*(1), 1-21. doi:10.1016/j.jenvman.2009.06.018

Gan, V. J. L., Deng, M., Tse, K. T., Chan, C. M., Lo, I. M. C., & Cheng, J. C. P. (2018). Holistic BIM framework for sustainable low carbon design of high-rise buildings. *Journal of Cleaner Production, 195*, 1091-1104. doi:https://doi-org.proxy.lib.uwaterloo.ca/10.1016/j.jclepro.2018.05.272

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy A new sustainability paradigm? *Journal of Cleaner Production, 143*, 757-768. doi:10.1016/j.jclepro.2016.12.048

Ghisellini, P., Ripa, M., & Ulgiati, S. (2018). *Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review* doi:https://doi.org/10.1016/j.jclepro.2017.11.207

Gibson, G., & Gebken, R. (2003). Design quality in pre-project planning: Applications of the project definition rating index. *Building Research and Information, 31*(5), 346-356. doi:10.1080/0961321032000087990

Gorgolewski, M. (2006). The implications of reuse and recycling for the design of steel buildings. *Canadian Journal of Civil Engineering, 33*(4), 489-496.

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

Greenstone, M., Kopits, E., & Wolverton, A. (2013). Developing a social cost of carbon for US regulatory analysis: A methodology and interpretation. *Review of Environmental Economics and Policy, 7*(1), 23-46. doi:10.1093/reep/res015

Guldager Jorgensen, K., & Somme, J. (2016). *Building a circular future*. Denmark: Danish Environmental Protection Agency.

Gustavsson, L., & Joelsson, A. (2010). Life cycle primary energy analysis of residential buildings. *Energy and Buildings, 42*(2), 210-220. doi:10.1016/j.enbuild.2009.08.017

Guy, B., & McLendon, S. (2000). Building deconstruction: Reuse and recycling of building materials. *Gainesville, FL: Center for Construction and Environment, Report to the Florida Department of Environmental Protection, September1999,*

Han, H. J., Yu, J. M., & Lee, D. H. (2013). Mathematical model and solution algorithms for selective disassembly sequencing with multiple target components and sequence-dependent setups. *International Journal of Production Research, 51*(16), 4997-5010. doi:10.1080/00207543.2013.788794

Hassanein, A., & Moselhi, O. (2005). Accelerating linear projects. *Construction Management and Economics, 23*(4), 377-385. doi:10.1080/01446190410001673571

Hatcher, G. D., Ijomah, W. L., & Windmill, J. F. C. (2011). *Design for remanufacture: A literature review and future research needs* doi:https://doi-org.proxy.lib.uwaterloo.ca/10.1016/j.jclepro.2011.06.019

Hein, M. F., & Houck, K. D. (2008). Construction challenges of adaptive reuse of historical buildings in europe. *International Journal of Construction Education and Research, 4*(2), 115-131. doi:10.1080/15578770802229466

Hélène Macher, Tania Landes, & Pierre Grussenmeyer. (2017). From point clouds to building information models: 3D semi-automatic reconstruction of indoors of existing buildings. *Applied Sciences, 7*(10), 1030. doi:10.3390/app7101030

Highfield, D., & Gorse, C. (2009). *Refurbishment and upgrading of buildings* (2nd ed ed.). New York, USA: Taylor & Francis Group.

Hill, R. C., & Bowen, P. A. (1997). Sustainable construction: Principles and a framework for attainment. *Construction Management and Economics, 15*(3), 223-239.

Hübner, F., Volk, R., Kühlen, A., & Schultmann, F. (2017). Review of project planning methods for deconstruction projects of buildings. *Built Environment Project and Asset Management, 7*(2), 212-226. doi:10.1108/BEPAM-11-2016-0075

Huovila, P. (2007). *Buildings and climate change: Status, challenges, and opportunities* UNEP/Earthprint.

Intergovernamental Panel on Climate Change (IPCC). (2007). In Metz B., Davidson O. R., Bosch P. R., Dave L. A. and Meyer L. A. (Eds.), *Climate change 2007: Mitigation. contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2015). *Climate change 2014: Mitigation of climate change* Cambridge University Press.

International Institute for Sustainable Development. (2016). Sustainable development. Retrieved from http://www.iisd.org/topic/sustainable-development

International Organization for Standardization (ISO). (1997). *ISO 14040 environmental management - life cycle assessment - principles and framework*. Paris: ANSI/ISO.

Isaac, S., Bock, T., & Stoliar, Y. (2016). A methodology for the optimal modularization of building design. *Automation in Construction, 65*, 116-124. doi:10.1016/j.autcon.2015.12.017

Jaillon, L., & Poon, C. S. (2014). Life cycle design and prefabrication in buildings: A review and case studies in hong kong. *Automation in Construction, 39*, 195-202. doi:10.1016/j.autcon.2013.09.006

Jalaei, F., & Jrade, A. (2014). An automated BIM model to conceptually design, analyze, simulate, and assess sustainable building projects. *Journal of Construction Engineering, 2014*

Jalaei, F. (2015). *Integrate building information modeling (BIM) and sustainable design at the conceptual stage of building projects* (Doctoral Dissertation). Available from UOTTAWA III.

Johansen, E., & Wilson, B. (2006). Investigating first planning in construction. *Construction Management and Economics, 24*(12), 1305-1314. doi:10.1080/01446190600863160

Kang, Y., Kim, C., Son, H., Lee, S., & Limsawasd, C. (2013). Comparison of preproject planning for green and conventional buildings. *Journal of Construction Engineering and Management, 139*(11) doi:10.1061/(ASCE)CO.1943-7862.0000760

Keeler, M., & Vaidya, P. (2016). *Fundamentals of integrated design for sustainable building* John Wiley & Sons.

Khan, Z. (2008). Design for assembly. *Assembly Automation, 28*(3), 200-206. doi:10.1108/01445150810889961

Kibert, C. J. (2007). The next generation of sustainable construction. *Building Research and Information, 35*(6), 595-601. doi:10.1080/09613210701467040

Kneifel, J. (2010). Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. *Energy and Buildings, 42*(3), 333-340. doi:10.1016/j.enbuild.2009.09.011

Kobyshev, N., Riemenschneider, H., Bódis-Szomorú, A., & Van Gool, L. (2017). Efficient architectural structural element decomposition. *Computer Vision and Image Understanding, 157*, 300-312. doi:10.1016/j.cviu.2016.06.004

Kokkos, A. (2014). *Computational modelling tools for the promotion of design for deconstruction* (Master dissertation). Available from Delft University of Technology.

KT Innovations®. (2015). Tally methods. Retrieved from http://www.choosetally.com/methods/

KT Innovations®, Thinkstep®, & Autodesk®. (2018). Tally [computer software]. USA: KT Innovations®;Thinkstep®;Autodesk®.

KT Innovations, thinkstep, & Autodesk. (2018). Tally [computer software]. USA: KT Innovations, thinkstep, and Autodesk.

Kumar, V., Hewage, K., Haider, H., & Sadiq, R. (2016). Sustainability evaluation framework for building cooling systems: A comparative study of snow storage and conventional chiller systems. *Clean Technologies and Environmental Policy, ,* 1-19. doi:10.1007/s10098-016-1198-8

Lacy, P., & Rutqvist, J. (2015). *Waste to wealth: The circular economy advantage*. London, UK: Palgrave Macmillan.

Laefer, D. F., & Truong-Hong, L. (2017). Toward automatic generation of 3D steel structures for building information modelling. *Automation in Construction, 74*, 66-77. doi:10.1016/j.autcon.2016.11.011

Langston, C. (2012). Validation of the adaptive reuse potential (ARP) model using iconCUR. *Facilities, 30*(3/4), 105-123.

Langston, C., & Smith, J. (2012). Modelling property management decisions using 'iconCUR'. *Automation in Construction, 22*, 406-413.

Langston, C. (2008). The sustainability implications of building adaptive reuse. Paper presented at the *CRIOCM 2008 International Research Symposium on Advancement of Construction Management and Real Estate,* Beijing, China.

Langston, C. (2013). The role of coordinate-based decision-making in the evaluation of sustainable built environments. *Construction Management and Economics, 31*(1), 62-77. doi:10.1080/01446193.2012.738920

Langston, C., Wong, F. K. W., Hui, E. C. M., & Shen, L. (2008). Strategic assessment of building adaptive reuse opportunities in hong kong. *Building and Environment, 43*(10), 1709-1718. doi:10.1016/j.buildenv.2007.10.017

Lin, K. L., & Haas, C. T. (1996). Multiple heavy lifts optimization. *Journal of Construction Engineering and Management, 122*(4), 354-362.

Liu, B., Wang, D., Xu, Y., Liu, C., & Luther, M. (2018). Embodied energy consumption of the construction industry and its international trade using multi-regional input–output analysis. *Energy and Buildings, 173*, 489-501. doi:10.1016/j.enbuild.2018.05.040

Lund, E., & Yost, P. (1997). Deconstruction-building disassembly and material salvage: The riverdale case study. *Upper Marlboro, Maryland: NAHB Research Center,* Luscuere, L. M. (2017). Materials passports: Optimising value recovery from materials. *Proceedings of Institution of Civil Engineers: Waste and Resource Management, 170*(1), 25-28. doi:10.1680/jwarm.16.00016

Lyngsgaard, S., & Guldager Jorgensen, K. (2013). *Cradle to cradle® - in the built environment: A manual for the danish building industry*. Danmark: Vugge Til Vugge Danmark and GXN with support from Realdania.

Mancini, L., De Camillis, C., & Pennington, D. (2013). Security of supply and scarcity of raw materials. *Towards a Methodological Framework for Sustainability Assessment,*

Mandolini, M., Favi, C., Germani, M., & Marconi, M. (2017). Time-based disassembly method: How to assess the best disassembly sequence and time of target components in complex products. *International Journal of Advanced Manufacturing Technology,* , 1-22. doi:10.1007/s00170-017-1201-5

Mastrucci, A., Marvuglia, A., Leopold, U., & Benetto, E. (2017). Life cycle assessment of building stocks from urban to transnational scales: A review. *Renewable and Sustainable Energy Reviews, 74,* 316-332. doi:10.1016/j.rser.2017.02.060

McGraw Hill Construction. (2011). *Prefabrication and modularization: Increasing productivity in the construction industry*

Mohamed, R., Boyle, R., Yang, A. Y., & Tangari, J. (2017). Adaptive reuse: A review and analysis of its relationship to the 3 es of sustainability. *Facilities, 35*(3/4), 138-154.

Mokhlesian, S., & Holmén, M. (2012). Business model changes and green construction processes. *Construction Management and Economics, 30*(9), 761-775. doi:10.1080/01446193.2012.694457

Moncaster, A. M., Pomponi, F., Symons, K. E., & Guthrie, P. M. (2018). Why method matters: Temporal, spatial and physical variations in LCA and their impact on choice of structural system. *Energy and Buildings, 173,* 389-398. doi:10.1016/j.enbuild.2018.05.039

Morris, P. W. G. (2011, Managing the front-end back to the beginning. *Project Perspectives 2011, XXXIII*, 4-8.

Morris, P. W. G. (2013). *Project management reconstructed*. Chicester: Wiley Blackwell.

Morris, P. W. G., & Edkins, A. (2013). Project inititiation: Managing the front-end. In P. Dinsmore, & J. Cabanis-Brewin (Eds.), *AMA handbook on project management* (pp. 35-44). New York: AMA.

National Association of Home Builders (NAHB). (2016). Certification green homes and products. Retrieved from http://www.homeinnovation.com/green

National Energy Board. (2016). Commodity prices and trade updates. Retrieved from https://www.neb-one.gc.ca/nrg/ntgrtd/mrkt/prcstrdrtcl/index-eng.html?pedisable=true

Natural Resources Canada. (2016). Transportation fuel prices. Retrieved from http://www.nrcan.gc.ca/energy/fuel-prices/4593

Ness, D., Swift, J., Ranasinghe, D. C., Xing, K., & Soebarto, V. (2015). Smart steel: New paradigms for the reuse of steel enabled by digital tracking and modelling. *Journal of Cleaner Production, 98,* 292-303. doi:10.1016/j.jclepro.2014.08.055

Nordhaus, W. D. (2017). In Nordhaus, William D (correspondence author), Nordhaus W. D.(Eds.), *Revisiting the social cost of carbon* doi:10.1073/pnas.1609244114

Ofori, G. (1998). Sustainable construction: Principles and a framework for attainment - comment. *Construction Management and Economics, 16*(2), 141-145.

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials, 23*(1), 28-39. doi:10.1016/j.conbuildmat.2007.11.012

Ortlepp, R., Gruhler, K., & Schiller, G. (2016). Material stocks in germany's non-domestic buildings: A new quantification method. *Building Research and Information, 44*(8), 840-862. doi:10.1080/09613218.2016.1112096

Patraucean, V., Armeni, I., Nahangi, M., Yeung, J., Brilakis, I., & Haas, C. (2015). State of research in automatic as-built modelling. Paper presented at the *32nd International Symposium on Automation and Robotics in Construction and Mining: Connected to the Future, Proceedings,*

Peuportier, B. (2001). Life cycle assessment applied to the comparative evaluation of single family houses in the french context. *Energy and Buildings, 33*(5), 443-450. doi:10.1016/S0378-7788(00)00101-8

Pinard, A., & Wade, M. (2012). *Listing of non-designated properties of cultural heritage value or interest on the municipal heritage register*. (Heritage Kitchener No. CSD-12-036). Kitchener, Ontario: Kitchener Community Services Department.

Plessis, C. D. (2007). A strategic framework for sustainable construction in developing countries. *Construction Management and Economics, 25*(1), 67-76. doi:10.1080/01446190600601313

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production, 143*, 710-718. doi:10.1016/j.jclepro.2016.12.055

Pun, S. K., Liu, C., Langston, C., Treloar, G., & Itoh, Y. (2006). Promoting the reuse and recycling of building demolition materials. *World Transactions on Engineering and Technology Education, 5*(1), 195.

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings, 42*(10), 1592-1600. doi:10.1016/j.enbuild.2010.05.007

Ramesh, T., Prakash, R., & Shukla, K. K. (2012). Life cycle energy analysis of a residential building with different envelopes and climates in indian context. *Applied Energy, 89*(1), 193-202. doi:10.1016/j.apenergy.2011.05.054

Revelle, C. A., & Whitlach, E. E. (1996). *Civil and environmental systems engineering*. Upper Saddle River, N.J.: Prentice Hall PTR.

Rios, F. C., Chong, W. K., & Grau, D. (2015). Design for disassembly and deconstruction - challenges and opportunities. *Procedia Engineering, 118*, 1296-1304. doi:10.1016/j.proeng.2015.08.485

Robertson Simmons Architects Incorporated. (2015). *Region of waterloo county courthouse renovations.* Unpublished manuscript. Retrieved April, 2016,

RSMeans. (2015). *Building construction cost data* (73th ed. ed.). United States of America: R.S. Means Company, Inc.

Sanchez Andrade, B., Hoepfl, M., Garcia Maldonado, J. G., & Corona Vasquez, B. (2014). Chapter 9 “Analysis of an affordable rural ecologic home for marginal communities in the sierra negra zone, state of puebla, méxico”. In L. G. Torres, & E. R. Bandala (Eds.), *Energy and evironment nowdays* (pp. 207). New York: Nova Science Publishers.

Sanchez, B., Rausch, C., Haas, C., & Saari, R. (2019). Multiobjective optimization analysis for selective disassembly planning of buildings. Paper presented at the *36th International Symposium on Automation and Robotics in Construction (ISARC),* Banff, AB, Canada.

Sanchez, B., & Haas, C. (2018a). Capital project planning for a circular economy. *Construction Management and Economics, 36(6),* 303-312. doi:10.1080/01446193.2018.1435895

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

Sanchez, B., Rausch, C., & Haas, C. (2019). Deconstruction programming for adaptive reuse of buildings. *Automation in Construction, Submitted in September 2018, (under review).*

Sandin, G., Peters, G. M., & Svanstrom, M. (2014). Life cycle assessment of construction materials: The influence of assumptions in end-of-life modelling. *International Journal of Life Cycle Assessment, 19*(4), 723-731. doi:10.1007/s11367-013-0686-x

Sára, B., Antonini, E., & Tarantini, M. (2000). Application of life cycle assessment (LCA) methodology for selective demolition and reuse-recycling of building materials and products. *Transport, 4*(R2), R3.

Sára, B., Antonini, E., & Tarantini, M. (2001). Application of life-cycle assessment (LCA) methodology for valorization of building demolition materials and products. Paper presented at the *Environmentally Conscious Manufacturing, , 4193* 382-391.

Sassi, P. (2008). Defining closed-loop material cycle construction. *Building Research and Information, 36*(5), 509-519. doi:10.1080/09613210801994208

Schultmann, F., & Sunke, N. (2007). Energy-oriented deconstruction and recovery planning. *Building Research and Information, 35*(6), 602-615. doi:10.1080/09613210701431210

Sheet, E. F. (2013). Social cost of carbon. *United States Environmental Protection Agency (EPA): Washington, DC, USA,* Shiers, D., Rapson, D., Roberts, C., & Keeping, M. (2006). Sustainable construction: The development and evaluation of an environmental profiling system for construction products. *Construction Management and Economics*, *24*(11), 1177-1184. doi:10.1080/01446190600892987

Shindell, D. T. (2015). The social cost of atmospheric release. *Climatic Change*, *130*(2), 313-326. doi:10.1007/s10584-015-1343-0

Shipley, R., Utz, S., & Parsons, M. (2006). Does adaptive reuse pay? A study of the business of building renovation in ontario, canada. *International Journal of Heritage Studies, 12*(6), 505-520. doi:10.1080/13527250600940181

Sieffert, Y., Huygen, J. M., & Daudon, D. (2014). Sustainable construction with repurposed materials in the context of a civil engineering–architecture collaboration. *Journal of Cleaner Production, 67*(Complete), 125-138. doi:10.1016/j.jclepro.2013.12.018

Silvestre, J. D., de Brito, J., & Pinheiro, M. D. (2014). Environmental impacts and benefits of the end-of-life of building materials - calculation rules, results and contribution to a "cradle to cradle" life cycle. *Journal of Cleaner Production, 66,* 37-45. doi:10.1016/j.jclepro.2013.10.028

Singh, M. (2013). Buildings and climate change. *Journal of Energy, Environment & Carbon Credits,* , 61-67.

Smith, S., & Hung, P. (2015). A novel selective parallel disassembly planning method for green design. *Journal of Engineering Design*, *26*(10-12), 283-301.

Smith, M. A. (1983). *An assessment of the potential problems occurring in the engineering phase of an industrial project* (Doctoral dissertation). Available from ProQuest Dissertations & Theses Global. (No. 8414450). Retrieved from http://search.proquest.com.proxy.lib.uwaterloo.ca/docview/303272364?accountid=14906

Smith, S., & Chen, W. -. (2012). Multiple-target selective disassembly sequence planning with disassembly sequence structure graphs. Paper presented at the *Proceedings of the ASME Design Engineering Technical Conference, , 3*(PARTS A AND B) 1305-1314. doi:10.1115/DETC2012-70154

Smith, S., Hsu, L. Y., & Smith, G. C. (2016). Partial disassembly sequence planning based on cost-benefit analysis. *Journal of Cleaner Production, 139*, 729-739. doi:10.1016/j.jclepro.2016.08.095

Smith, S., Smith, G., & Chen, W. -. (2012). Disassembly sequence structure graphs: An optimal approach for multiple-target selective disassembly sequence planning. *Advanced Engineering Informatics, 26*(2), 306-316. doi:10.1016/j.aei.2011.11.003

Smith, S. S., & Chen, W. (2011). Rule-based recursive selective disassembly sequence planning for green design. *Advanced Engineering Informatics, 25*(1), 77-87. doi:http://dx.doi.org/10.1016/j.aei.2010.03.002

Soh, S., Ong, S. K., & Nee, A. Y. C. (2016). Design for assembly and disassembly for remanufacturing. *Assembly Automation, 36*(1), 12-24. doi:10.1108/AA-05-2015-040

Sosa, M. E., Eppinger, S. D., & Rowles, C. M. (2007). A network approach to define modularity of components in complex products. *Journal of Mechanical Design, Transactions of the ASME, 129*(11), 1118-1129. doi:10.1115/1.2771182

Srinivasan, R. S., Ingwersen, W., Trucco, C., Ries, R., & Campbell, D. (2014). Comparison of energy-based indicators used in life cycle assessment tools for buildings. *Building and Environment, 79*, 138-151. doi:10.1016/j.buildenv.2014.05.006

Statistics Canada. (2015). Gross domestic product. Retrieved from http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/manuf10-eng.htm

Steel Recycling Institute. (2016). Steel takes LEED with recycled content modern steel production technologies. Retrieved from www.recycle-steel.org

Stephan, A., & Athanassiadis, A. (2017). Quantifying and mapping embodied environmental requirements of urban building stocks. *Building and Environment, 114*, 187-202. doi:10.1016/j.buildenv.2016.11.043

Tan, Y., Shen, L., & Langston, C. (2014). A fuzzy approach for adaptive reuse selection of industrial buildings in hong kong. *International Journal of Strategic Property Management, 18*(1), 66-76. doi:10.3846/1648715X.2013.864718

Teo, E. A. L., & Lin, G. (2011). Building adaption model in assessing adaption potential of public housing in singapore. *Building and Environment, 46*(7), 1370-1379. doi:10.1016/j.buildenv.2011.01.003

Teo, M. M. M., & Loosemore, M. (2001). A theory of waste behaviour in the construction industry. *Construction Management and Economics, 19*(7), 741-751. doi:10.1080/01446190110067037

Thormark, C. (2000). Environmental analysis of a building with reused building materials. *International Journal of Low Energy & Sustainable Building,*

Tseng, H., Chang, C., & Cheng, C. (2010). Disassembly-oriented assessment methodology for product modularity. *International Journal of Production Research, 48*(14), 4297-4320. doi:10.1080/00207540902893433

Turntoo®. (2019). Idea as material. Retrieved from http://turntoo.com/en/publications/

Unalan, B., Tanrivermis, H., Bulbul, M., Celani, A., & Ciaramella, A. (2016). Impact of embodied carbon in the life cycle of buildings on climate change for a sustainable future. *International Journal for Housing Science and its Applications, 40*(1), 61-71.

United Nations. (2016). The sustainable development agenda. Retrieved from http://www.un.org/sustainabledevelopment/development-agenda/

United Nations (UN). (2017). *Towards a zero-emission, efficient, and resilient buildings and construction sector* UN.

United Nations Environment Program (UNEP). (2016). Sustainable buildings and climate initiative. Retrieved from http://www.unep.org/sbci/AboutSBCI/Background.asp

United Nations Environment Programme (UNEP). (2009). Buildings and climate change: Summary for decision-makers. *United Nations Environmental Programme, Sustainable Buildings and Climate Initiative, Paris,* , 1-62.

United States Environmental Protection Agency (EPA). (2016). Tool for reduction and assessment of chemicals and other environmental impacts (TRACI). Retrieved from https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

US Environmental Protection Agency (USEPA). (2016). Learn about sustainability. Retrieved from https://www.epa.gov/sustainability/learn-about-sustainability#what

US Environmental Protection Agency (USEPA). (2016b). Green building. Retrieved from https://archive.epa.gov/greenbuilding/web/html/about.html

US General Services Administration (GSA). (2007). *BIM guide overview*. Washington, D C: U.S. General Services Administration.

Van Ast, L., Maclean, R., & Sireyjol, A. (2013). White paper: Valuing water to drive more effective decisions. *Truecost PLC White Paper,* Vilches, A., Garcia-Martinez, A., & Sanchez-Montañes, B. (2017). Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy and Buildings, 135*, 286-301. doi:10.1016/j.enbuild.2016.11.042

Viscusi, W. K. (2005). Monetizing the benefits of risk and environmental regulation. *Fordham Urban Law Journal, 33*(4), 1003.

Volk, R., Luu, T. H., Mueller-Roemer, J. S., Sevilmis, N., & Schultmann, F. (2018). Deconstruction project planning of existing buildings based on automated acquisition and reconstruction of building information. *Automation in Construction, 91*, 226-245. doi:10.1016/j.autcon.2018.03.017

Volk, R., Stengel, J., & Schultmann, F. (2014). Building information modeling (BIM) for existing buildings - literature review and future needs. *Automation in Construction, 43*, 204-204.

Whyte, J. K., & Hartmann, T. (2017). How digitizing building information transforms the built environment. *Building Research and Information, 45*(6), 591-595. doi:10.1080/09613218.2017.1324726

Wilkinson, S. J., James, K., & Reed, R. (2009). Using building adaptation to deliver sustainability in australia. *Structural Survey, 27*(1), 46-61. doi:10.1108/02630800910941683

Wilson, C. (2010). *Adaptive reuse of industrial buildings in toronto, ontario: Evaluating criteria for determining building selection* (Master dissertation). Available from Queen’s University.

Won, J., & Cheng, J. C. P. (2017). Identifying potential opportunities of building information modeling for construction and demolition waste management and minimization. *Automation in Construction, 79*, 3-18. doi:https://doi.org/10.1016/j.autcon.2017.02.002

World Economic Forum. (2016). *Shaping the future of construction A breakthrough in mindset and technology*. Cologny, Geneva, Switzerland: World Economic Forum.

Wu, W., & Issa, R. R. A. (2015). An integrated green BIM process model (IGBPM) for BIM execution planning in green building projects. In R. R. A. Issa, & S. Olbina (Eds.), *Building information modeling: Applications and practices* (pp. 135). Reston, Virginia, USA: American Society of Civil Engineers (ASCE).

Xanthopoulos, A., Aidonis, D., Vlachos, D., & Iakovou, E. (2012). A planning optimisation framework for construction and demolition waste management. *International Journal of Industrial and Systems Engineering*, *10*(3), 257-276. doi:10.1504/IJISE.2012.045675

Xia, B., Xiong, B., Skitmore, M., Wu, P., & Hu, F. (2016). Investigating the impact of project definition clarity on project performance: Structural equation modeling study. *Journal of Management in Engineering, 32*(1) doi:10.1061/(ASCE)ME.1943-5479.0000386

Yeung, J., Walbridge, S., & Haas, C. (2015). The role of geometric characterization in supporting structural steel reuse decisions. *Resources, Conservation and Recycling, 104*, 120-130. doi:10.1016/j.resconrec.2015.08.017

Yeung, J., Walbridge, S., Haas, C., & Saari, R. (2017a). Understanding the total life cycle cost implications of reusing structural steel. *Environment Systems and Decisions*, *37*(1), 101-120. doi:10.1007/s10669-016-9621-6

Yeung, J., Walbridge, S., Haas, C., & Saari, R. (2017b). Understanding the total life cycle cost implications of reusing structural steel. *Environment Systems and Decisions, 37*(1), 101-120. doi:10.1007/s10669-016-9621-6

Yeung, J. (2016). *Development of analysis tools for the facilitation of increased structural steel reuse* (Doctoral dissertation). Available from University of Waterloo. Retrieved from http://hdl.handle.net/10012/10625

Yudelson, J. (2009). *Greening existing buildings*. USA: McGraw-Hill Education.

Zabalza Bribian, I., Aranda Uson, A., & Scarpellini, S. (2009). Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment, 44*(12), 2510-2520. doi:10.1016/j.buildenv.2009.05.001

Zabalza Bribian, I., Valero Capilla, A., & Aranda Uson, A. (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment, 46*(5), 1133-1140. doi:10.1016/j.buildenv.2010.12.002

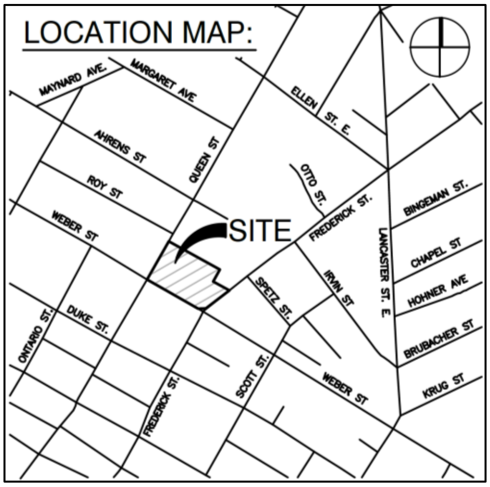
Zanakis, S. H., & Evans, J. R. (1981). Heuristic "optimization": Why, when, and how to use it. *Interfaces, 11*(5), 84-91.

Zhang, Z., Wu, X., Yang, X., & Zhu, Y. (2006). BEPAS - a life cycle building environmental performance assessment model. *Building and Environment, 41*(5), 669-675. doi:10.1016/j.buildenv.2005.02.028

Zhou, Z., Liu, J., Pham, D. T., Xu, W., Ramirez, F. J., Ji, C., & Liu, Q. (2018). Disassembly sequence planning: Recent developments and future trends. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* doi:10.1177/0954405418789975

Appendix A: Region of Waterloo county courthouse renovations

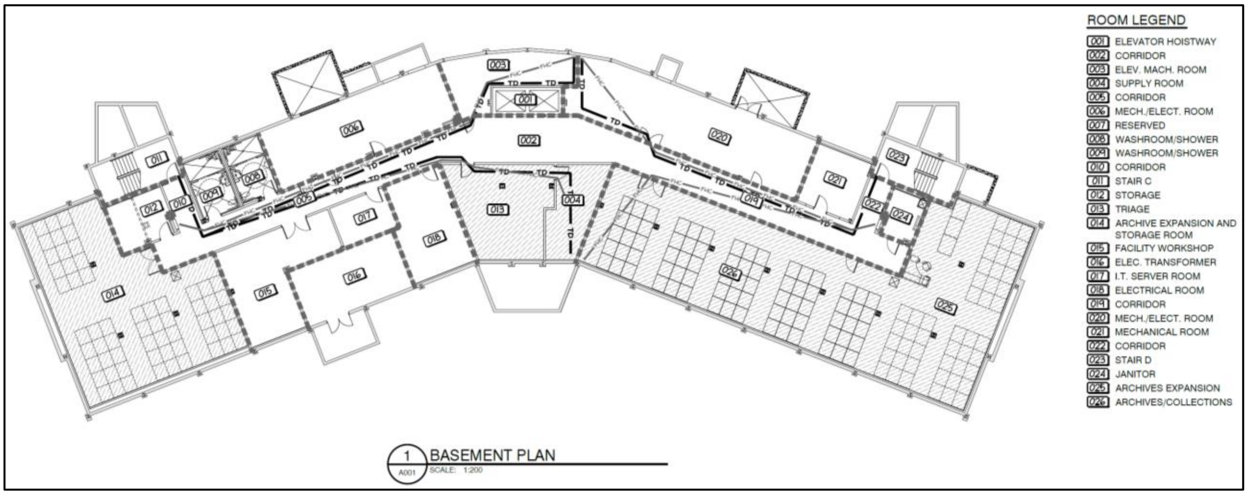
Location Map



SOURCE: (Robertson Simmons Architects Incorporated, 2015)

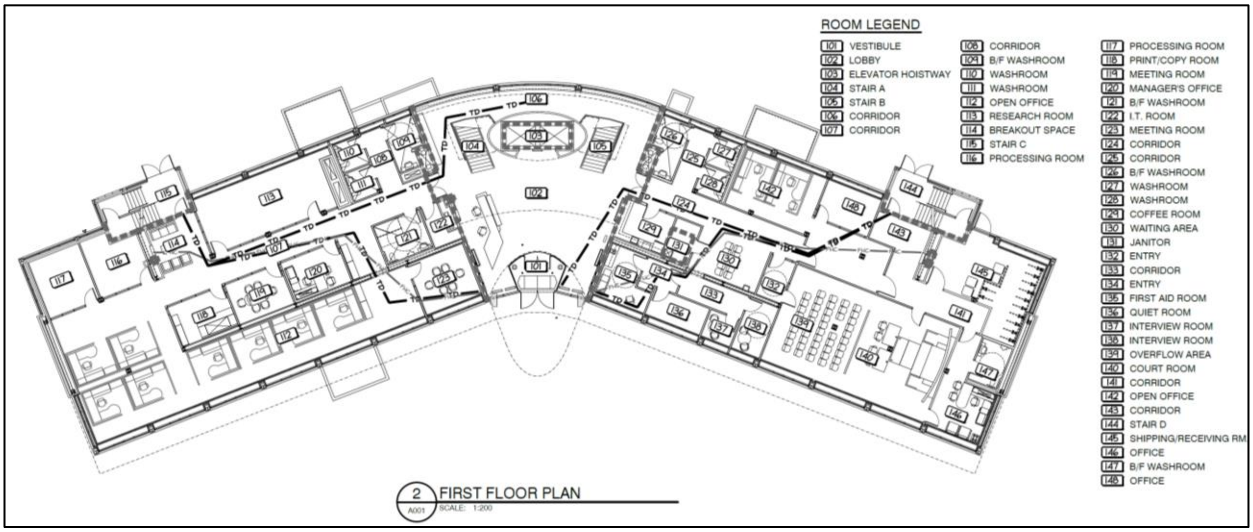
Region of Waterloo County Courthouse

Basement Layout



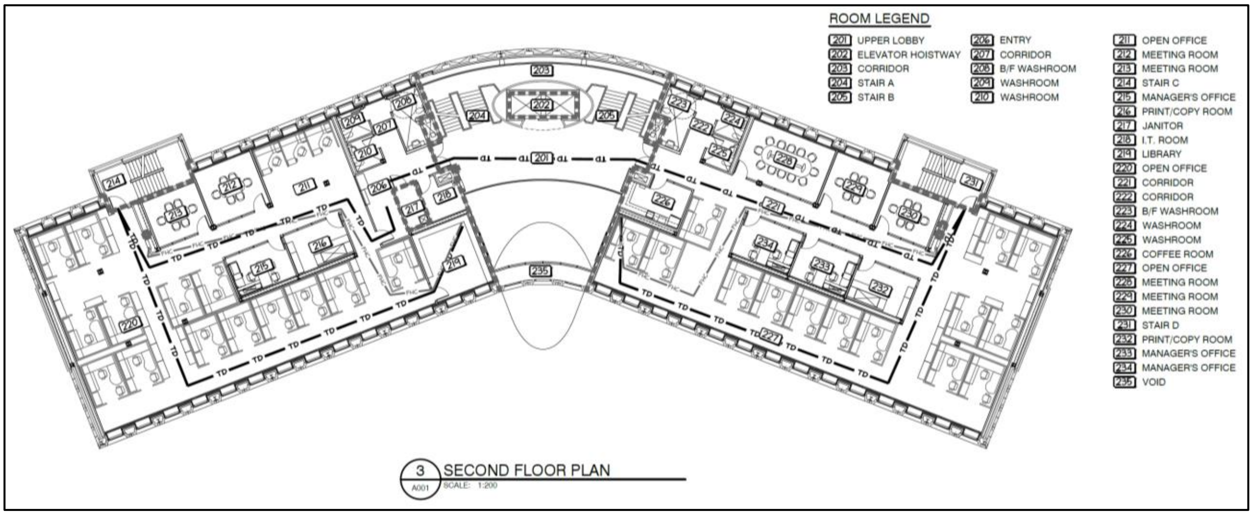
SOURCE: (Robertson Simmons Architects Incorporated, 2015)

First Floor Layout



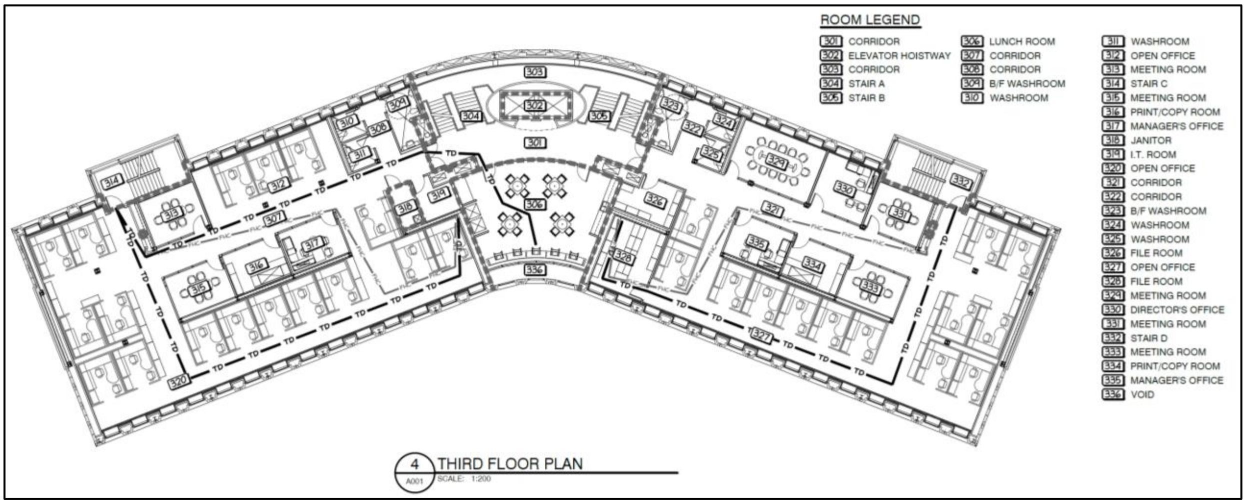
SOURCE: (Robertson Simmons Architects Incorporated, 2015)

Second Floor Layout



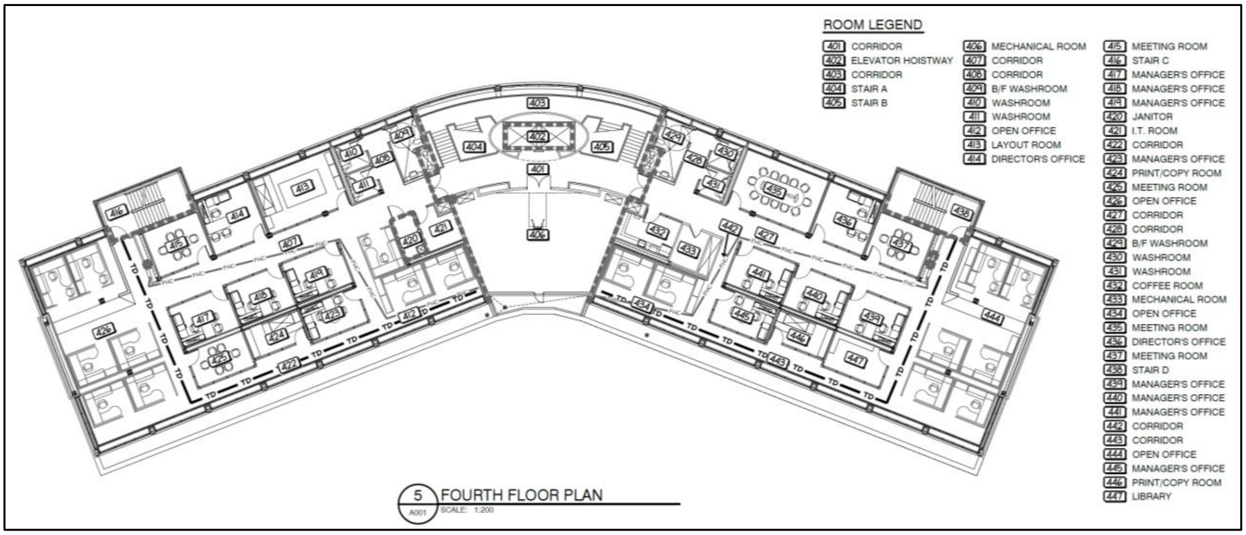
SOURCE: (Robertson Simmons Architects Incorporated, 2015)

Third Floor Layout



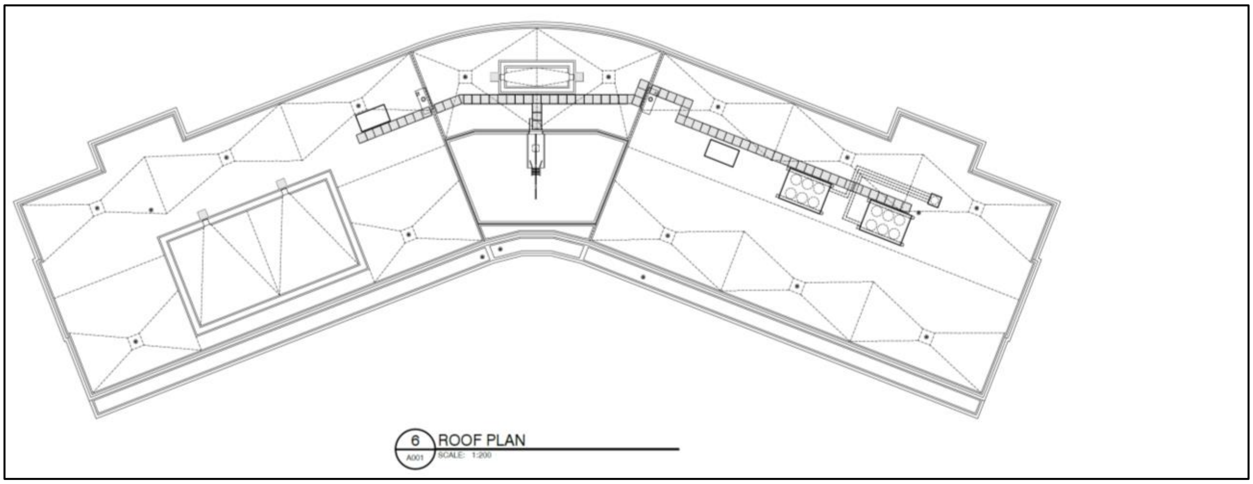
SOURCE: (Robertson Simmons Architects Incorporated, 2015)

Fourth Floor Layout



SOURCE: (Robertson Simmons Architects Incorporated, 2015)

Roof Layout



SOURCE: (Robertson Simmons Architects Incorporated, 2015)

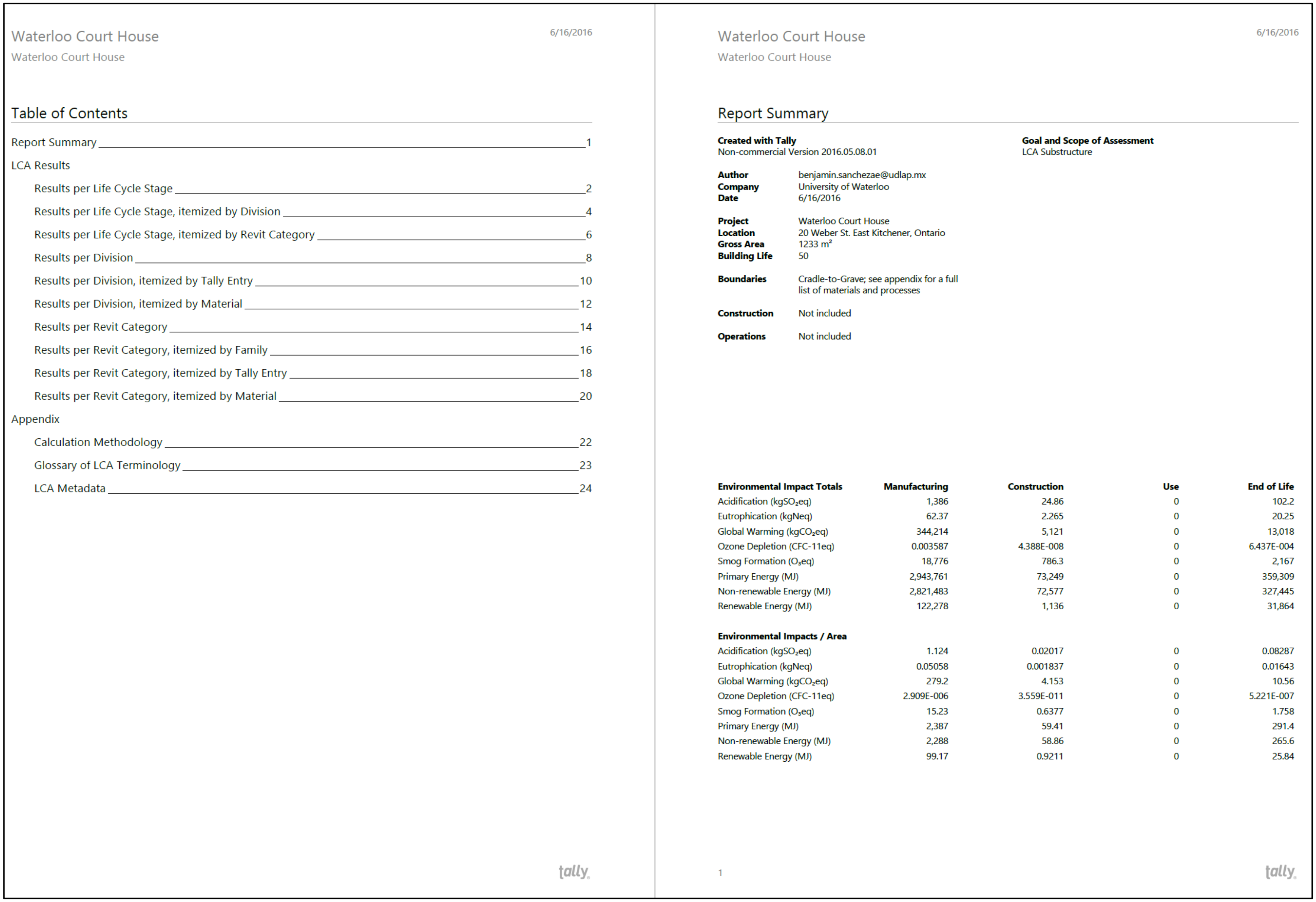
Appendix B: Tally LCA reports for the existing structure of the Waterloo county courthouse building

Tally LCA report for the existing substructure

Waterloo Court House

Waterloo Court House

6/16/2016



Waterloo Court House
Waterloo Court House

6/16/2016

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tally.

Waterloo Court House
Waterloo Court House

6/16/2016

Report Summary

Created with Tally
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Goal and Scope of Assessment
LCA Substructure

Author	benjamin.sanchezae@udlap.mx
Company	University of Waterloo
Date	6/16/2016
Project	Waterloo Court House
Location	20 Weber St. East Kitchener, Ontario
Gross Area	1233 m²
Building Life	50
Boundaries	Cradle-to-Grave; see appendix for a full list of materials and processes
Construction	Not included
Operations	Not included

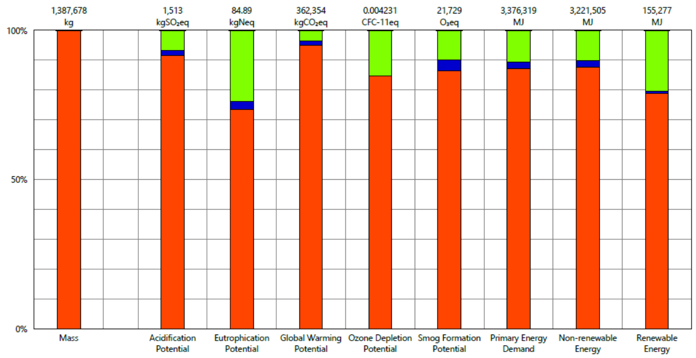
Environmental Impact Totals	Manufacturing	Construction	Use	End of Life
Acidification (kgSO$_2$eq)	1,386	24.86	0	102.2
Eutrophication (kgNeq)	62.37	2.265	0	20.25
Global Warming (kgCO$_2$eq)	344,214	5,121	0	13,018
Ozone Depletion (CFC-11eq)	0.003587	4.388E-008	0	6.437E-004
Smog Formation (O$_3$eq)	18,776	786.3	0	2,167
Primary Energy (MJ)	2,943,761	73,249	0	359,309
Non-renewable Energy (MJ)	2,821,483	72,577	0	327,445
Renewable Energy (MJ)	122,278	1,136	0	31,864

Environmental Impacts / Area				
Acidification (kgSO$_2$eq)	1.124	0.02017	0	0.08287
Eutrophication (kgNeq)	0.05058	0.001837	0	0.01643
Global Warming (kgCO$_2$eq)	279.2	4.153	0	10.56
Ozone Depletion (CFC-11eq)	2.909E-006	3.559E-011	0	5.221E-007
Smog Formation (O$_3$eq)	15.23	0.6377	0	1.758
Primary Energy (MJ)	2,387	59.41	0	291.4
Non-renewable Energy (MJ)	2,288	58.86	0	265.6
Renewable Energy (MJ)	99.17	0.9211	0	25.84

1

tally.

Results per Life Cycle Stage

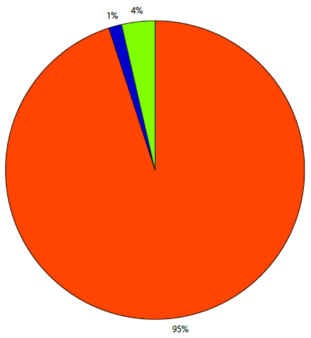


Legend

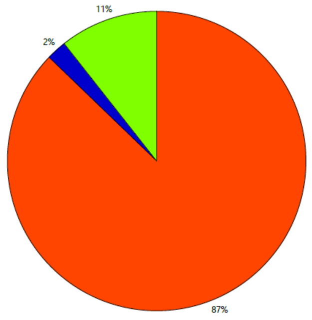
— Net value (impacts + credits)

Life Cycle Stages
- 🟥 Manufacturing
- 🟦 Transportation
- ■ Maintenance and Replacement
- 🟩 End of Life

Results per Life Cycle Stage



Global Warming Potential



Primary Energy Demand

Legend

— Net value (impacts + credits)

Life Cycle Stages
- 🟥 Manufacturing
- 🟦 Transportation
- ■ Maintenance and Replacement
- 🟩 End of Life

Waterloo Court House

Waterloo Court House

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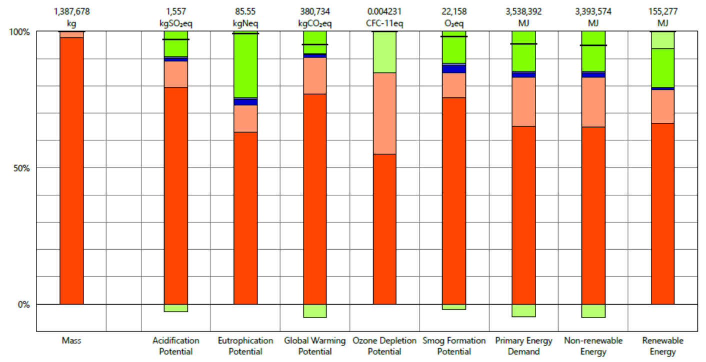
Results per Life Cycle Stage, itemized by Division



Legend

— Net value (impacts + credits)

Manufacturing
- 🟥 03 - Concrete
- 🟧 05 - Metals

Transportation
- 🟦 03 - Concrete
- 🟪 05 - Metals

Maintenance and Replacement
- 🟦 03 - Concrete
- 🟦 05 - Metals

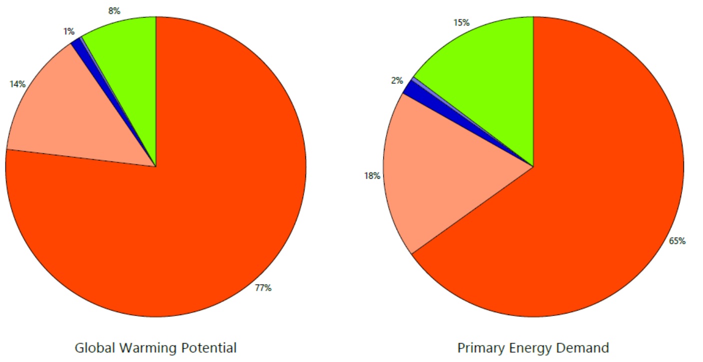
End of Life
- 🟩 03 - Concrete
- 🟩 05 - Metals

Waterloo Court House

Waterloo Court House

6/16/2016

Results per Life Cycle Stage, itemized by Division



Legend

— Net value (impacts + credits)

Manufacturing
- 🟥 03 - Concrete
- 🟧 05 - Metals

Transportation
- 🟦 03 - Concrete
- 🟪 05 - Metals

Maintenance and Replacement
- 🟦 03 - Concrete
- 🟦 05 - Metals

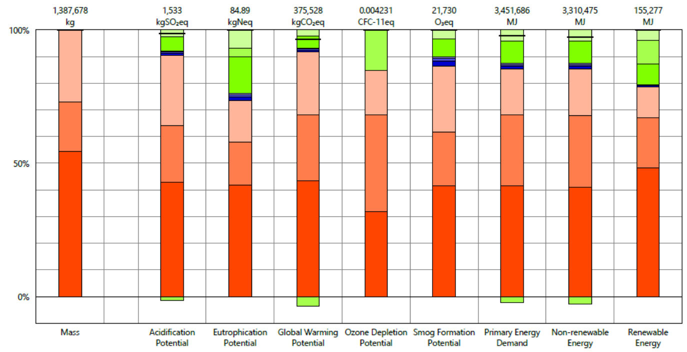
End of Life
- 🟩 03 - Concrete
- 🟩 05 - Metals

Waterloo Court House

Waterloo Court House

6/16/2016

Results per Life Cycle Stage, itemized by Revit Category



Legend

— Net value (impacts + credits)

Manufacturing
- Floors
- Structure
- Walls

Transportation
- Floors
- Structure
- Walls

Maintenance and Replacement
- Floors
- Structure
- Walls

End of Life
- Floors
- Structure
- Walls

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tally.

Waterloo Court House

Waterloo Court House

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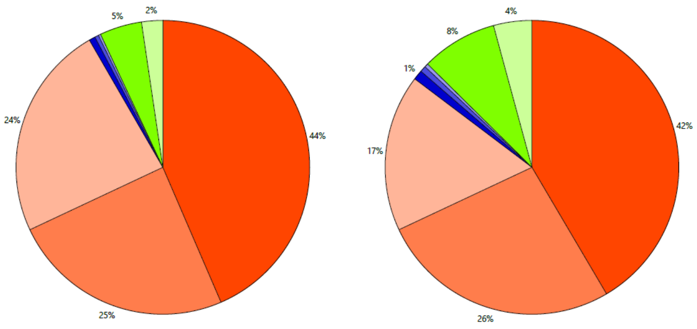
Results per Life Cycle Stage, itemized by Revit Category



Global Warming Potential

Primary Energy Demand

Legend

— Net value (impacts + credits)

Manufacturing
- Floors
- Structure
- Walls

Transportation
- Floors
- Structure
- Walls

Maintenance and Replacement
- Floors
- Structure
- Walls

End of Life
- Floors
- Structure
- Walls

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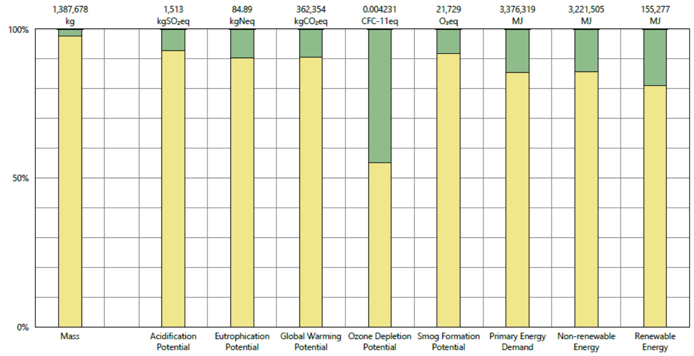
tally.

Waterloo Court House

Waterloo Court House

Results per Division



Legend

Divisions

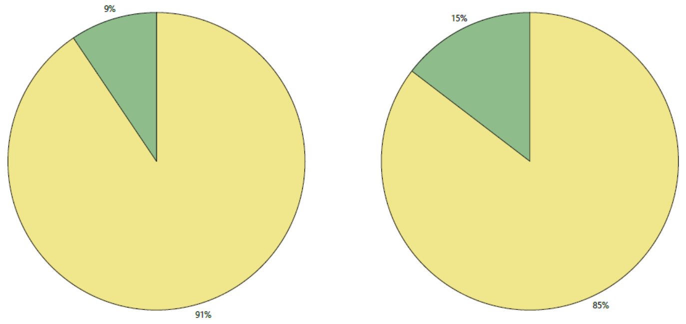
🟨 03 - Concrete

🟩 05 - Metals

Waterloo Court House

Waterloo Court House

Results per Division



Global Warming Potential

Primary Energy Demand

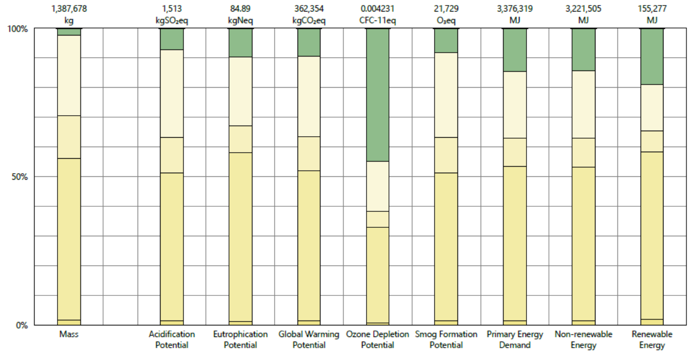
Legend

Divisions

🟨 03 - Concrete

🟩 05 - Metals

Results per Division, itemized by Tally Entry

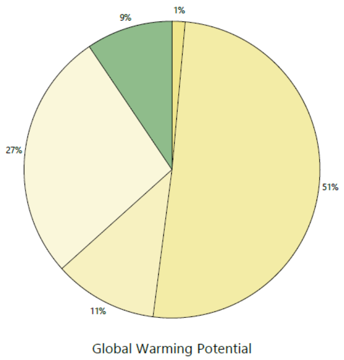


Legend

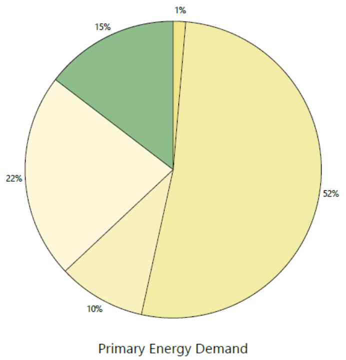
03 - Concrete
- 🟨 Cast-in-place concrete, reinforced structural concrete, 3000 psi (20 Mpa)
- 🟨 Cast-in-place concrete, slab on grade
- 🟨 Reinforced concrete footing, custom
- 🟨 Reinforced concrete foundation wall

05 - Metals
- 🟩 Steel, WT section

Results per Division, itemized by Tally Entry



Global Warming Potential



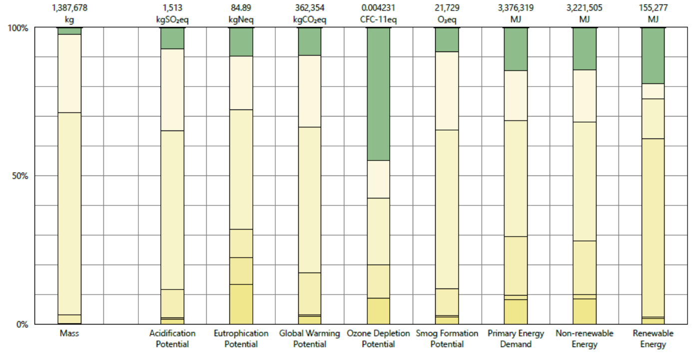
Primary Energy Demand

Legend

03 - Concrete
- 🟨 Cast-in-place concrete, reinforced structural concrete, 3000 psi (20 Mpa)
- 🟨 Cast-in-place concrete, slab on grade
- 🟨 Reinforced concrete footing, custom
- 🟨 Reinforced concrete foundation wall

05 - Metals
- 🟩 Steel, WT section

Results per Division, itemized by Material



Legend

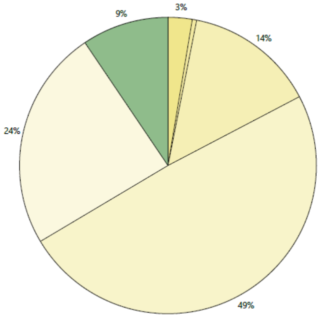
03 - Concrete

▨ Expanded polystyrene (EPS), board
▨ Polyethelene sheet vapor barrier (HDPE)
▨ Steel, reinforcing rod
▨ Structural concrete, 3000 psi, 30% fly ash
▨ Structural concrete, 3000 psi, generic

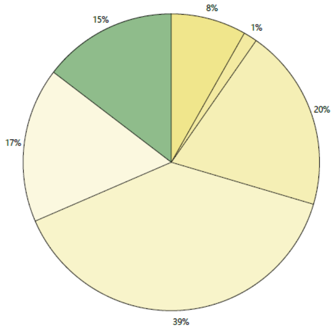
05 - Metals

🟩 Hot rolled structural steel

Results per Division, itemized by Material



Global Warming Potential



Primary Energy Demand

Legend

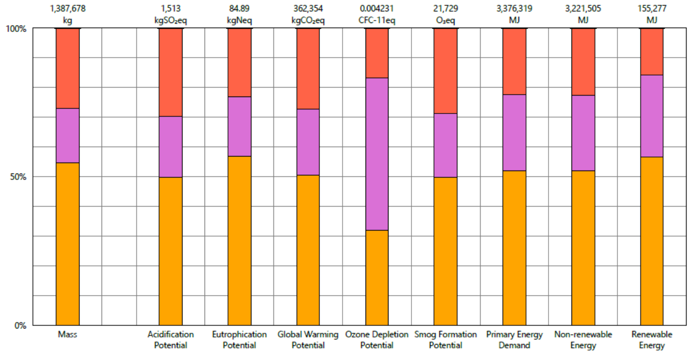
03 - Concrete

▨ Expanded polystyrene (EPS), board
▨ Polyethelene sheet vapor barrier (HDPE)
▨ Steel, reinforcing rod
▨ Structural concrete, 3000 psi, 30% fly ash
▨ Structural concrete, 3000 psi, generic

05 - Metals

🟩 Hot rolled structural steel

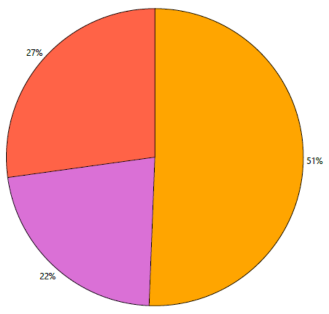
Results per Revit Category



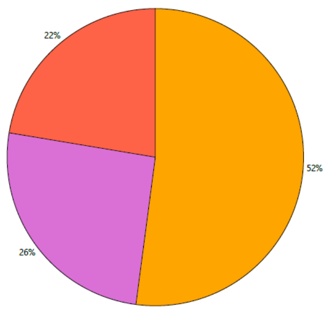
Legend

Revit Categories
- 🟧 Floors
- 🟪 Structure
- 🟥 Walls

Results per Revit Category



Global Warming Potential



Primary Energy Demand

Legend

Revit Categories
- 🟧 Floors
- 🟪 Structure
- 🟥 Walls

Waterloo Court House

Waterloo Court House

6/16/2016

Results per Revit Category, itemized by Family

Legend

Floors

- 🟧 CH_152mm Concrete Slab
- 🟨 CH_152mm Foundation Slab

Structure

- 🟪 C Shapes: C10X15.3
- 🟪 C Shapes: C8X11.5
- 🟪 M_Footing-Rectangular: Z1_CH_EX_1370 x 1370 x 381
- 🟪 M_Footing-Rectangular: Z2_CH_EX_1525 x 1525 x 406
- 🟪 M_Footing-Rectangular: Z3_CH_EX_1830 x 1830 x 457
- 🟪 M_Footing-Rectangular: Z4_CH_EX_1066 x 1066 x 381
- 🟪 M_Footing-Rectangular: Z5_CH_EX_2591 x 2133 x 533
- 🟪 M_Footing-Rectangular: Z6_CH_EX_1675 x 1675 x 432
- 🟪 Rectangular Column: CH_Concrete Covering Columns Basement 360X360
- 🟪 S Shapes: S8X18.4
- 🟪 W Shapes: W10X22
- 🟪 W Shapes: W10X26
- 🟪 W Shapes: W10X33
- 🟪 W Shapes: W12X26
- 🟪 W Shapes: W8X18
- 🟪 W Shapes-Column: W6X20
- 🟪 W Shapes-Column: W8X24
- 🟪 W Shapes-Column: W8X31
- 🟪 W Shapes-Column: W8X35
- 🟪 W Shapes-Column: W8X48
- 🟪 W Shapes-Column: W8X58
- 🟪 W-Wide Flange: W12X40

Walls

- 🟥 CH_Bearing Footing_BSA - 400 x 200
- 🟥 CH_WF1_CONCRETE_EXTERIOR FOUNDATION WALL_WITH INTERIOR STUD WALL_INSULATION_BSA
- 🟥 CH_WF1_SIMPLE CONCRETE_EXTERIOR FOUNDATION WALL_BSA

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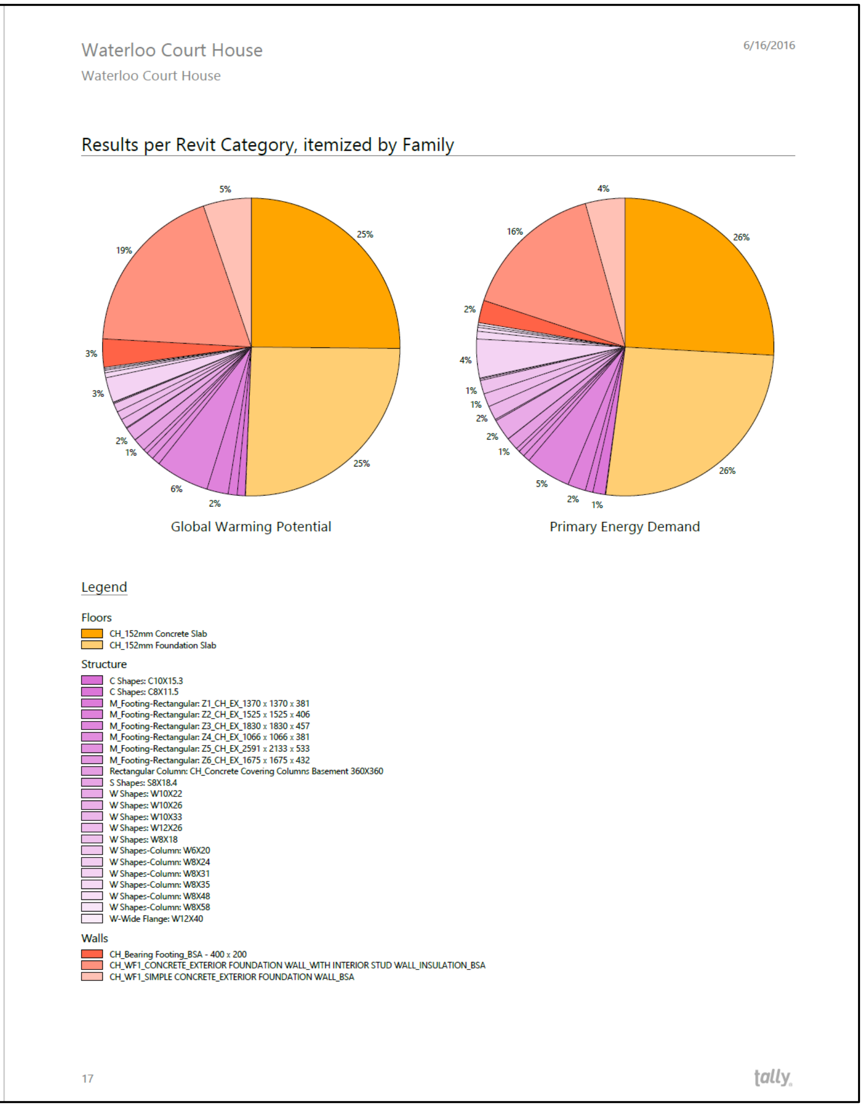

Waterloo Court House

Waterloo Court House

6/16/2016

Results per Revit Category, itemized by Family

Global Warming Potential

Primary Energy Demand

Legend

Floors

- 🟧 CH_152mm Concrete Slab
- 🟨 CH_152mm Foundation Slab

Structure

- 🟪 C Shapes: C10X15.3
- 🟪 C Shapes: C8X11.5
- 🟪 M_Footing-Rectangular: Z1_CH_EX_1370 x 1370 x 381
- 🟪 M_Footing-Rectangular: Z2_CH_EX_1525 x 1525 x 406
- 🟪 M_Footing-Rectangular: Z3_CH_EX_1830 x 1830 x 457
- 🟪 M_Footing-Rectangular: Z4_CH_EX_1066 x 1066 x 381
- 🟪 M_Footing-Rectangular: Z5_CH_EX_2591 x 2133 x 533
- 🟪 M_Footing-Rectangular: Z6_CH_EX_1675 x 1675 x 432
- 🟪 Rectangular Column: CH_Concrete Covering Columns Basement 360X360
- 🟪 S Shapes: S8X18.4
- 🟪 W Shapes: W10X22
- 🟪 W Shapes: W10X26
- 🟪 W Shapes: W10X33
- 🟪 W Shapes: W12X26
- 🟪 W Shapes: W8X18
- 🟪 W Shapes-Column: W6X20
- 🟪 W Shapes-Column: W8X24
- 🟪 W Shapes-Column: W8X31
- 🟪 W Shapes-Column: W8X35
- 🟪 W Shapes-Column: W8X48
- 🟪 W Shapes-Column: W8X58
- 🟪 W-Wide Flange: W12X40

Walls

- 🟥 CH_Bearing Footing_BSA - 400 x 200
- 🟥 CH_WF1_CONCRETE_EXTERIOR FOUNDATION WALL_WITH INTERIOR STUD WALL_INSULATION_BSA
- 🟥 CH_WF1_SIMPLE CONCRETE_EXTERIOR FOUNDATION WALL_BSA

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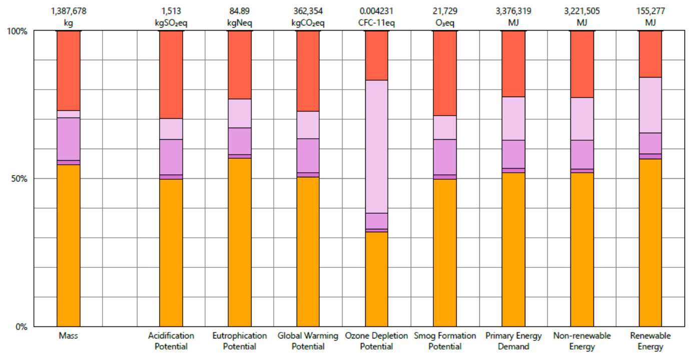
Results per Revit Category, itemized by Tally Entry



Legend

Floors

🟧 Cast-in-place concrete, slab on grade

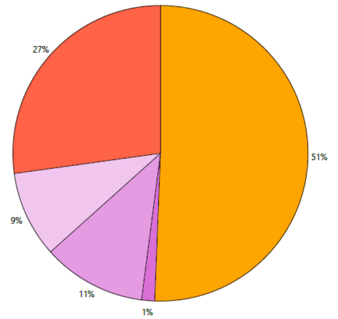
Structure

🟪 Cast-in-place concrete, reinforced structural concrete, 3000 psi (20 Mpa)
🟪 Reinforced concrete footing, custom
🟪 Steel, WT section

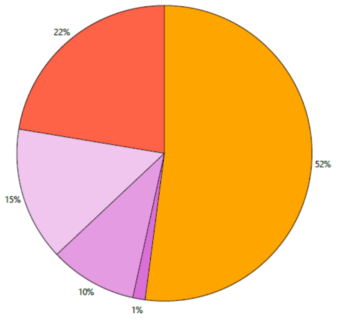
Walls

🟥 Reinforced concrete foundation wall

Results per Revit Category, itemized by Tally Entry



Global Warming Potential



Primary Energy Demand

Legend

Floors

🟧 Cast-in-place concrete, slab on grade

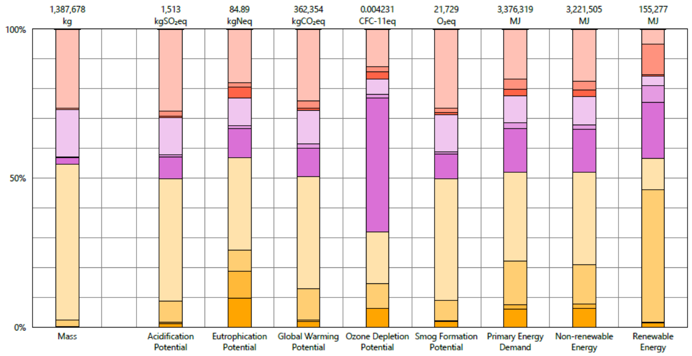
Structure

🟪 Cast-in-place concrete, reinforced structural concrete, 3000 psi (20 Mpa)
🟪 Reinforced concrete footing, custom
🟪 Steel, WT section

Walls

🟥 Reinforced concrete foundation wall

Results per Revit Category, itemized by Material



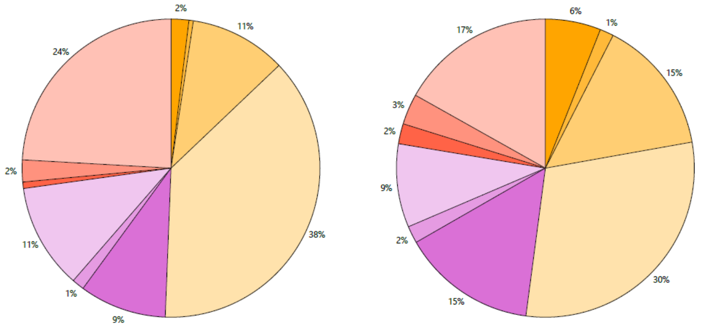
Legend

Floors
- 🟧 Expanded polystyrene (EPS), board
- 🟧 Polyethelene sheet vapor barrier (HDPE)
- 🟧 Steel, reinforcing rod
- 🟧 Structural concrete, 3000 psi, 30% fly ash

Structure
- 🟪 Hot rolled structural steel
- 🟪 Steel, reinforcing rod
- 🟪 Structural concrete, 3000 psi, 30% fly ash

Walls
- 🟥 Expanded polystyrene (EPS), board
- 🟥 Steel, reinforcing rod
- 🟥 Structural concrete, 3000 psi, generic

Results per Revit Category, itemized by Material



Global Warming Potential

Primary Energy Demand

Legend

Floors
- 🟧 Expanded polystyrene (EPS), board
- 🟧 Polyethelene sheet vapor barrier (HDPE)
- 🟧 Steel, reinforcing rod
- 🟧 Structural concrete, 3000 psi, 30% fly ash

Structure
- 🟪 Hot rolled structural steel
- 🟪 Steel, reinforcing rod
- 🟪 Structural concrete, 3000 psi, 30% fly ash

Walls
- 🟥 Expanded polystyrene (EPS), board
- 🟥 Steel, reinforcing rod
- 🟥 Structural concrete, 3000 psi, generic

Calculation Methodology

Studied objects
The life cycle analysis (LCA) results reported represent either an analysis of a single building or a comparative analysis of two or more building design options. The single building may represent the complete architectural, structural, and finish systems of a building or a subset of those systems, and it may be used to compare the relative environmental impacts associated with building components or for comparative study with one or more reference buildings. Design options may represent a full building across various stages of the design process, or they may represent multiple schemes of a full or partial building that are being compared to one another across a range of evaluation criteria.

Functional unit and reference flow
The functional unit of a single building is the usable floor space of the building under study. For a design option comparison of a partial building, the functional unit is the complete set of building systems that performs a given function. The reference flow is the amount of material required to produce a building or portion thereof, and is designed according to the given goal and scope of the assessment over the full life of the building. If construction impacts are included in the assessment, the reference flow also includes the energy, water, and fuel consumed on the building site during construction. If operational energy is included in the assessment, the reference flow includes the electrical and thermal energy consumed on site over the life of the building. It is the responsibility of the modeler to assure that reference buildings or design options are functionally equivalent in terms of scope, size, and relevant performance. The expected life of the building has a default value of 60 years and can be modified by the practitioner.

System boundaries and delimitations
The analysis accounts for the full cradle-to-grave life cycle of the design options studied, including material manufacturing, maintenance and replacement, eventual end-of-life, and the materials and energy used across all life cycle stages. Optionally, the construction impacts and operational energy of the building can be included within the scope.

Architectural materials and assemblies include all materials required for the product's manufacturing and use including hardware, sealants, adhesives, coatings, and finishing. The materials are included up to a 1% cut-off factor by mass with the exception of known materials that have high environmental impacts at low levels. In these cases, a 1% cut-off was implemented by impact.

Manufacturing [EN 15804 A1-A3] include processes wherever possible. This includes raw material extraction and processing, intermediate transportation, and final manufacturing and assembly. The manufacturing scope is listed for each entry, detailing any specific inclusions or exclusions that fall outside of the cradle-to-gate scope. Infrastructure (buildings and machinery) required for the manufacturing and assembly of building materials are not included and are considered outside the scope of assessment.

Transportation [EN 15804 A4] between the manufacturer and building site is included separately and can be modified by the practitioner. Transportation at the product's end-of-life is excluded from this study.

Construction [EN 15804 A5] is based on the anticipated or measured energy and water consumed during the construction of the building.

Maintenance and replacement [EN 15804 B2-B5] encompasses the replacement of materials in accordance with the expected service life. This includes the end-of-life treatment of the existing products [EN 15804 C2-C4], transportation to site, and cradle-to-gate manufacturing of the replacement products. The service life is specified separately for each product.

Operational energy treatment [EN 15804 B6] is based on the anticipated energy consumed at the building site over the lifetime of the building. Each associated dataset includes relevant upstream impacts associated with extraction of energy resources (such as coal or crude oil), including refining, combustion, transmission, losses, and other associated factors. For further detail, see Energy Metadata in the appendix.

End-of-life treatment [EN 15804 C2-C4] is based on average US construction and demolition waste treatment methods and rates. This includes the relevant material collection rates for recycling, processing requirements for recycled materials, incineration rates, and landfilling rates. Along with processing requirements, the recycling of materials is modeled using an avoided burden approach, where the burden of primary material production is allocated to the subsequent life cycle based on the quantity of recovered secondary material. Incineration of materials includes credit for average US energy recovery rates. The impacts associated with landfilling are based on average material properties, such as plastic waste, biodegradable waste, or inert material. Specific end-of-life scenarios are detailed for each entry.

Data source and quality
Tally utilizes a custom designed LCA database that combines material attributes, assembly details, and architectural specifications with environmental impact data resulting from the collaboration between KieranTimberlake and thinkstep. LCA modeling was conducted in GaBi 6 using GaBi databases and in accordance with GaBi databases and modeling principles.

The data used are intended to represent the US and the year 2013. Where representative data were unavailable, proxy data were used. The datasets used, their geographic region, and year of reference are listed for each entry. An effort was made to choose proxy datasets that are technologically consistent with the relevant entry.

Uncertainty in results can stem from both the data used and its application. Data quality is judged by: its measured, calculated, or estimated precision; its completeness, such as unreported emissions; its consistency, or degree of uniformity of the methodology applied on a study serving as a data source; and geographical, temporal, and technological representativeness. The GaBi LCI databases have been used in LCA models worldwide in both industrial and scientific applications. These LCI databases have additionally been used both as internal and critically reviewed and published studies. Uncertainty introduced by the use of proxy data is reduced by using technologically, geographically, and/or temporally similar data. It is the responsibility of the modeler to appropriately apply the predefined material entries to the building under study.

Tally methodology is consistent with LCA standards ISO 14040-14044.

Glossary of LCA Terminology

Environmental Impact Categories
The following list provides a description of environmental impact categories reported according to the TRACI 2.1 characterization scheme. References: [Bare 2010, EPA 2012, Guinée 2001]

Acidification Potential (AP) kg SO_2 eq
A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline, and the deterioration of building materials.

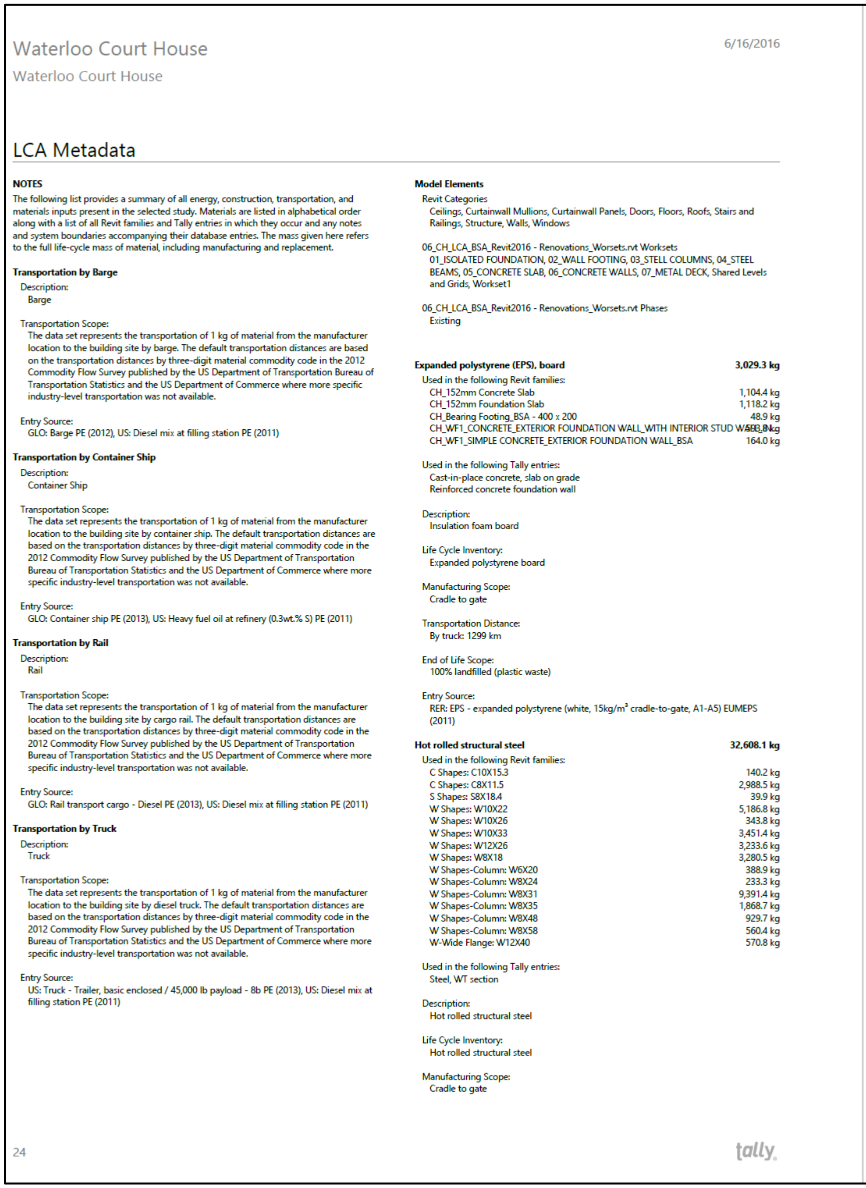
Eutrophication Potential (EP) kg N eq
Eutrophication covers potential impacts of excessively high levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.

Global Warming Potential (GWP) kg CO_2 eq
A measure of greenhouse gas emissions, such as carbon dioxide and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health, and material welfare.

Ozone Depletion Potential (ODP) kg CFC-11 eq
A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants.

Smog Formation Potential (SFP) kg O_3 eq
Ground level ozone is created by various chemical reactions, which occur between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in sunlight. Human health effects can result in a variety of respiratory issues including increasing symptoms of bronchitis, asthma, and emphysema. Permanent lung damage may result from prolonged exposure to ozone. Ecological impacts include damage to various ecosystems and crop damage. The primary sources of ozone precursors are motor vehicles, electric power utilities, and industrial facilities.

Primary Energy Demand (PED) MJ (lower heating value)
A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) and energy demand from renewable resources (e.g. hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.



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LCA Metadata

NOTES

The following list provides a summary of all energy, construction, transportation, and materials inputs present in the selected study. Materials are listed in alphabetical order along with a list of all Revit families and Tally entries in which they occur and any notes and system boundaries accompanying their database entries. The mass given here refers to the full life-cycle mass of material, including manufacturing and replacement.

Transportation by Barge

Description:
Barge

Transportation Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by barge. The default transportation distances are based on the transportation distances by three-digit material commodity code in the 2012 Commodity Flow Survey published by the US Department of Transportation Bureau of Transportation Statistics and the US Department of Commerce where more specific industry-level transportation was not available.

Entry Source:
GLO: Barge PE (2012), US: Diesel mix at filling station PE (2011)

Transportation by Container Ship

Description:
Container Ship

Transportation Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by container ship. The default transportation distances are based on the transportation distances by three-digit material commodity code in the 2012 Commodity Flow Survey published by the US Department of Transportation Bureau of Transportation Statistics and the US Department of Commerce where more specific industry-level transportation was not available.

Entry Source:
GLO: Container ship PE (2013), US: Heavy fuel oil at refinery (0.3wt.% S) PE (2011)

Transportation by Rail

Description:
Rail

Transportation Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by cargo rail. The default transportation distances are based on the transportation distances by three-digit material commodity code in the 2012 Commodity Flow Survey published by the US Department of Transportation Bureau of Transportation Statistics and the US Department of Commerce where more specific industry-level transportation was not available.

Entry Source:
GLO: Rail transport cargo - Diesel PE (2013), US: Diesel mix at filling station PE (2011)

Transportation by Truck

Description:
Truck

Transportation Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by diesel truck. The default transportation distances are based on the transportation distances by three-digit material commodity code in the 2012 Commodity Flow Survey published by the US Department of Transportation Bureau of Transportation Statistics and the US Department of Commerce where more specific industry-level transportation was not available.

Entry Source:
US: Truck - Trailer, basic enclosed / 45,000 lb payload - 8b PE (2013), US: Diesel mix at filling station PE (2011)

Model Elements

Revit Categories
Ceilings, Curtainwall Mullions, Curtainwall Panels, Doors, Floors, Roofs, Stairs and Railings, Structure, Walls, Windows

06_CH_LCA_BSA_Revit2016 - Renovations_Worsets.rvt Worksets
01_ISOLATED FOUNDATION, 02_WALL FOOTING, 03_STELL COLUMNS, 04_STEEL BEAMS, 05_CONCRETE SLAB, 06_CONCRETE WALLS, 07_METAL DECK, Shared Levels and Grids, Workset1

06_CH_LCA_BSA_Revit2016 - Renovations_Worsets.rvt Phases
Existing

Expanded polystyrene (EPS), board	**3,029.3 kg**
Used in the following Revit families:	
CH_152mm Concrete Slab	1,104.4 kg
CH_152mm Foundation Slab	1,118.2 kg
CH_Bearing Footing_BSA - 400 x 200	48.9 kg
CH_WF1_CONCRETE_EXTERIOR FOUNDATION WALL_WITH INTERIOR STUD WA	593.8 kg
CH_WF1_SIMPLE CONCRETE_EXTERIOR FOUNDATION WALL_BSA	164.0 kg

Used in the following Tally entries:
Cast-in-place concrete, slab on grade
Reinforced concrete foundation wall

Description:
Insulation foam board

Life Cycle Inventory:
Expanded polystyrene board

Manufacturing Scope:
Cradle to gate

Transportation Distance:
By truck: 1299 km

End of Life Scope:
100% landfilled (plastic waste)

Entry Source:
RER: EPS - expanded polystyrene (white, 15kg/m^3 cradle-to-gate, A1-A5) EUMEPS (2011)

Hot rolled structural steel	**32,608.1 kg**
Used in the following Revit families:	
C Shapes: C10X15.3	140.2 kg
C Shapes: C8X11.5	2,988.5 kg
S Shapes: S8X18.4	39.9 kg
W Shapes: W10X22	5,186.8 kg
W Shapes: W10X26	343.8 kg
W Shapes: W10X33	3,451.4 kg
W Shapes: W12X26	3,233.6 kg
W Shapes: W8X18	3,280.5 kg
W Shapes-Column: W6X20	388.9 kg
W Shapes-Column: W8X24	233.3 kg
W Shapes-Column: W8X31	9,391.4 kg
W Shapes-Column: W8X35	1,868.7 kg
W Shapes-Column: W8X48	929.7 kg
W Shapes-Column: W8X58	560.4 kg
W-Wide Flange: W12X40	570.8 kg

Used in the following Tally entries:
Steel, WT section

Description:
Hot rolled structural steel

Life Cycle Inventory:
Hot rolled structural steel

Manufacturing Scope:
Cradle to gate

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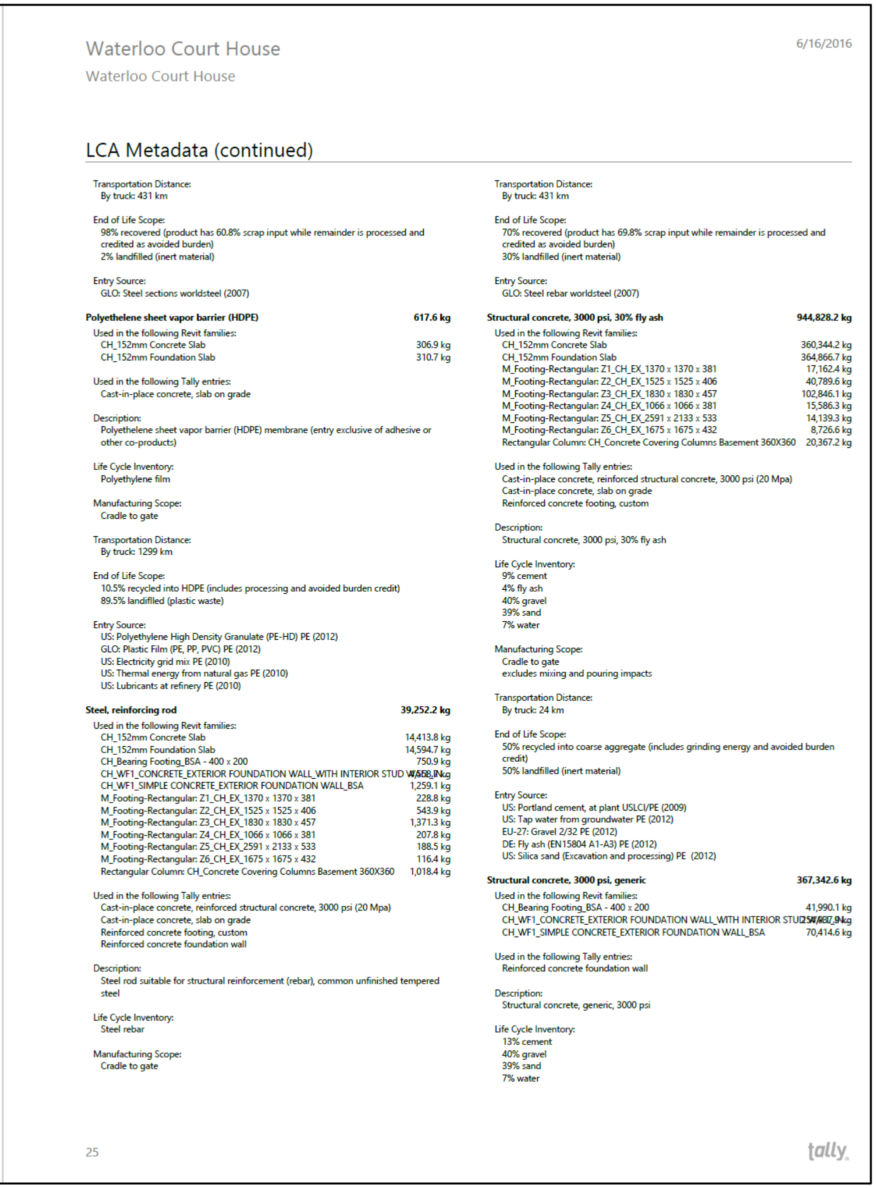
tally



Waterloo Court House

Waterloo Court House

6/16/2016

LCA Metadata (continued)

Transportation Distance:
By truck: 431 km

End of Life Scope:
98% recovered (product has 60.8% scrap input while remainder is processed and credited as avoided burden)
2% landfilled (inert material)

Entry Source:
GLO: Steel sections worldsteel (2007)

Polyethelene sheet vapor barrier (HDPE)	**617.6 kg**
Used in the following Revit families:	
CH_152mm Concrete Slab	306.9 kg
CH_152mm Foundation Slab	310.7 kg

Used in the following Tally entries:
Cast-in-place concrete, slab on grade

Description:
Polyethelene sheet vapor barrier (HDPE) membrane (entry exclusive of adhesive or other co-products)

Life Cycle Inventory:
Polyethylene film

Manufacturing Scope:
Cradle to gate

Transportation Distance:
By truck: 1299 km

End of Life Scope:
10.5% recycled into HDPE (includes processing and avoided burden credit)
89.5% landiflled (plastic waste)

Entry Source:
US: Polyethylene High Density Granulate (PE-HD) PE (2012)
GLO: Plastic Film (PE, PP, PVC) PE (2012)
US: Electricity grid mix PE (2010)
US: Thermal energy from natural gas PE (2010)
US: Lubricants at refinery PE (2010)

Steel, reinforcing rod	**39,252.2 kg**
Used in the following Revit families:	
CH_152mm Concrete Slab	14,413.8 kg
CH_152mm Foundation Slab	14,594.7 kg
CH_Bearing Footing_BSA - 400 x 200	750.9 kg
CH_WF1_CONCRETE_EXTERIOR FOUNDATION WALL_WITH INTERIOR STUD W	4,558.7 kg
CH_WF1_SIMPLE CONCRETE_EXTERIOR FOUNDATION WALL_BSA	1,259.1 kg
M_Footing-Rectangular: Z1_CH_EX_1370 x 1370 x 381	228.8 kg
M_Footing-Rectangular: Z2_CH_EX_1525 x 1525 x 406	543.9 kg
M_Footing-Rectangular: Z3_CH_EX_1830 x 1830 x 457	1,371.3 kg
M_Footing-Rectangular: Z4_CH_EX_1066 x 1066 x 381	207.8 kg
M_Footing-Rectangular: Z5_CH_EX_2591 x 2133 x 533	188.5 kg
M_Footing-Rectangular: Z6_CH_EX_1675 x 1675 x 432	116.4 kg
Rectangular Column: CH_Concrete Covering Columns Basement 360X360	1,018.4 kg

Used in the following Tally entries:
Cast-in-place concrete, reinforced structural concrete, 3000 psi (20 Mpa)
Cast-in-place concrete, slab on grade
Reinforced concrete footing, custom
Reinforced concrete foundation wall

Description:
Steel rod suitable for structural reinforcement (rebar), common unfinished tempered steel

Life Cycle Inventory:
Steel rebar

Manufacturing Scope:
Cradle to gate

Transportation Distance:
By truck: 431 km

End of Life Scope:
70% recovered (product has 69.8% scrap input while remainder is processed and credited as avoided burden)
30% landfilled (inert material)

Entry Source:
GLO: Steel rebar worldsteel (2007)

Structural concrete, 3000 psi, 30% fly ash	**944,828.2 kg**
Used in the following Revit families:	
CH_152mm Concrete Slab	360,344.2 kg
CH_152mm Foundation Slab	364,866.7 kg
M_Footing-Rectangular: Z1_CH_EX_1370 x 1370 x 381	17,162.4 kg
M_Footing-Rectangular: Z2_CH_EX_1525 x 1525 x 406	40,789.6 kg
M_Footing-Rectangular: Z3_CH_EX_1830 x 1830 x 457	102,846.1 kg
M_Footing-Rectangular: Z4_CH_EX_1066 x 1066 x 381	15,586.3 kg
M_Footing-Rectangular: Z5_CH_EX_2591 x 2133 x 533	14,139.3 kg
M_Footing-Rectangular: Z6_CH_EX_1675 x 1675 x 432	8,726.6 kg
Rectangular Column: CH_Concrete Covering Columns Basement 360X360	20,367.2 kg

Used in the following Tally entries:
Cast-in-place concrete, reinforced structural concrete, 3000 psi (20 Mpa)
Cast-in-place concrete, slab on grade
Reinforced concrete footing, custom

Description:
Structural concrete, 3000 psi, 30% fly ash

Life Cycle Inventory:
9% cement
4% fly ash
40% gravel
39% sand
7% water

Manufacturing Scope:
Cradle to gate
excludes mixing and pouring impacts

Transportation Distance:
By truck: 24 km

End of Life Scope:
50% recycled into coarse aggregate (includes grinding energy and avoided burden credit)
50% landfilled (inert material)

Entry Source:
US: Portland cement, at plant USLCI/PE (2009)
US: Tap water from groundwater PE (2012)
EU-27: Gravel 2/32 PE (2012)
DE: Fly ash (EN15804 A1-A3) PE (2012)
US: Silica sand (Excavation and processing) PE (2012)

Structural concrete, 3000 psi, generic	**367,342.6 kg**
Used in the following Revit families:	
CH_Bearing Footing_BSA - 400 x 200	41,990.1 kg
CH_WF1_CONCRETE_EXTERIOR FOUNDATION WALL_WITH INTERIOR STU	254,937.9 kg
CH_WF1_SIMPLE CONCRETE_EXTERIOR FOUNDATION WALL_BSA	70,414.6 kg

Used in the following Tally entries:
Reinforced concrete foundation wall

Description:
Structural concrete, generic, 3000 psi

Life Cycle Inventory:
13% cement
40% gravel
39% sand
7% water

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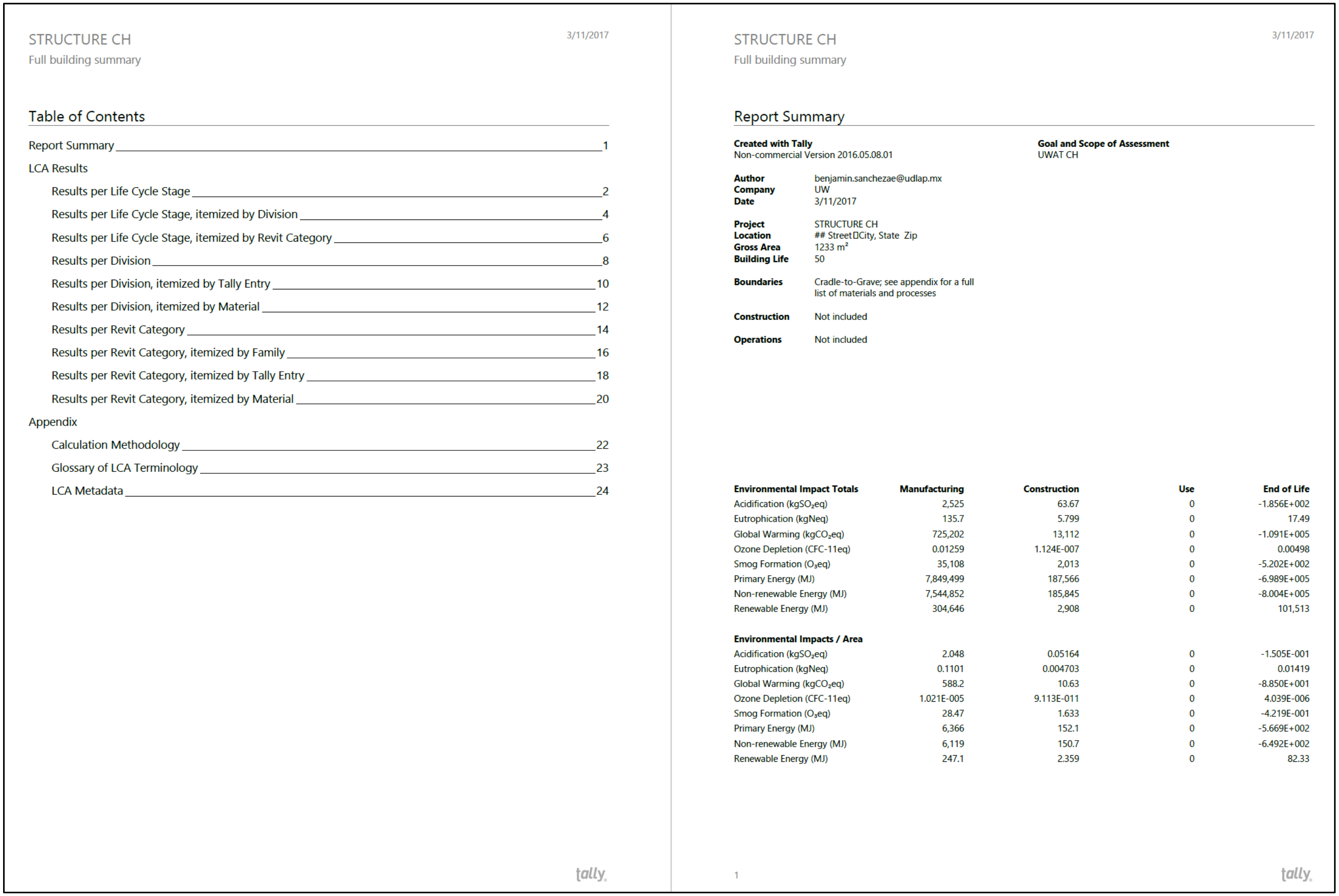
tally

Tally LCA report for the existing superstructure

STRUCTURE CH

Full building summary

3/11/2017



STRUCTURE CH
Full building summary

3/11/2017

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Full building summary

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Report Summary

Created with Tally
Non-commercial Version 2016.05.08.01

Goal and Scope of Assessment
UWAT CH

Author	benjamin.sanchezae@udlap.mx
Company	UW
Date	3/11/2017
Project	STRUCTURE CH
Location	## Street□City, State Zip
Gross Area	1233 m²
Building Life	50
Boundaries	Cradle-to-Grave; see appendix for a full list of materials and processes
Construction	Not included
Operations	Not included

Environmental Impact Totals	**Manufacturing**	**Construction**	**Use**	**End of Life**
Acidification ($kgSO_2eq$)	2,525	63.67	0	-1.856E+002
Eutrophication (kgNeq)	135.7	5.799	0	17.49
Global Warming ($kgCO_2eq$)	725,202	13,112	0	-1.091E+005
Ozone Depletion (CFC-11eq)	0.01259	1.124E-007	0	0.00498
Smog Formation (O_3eq)	35,108	2,013	0	-5.202E+002
Primary Energy (MJ)	7,849,499	187,566	0	-6.989E+005
Non-renewable Energy (MJ)	7,544,852	185,845	0	-8.004E+005
Renewable Energy (MJ)	304,646	2,908	0	101,513
Environmental Impacts / Area				
Acidification ($kgSO_2eq$)	2.048	0.05164	0	-1.505E-001
Eutrophication (kgNeq)	0.1101	0.004703	0	0.01419
Global Warming ($kgCO_2eq$)	588.2	10.63	0	-8.850E+001
Ozone Depletion (CFC-11eq)	1.021E-005	9.113E-011	0	4.039E-006
Smog Formation (O_3eq)	28.47	1.633	0	-4.219E-001
Primary Energy (MJ)	6,366	152.1	0	-5.669E+002
Non-renewable Energy (MJ)	6,119	150.7	0	-6.492E+002
Renewable Energy (MJ)	247.1	2.359	0	82.33

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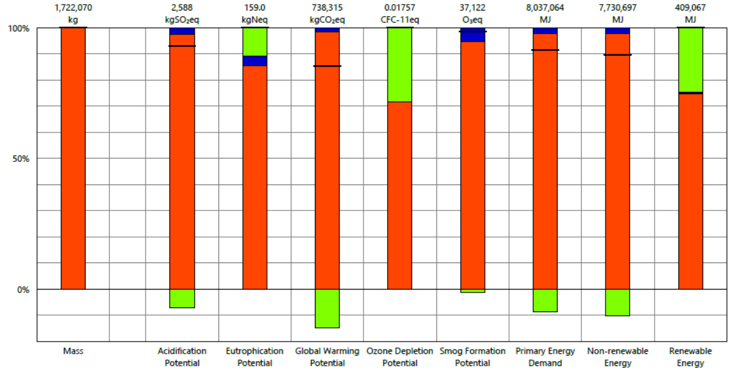
Results per Life Cycle Stage

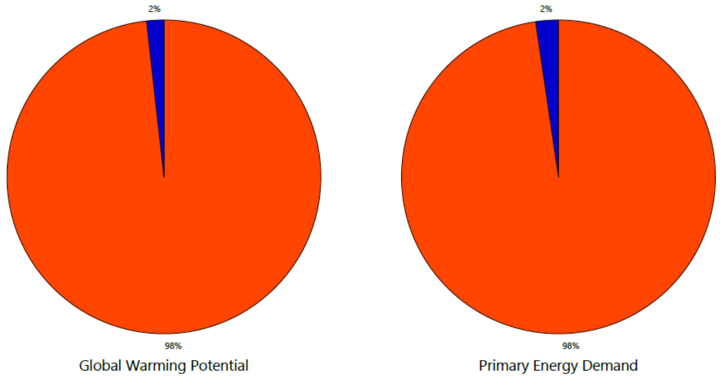


Legend

— Net value (impacts + credits)

Life Cycle Stages
- 🟥 Manufacturing
- 🟦 Transportation
- 🟩 Maintenance and Replacement
- 🟩 End of Life

Results per Life Cycle Stage

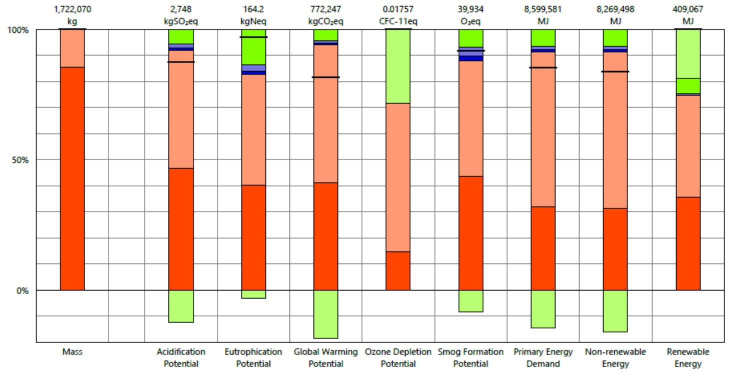


Legend

— Net value (impacts + credits)

Life Cycle Stages
- 🟥 Manufacturing
- 🟦 Transportation
- 🟩 Maintenance and Replacement
- 🟩 End of Life

Results per Life Cycle Stage, itemized by Division



Legend

— Net value (impacts + credits)

Manufacturing
- 🟥 03 - Concrete
- 🟥 05 - Metals

Transportation
- 🟦 03 - Concrete
- 🟦 05 - Metals

Maintenance and Replacement
- 🟦 03 - Concrete
- 🟦 05 - Metals

End of Life
- 🟩 03 - Concrete
- 🟩 05 - Metals

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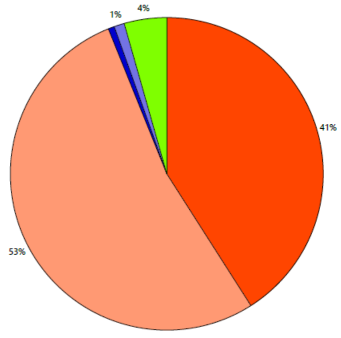
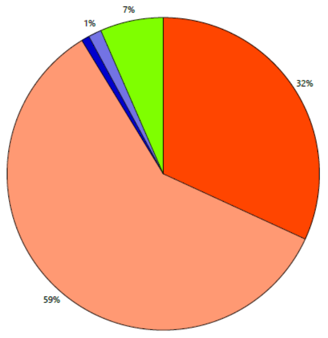
Results per Life Cycle Stage, itemized by Division



Global Warming Potential



Primary Energy Demand

Legend

— Net value (impacts + credits)

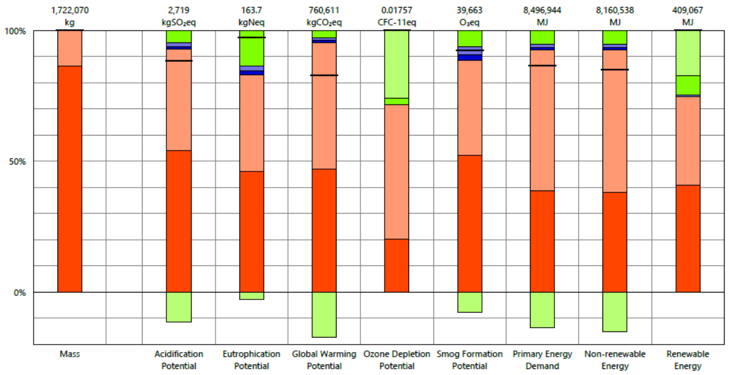
Manufacturing
- 🟥 03 - Concrete
- 🟥 05 - Metals

Transportation
- 🟦 03 - Concrete
- 🟦 05 - Metals

Maintenance and Replacement
- 🟦 03 - Concrete
- 🟦 05 - Metals

End of Life
- 🟩 03 - Concrete
- 🟩 05 - Metals

Results per Life Cycle Stage, itemized by Revit Category



Legend

— Net value (impacts + credits)

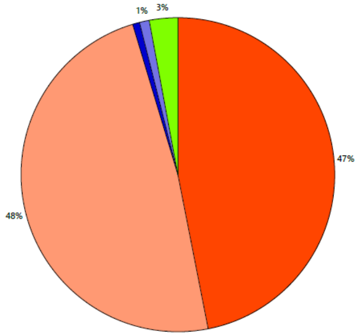
Manufacturing
- 🟥 Floors
- 🟧 Structure

Transportation
- 🟦 Floors
- 🟪 Structure

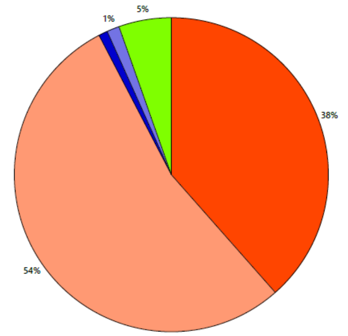
Maintenance and Replacement
- 🟦 Floors
- 🟦 Structure

End of Life
- 🟩 Floors
- 🟩 Structure

Results per Life Cycle Stage, itemized by Revit Category



Global Warming Potential



Primary Energy Demand

Legend

— Net value (impacts + credits)

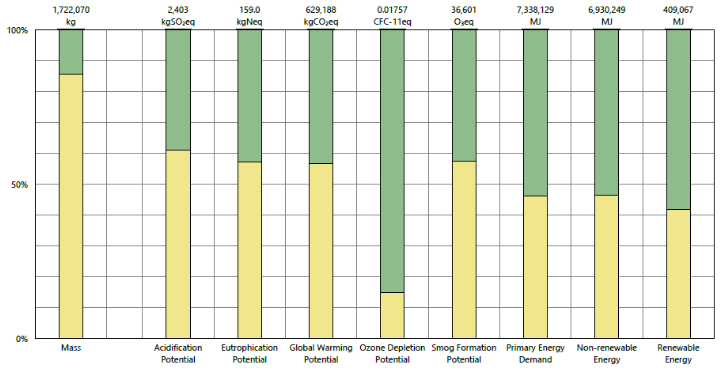
Manufacturing
- 🟥 Floors
- 🟧 Structure

Transportation
- 🟦 Floors
- 🟪 Structure

Maintenance and Replacement
- 🟦 Floors
- 🟦 Structure

End of Life
- 🟩 Floors
- 🟩 Structure

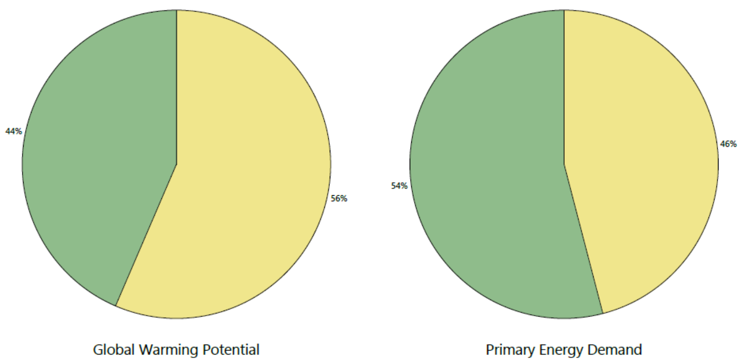
Results per Division



Legend

Divisions
🟨 03 - Concrete
🟩 05 - Metals

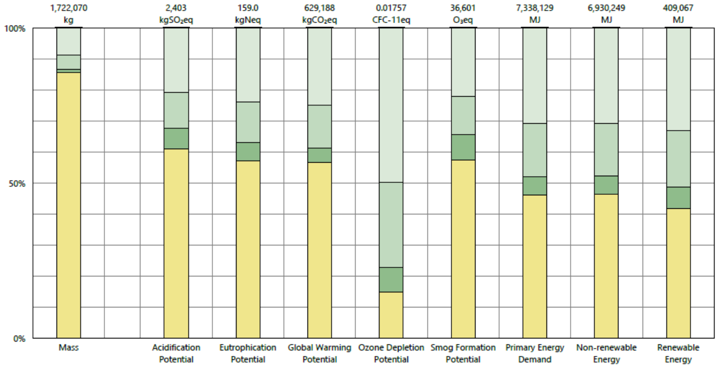
Results per Division



Legend

Divisions
🟨 03 - Concrete
🟩 05 - Metals

Results per Division, itemized by Tally Entry

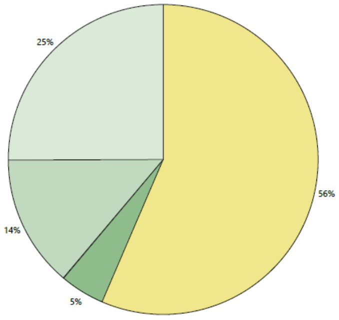


Legend

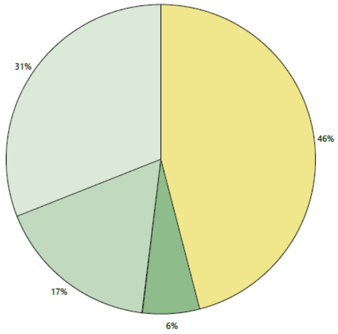
03 - Concrete
🟨 Cast-in-place concrete, slab on grade

05 - Metals
🟩 Steel, form deck
🟩 Steel, M section
🟩 Steel, wide flange shape
🟩 Steel, WT section

Results per Division, itemized by Tally Entry



Global Warming Potential



Primary Energy Demand

Legend

03 - Concrete
🟨 Cast-in-place concrete, slab on grade

05 - Metals
🟩 Steel, form deck
🟩 Steel, M section
🟩 Steel, wide flange shape
🟩 Steel, WT section

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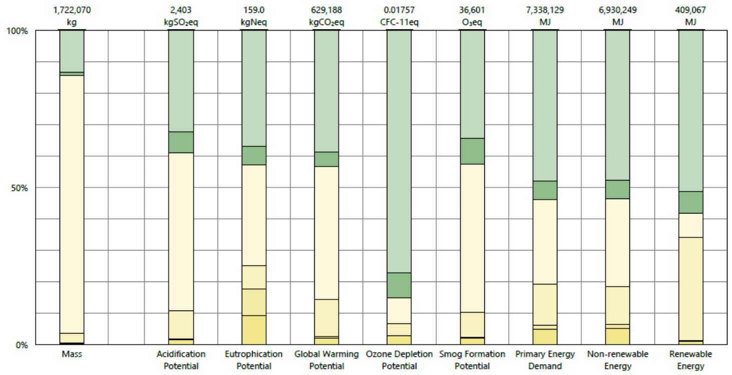
Results per Division, itemized by Material



Legend

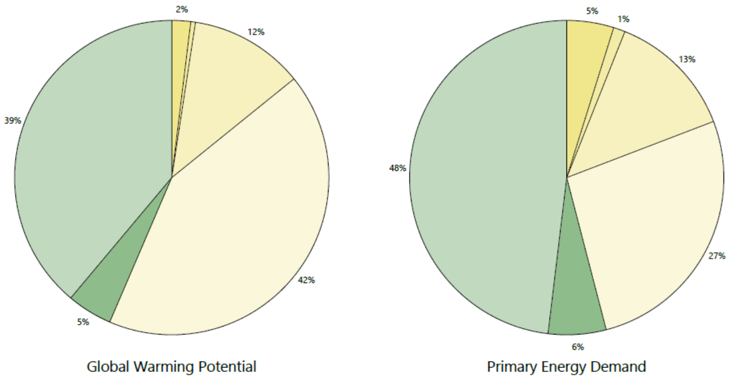
03 - Concrete
- 🟨 Expanded polystyrene (EPS), board
- 🟨 Polyethelene sheet vapor barrier (HDPE)
- 🟨 Steel, reinforcing rod
- 🟨 Structural concrete, 3000 psi, 30% fly ash

05 - Metals
- 🟩 Galvanized steel form deck
- 🟩 Hot rolled structural steel

STRUCTURE CH
Full building summary

3/11/2017

Results per Division, itemized by Material



Legend

03 - Concrete
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- 🟨 Polyethelene sheet vapor barrier (HDPE)
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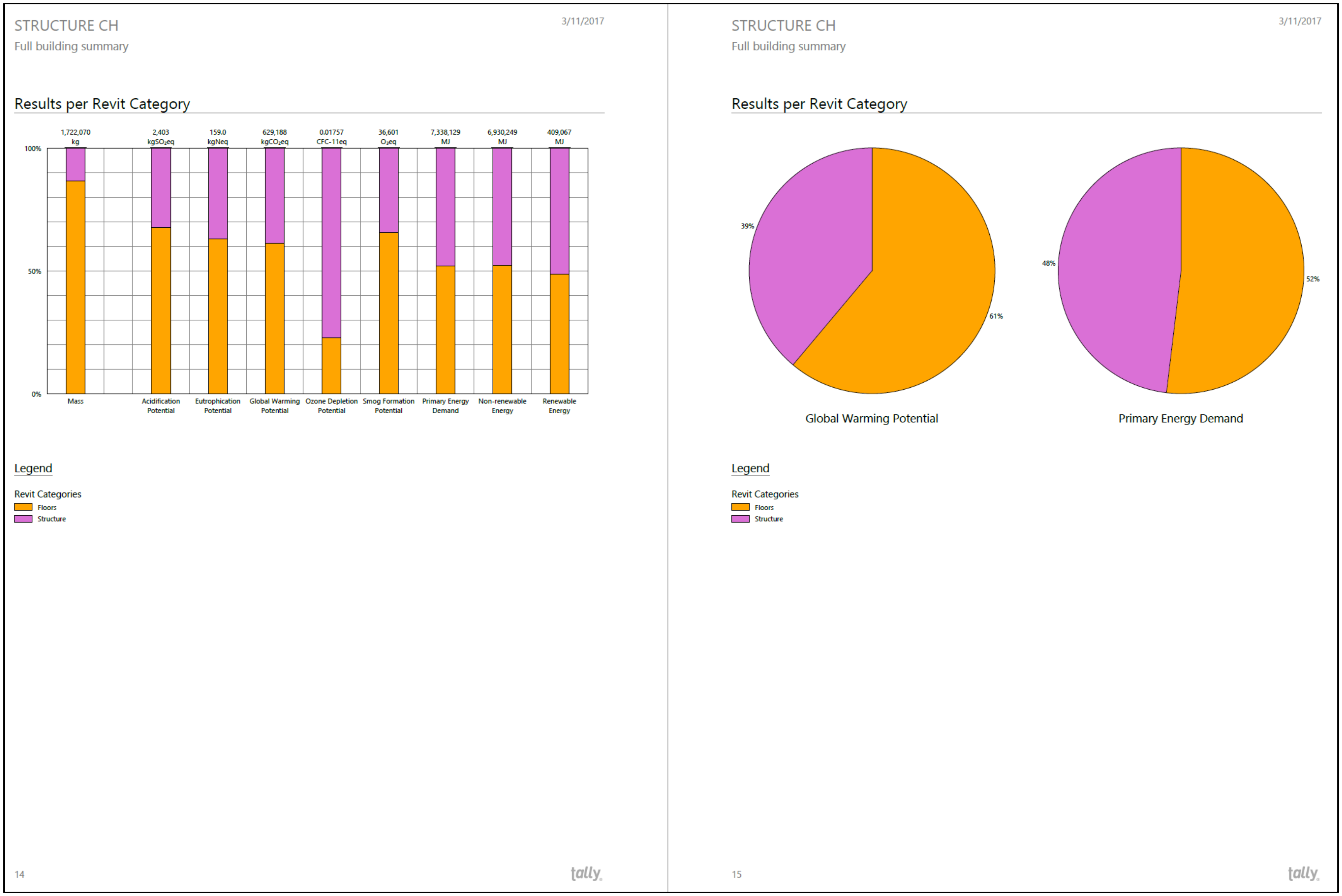
- 🟨 Structural concrete, 3000 psi, 30% fly ash

05 - Metals
- 🟩 Galvanized steel form deck
- 🟩 Hot rolled structural steel



STRUCTURE CH

Full building summary

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Results per Revit Category

Legend

Revit Categories

- 🟧 Floors
- 🟪 Structure

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tally.

STRUCTURE CH

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Results per Revit Category

Global Warming Potential

Primary Energy Demand

Legend

Revit Categories

- 🟧 Floors
- 🟪 Structure

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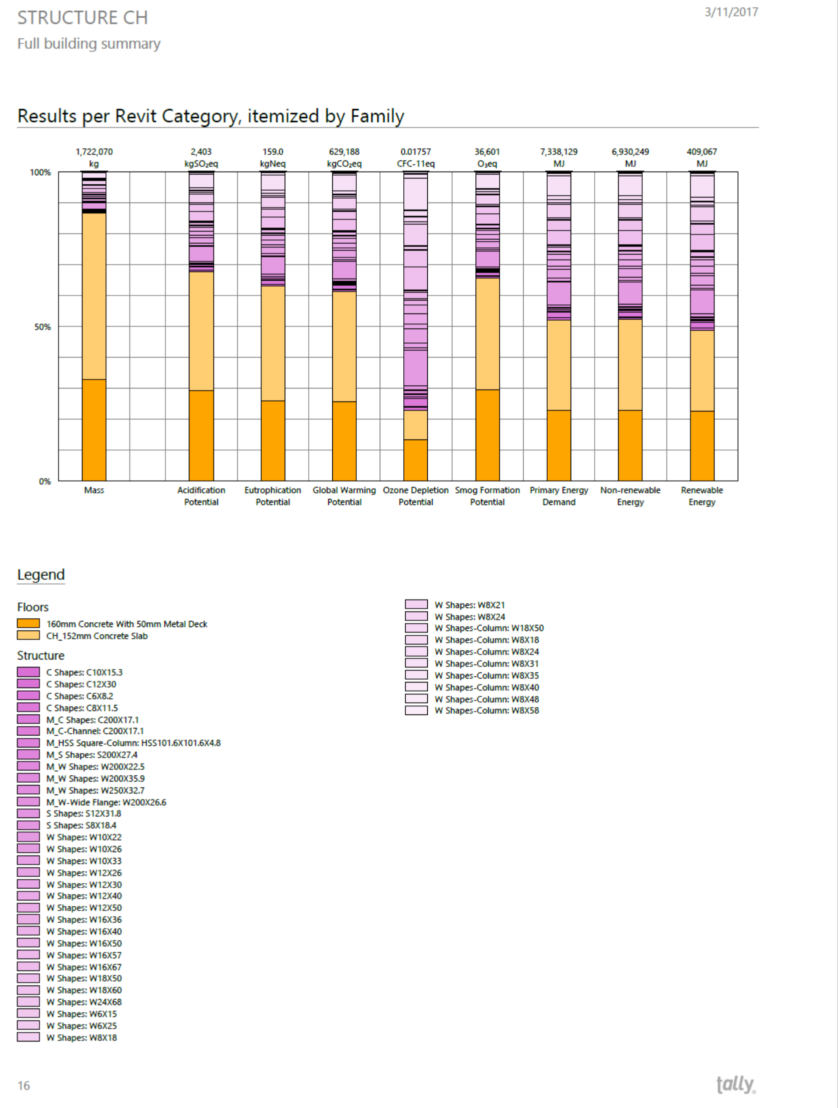
tally.



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Results per Revit Category, itemized by Family

Legend

Floors

- 🟧 160mm Concrete With 50mm Metal Deck
- 🟨 CH_152mm Concrete Slab

Structure

- 🟪 C Shapes: C10X15.3
- 🟪 C Shapes: C12X30
- 🟪 C Shapes: C6X8.2
- 🟪 C Shapes: C8X11.5
- 🟪 M_C Shapes: C200X17.1
- 🟪 M_C-Channel: C200X17.1
- 🟪 M_HSS Square-Column: HSS101.6X101.6X4.8
- 🟪 M_S Shapes: S200X27.4
- 🟪 M_W Shapes: W200X22.5
- 🟪 M_W Shapes: W200X35.9
- 🟪 M_W Shapes: W250X32.7
- 🟪 M_W-Wide Flange: W200X26.6
- 🟪 S Shapes: S12X31.8
- 🟪 S Shapes: S8X18.4
- 🟪 W Shapes: W10X22
- 🟪 W Shapes: W10X26
- 🟪 W Shapes: W10X33
- 🟪 W Shapes: W12X26
- 🟪 W Shapes: W12X30
- 🟪 W Shapes: W12X40
- 🟪 W Shapes: W12X50
- 🟪 W Shapes: W16X36
- 🟪 W Shapes: W16X40
- 🟪 W Shapes: W16X50
- 🟪 W Shapes: W16X57
- 🟪 W Shapes: W16X67
- 🟪 W Shapes: W18X50
- 🟪 W Shapes: W18X60
- 🟪 W Shapes: W24X68
- 🟪 W Shapes: W6X15
- 🟪 W Shapes: W6X25
- 🟪 W Shapes: W8X18
- 🟪 W Shapes: W8X21
- 🟪 W Shapes: W8X24
- 🟪 W Shapes-Column: W18X50
- 🟪 W Shapes-Column: W8X18
- 🟪 W Shapes-Column: W8X24
- 🟪 W Shapes-Column: W8X31
- 🟪 W Shapes-Column: W8X35
- 🟪 W Shapes-Column: W8X40
- 🟪 W Shapes-Column: W8X48
- 🟪 W Shapes-Column: W8X58

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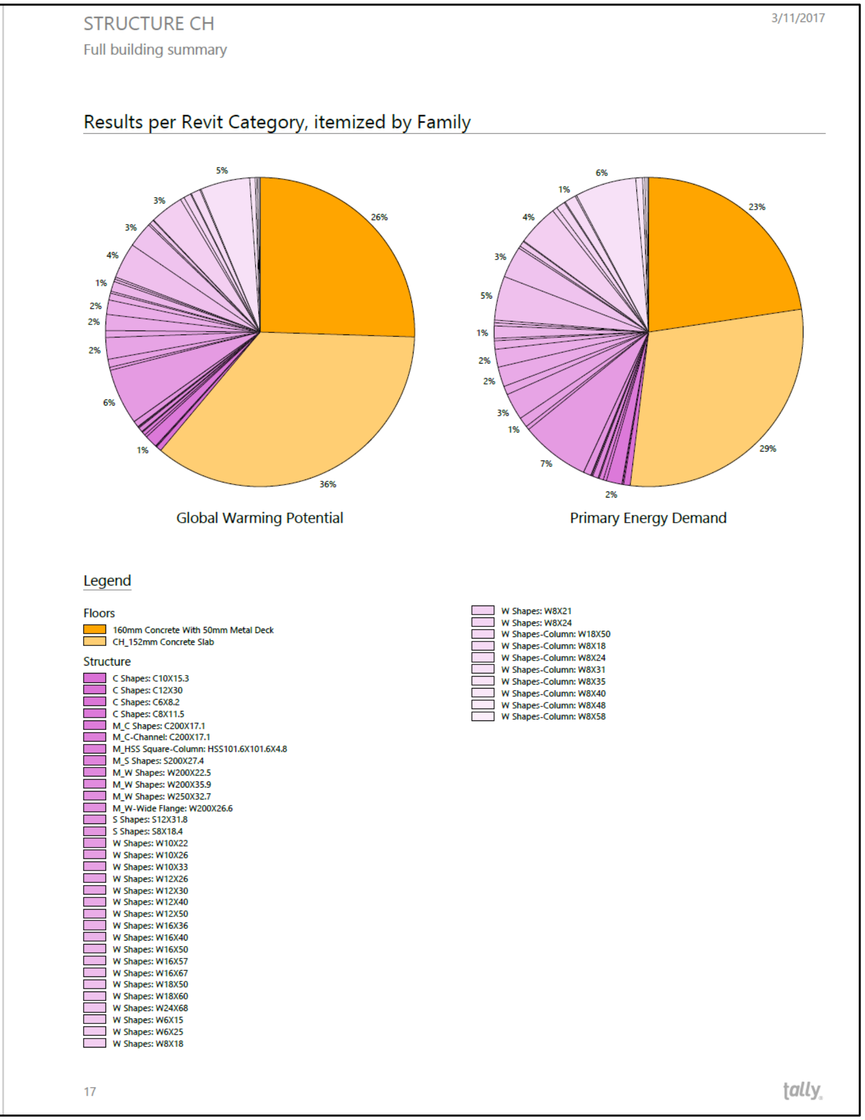
tally.



STRUCTURE CH

Full building summary

3/11/2017

Results per Revit Category, itemized by Family

Global Warming Potential

Primary Energy Demand

Legend

Floors

- 🟧 160mm Concrete With 50mm Metal Deck
- 🟨 CH_152mm Concrete Slab

Structure

- 🟪 C Shapes: C10X15.3
- 🟪 C Shapes: C12X30
- 🟪 C Shapes: C6X8.2
- 🟪 C Shapes: C8X11.5
- 🟪 M_C Shapes: C200X17.1
- 🟪 M_C-Channel: C200X17.1
- 🟪 M_HSS Square-Column: HSS101.6X101.6X4.8
- 🟪 M_S Shapes: S200X27.4
- 🟪 M_W Shapes: W200X22.5
- 🟪 M_W Shapes: W200X35.9
- 🟪 M_W Shapes: W250X32.7
- 🟪 M_W-Wide Flange: W200X26.6
- 🟪 S Shapes: S12X31.8
- 🟪 S Shapes: S8X18.4
- 🟪 W Shapes: W10X22
- 🟪 W Shapes: W10X26
- 🟪 W Shapes: W10X33
- 🟪 W Shapes: W12X26
- 🟪 W Shapes: W12X30
- 🟪 W Shapes: W12X40
- 🟪 W Shapes: W12X50
- 🟪 W Shapes: W16X36
- 🟪 W Shapes: W16X40
- 🟪 W Shapes: W16X50
- 🟪 W Shapes: W16X57
- 🟪 W Shapes: W16X67
- 🟪 W Shapes: W18X50
- 🟪 W Shapes: W18X60
- 🟪 W Shapes: W24X68
- 🟪 W Shapes: W6X15
- 🟪 W Shapes: W6X25
- 🟪 W Shapes: W8X18
- 🟪 W Shapes: W8X21
- 🟪 W Shapes: W8X24
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- 🟪 W Shapes-Column: W8X18
- 🟪 W Shapes-Column: W8X24
- 🟪 W Shapes-Column: W8X31
- 🟪 W Shapes-Column: W8X35
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- 🟪 W Shapes-Column: W8X58

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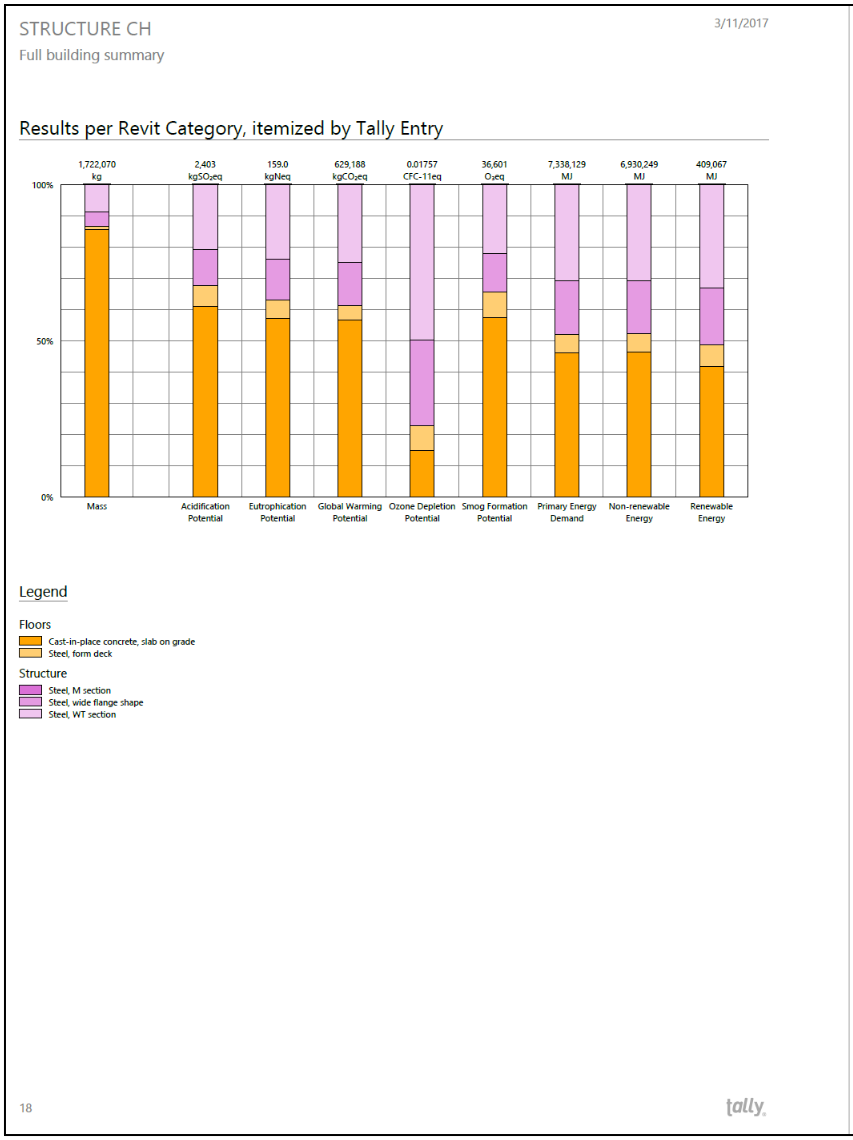
tally.



STRUCTURE CH

Full building summary

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Results per Revit Category, itemized by Tally Entry

Legend

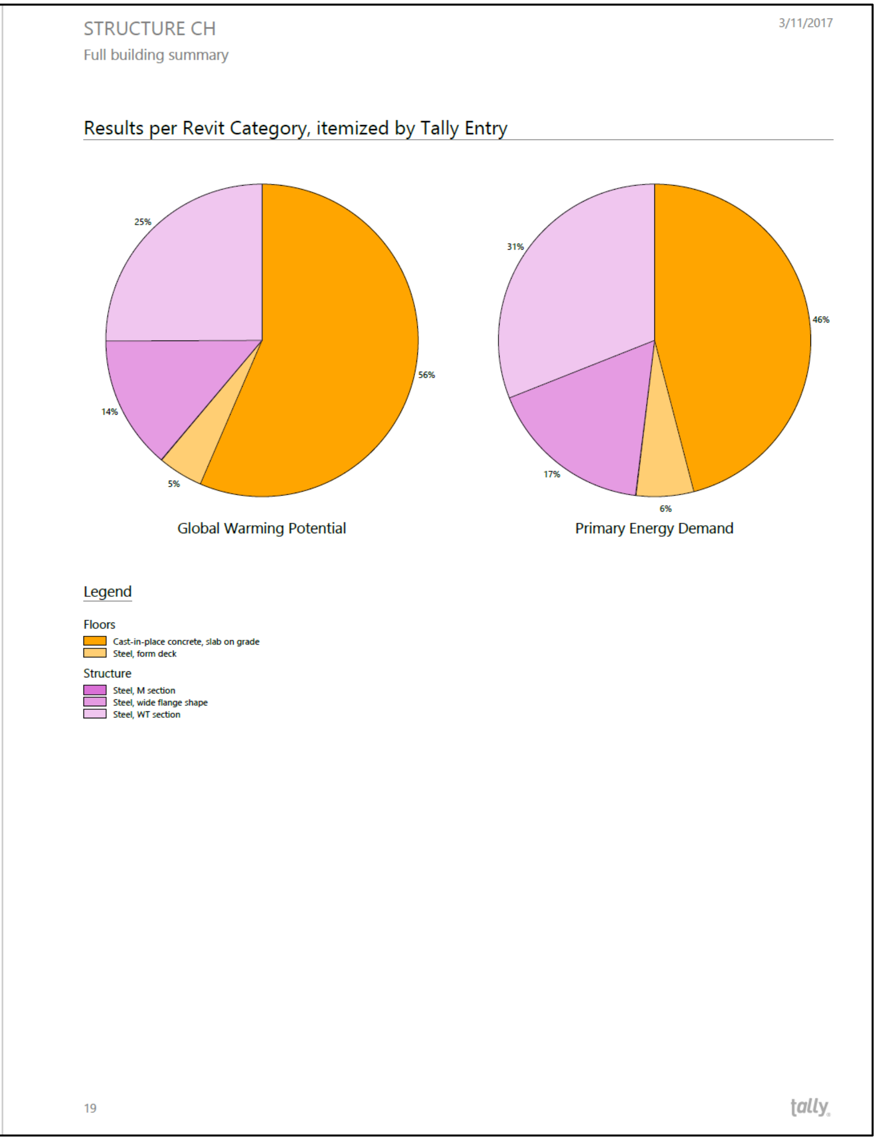
Floors

🟧 Cast-in-place concrete, slab on grade
🟨 Steel, form deck

Structure

🟪 Steel, M section
🟪 Steel, wide flange shape
🟪 Steel, WT section

18



STRUCTURE CH

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Results per Revit Category, itemized by Tally Entry

Global Warming Potential

Primary Energy Demand

Legend

Floors

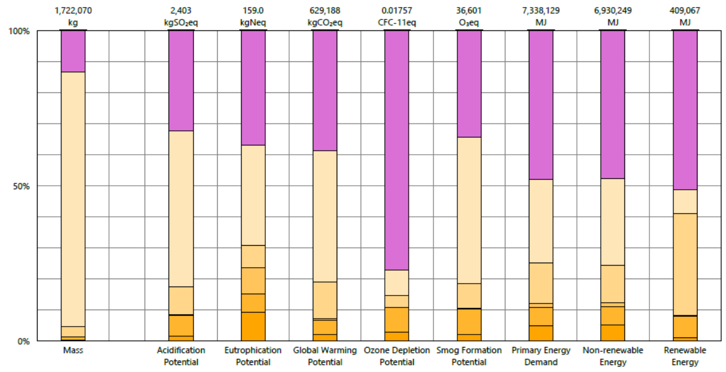
🟧 Cast-in-place concrete, slab on grade
🟨 Steel, form deck

Structure

🟪 Steel, M section
🟪 Steel, wide flange shape
🟪 Steel, WT section

19

Results per Revit Category, itemized by Material



Legend

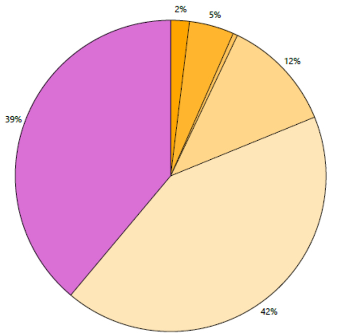
Floors

- ■ Expanded polystyrene (EPS), board
- ■ Galvanized steel form deck
- ■ Polyethelene sheet vapor barrier (HDPE)
- ■ Steel, reinforcing rod
- ■ Structural concrete, 3000 psi, 30% fly ash

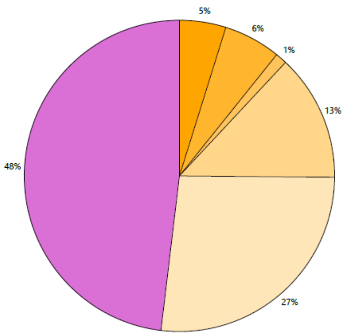
Structure

- ■ Hot rolled structural steel

Results per Revit Category, itemized by Material



Global Warming Potential



Primary Energy Demand

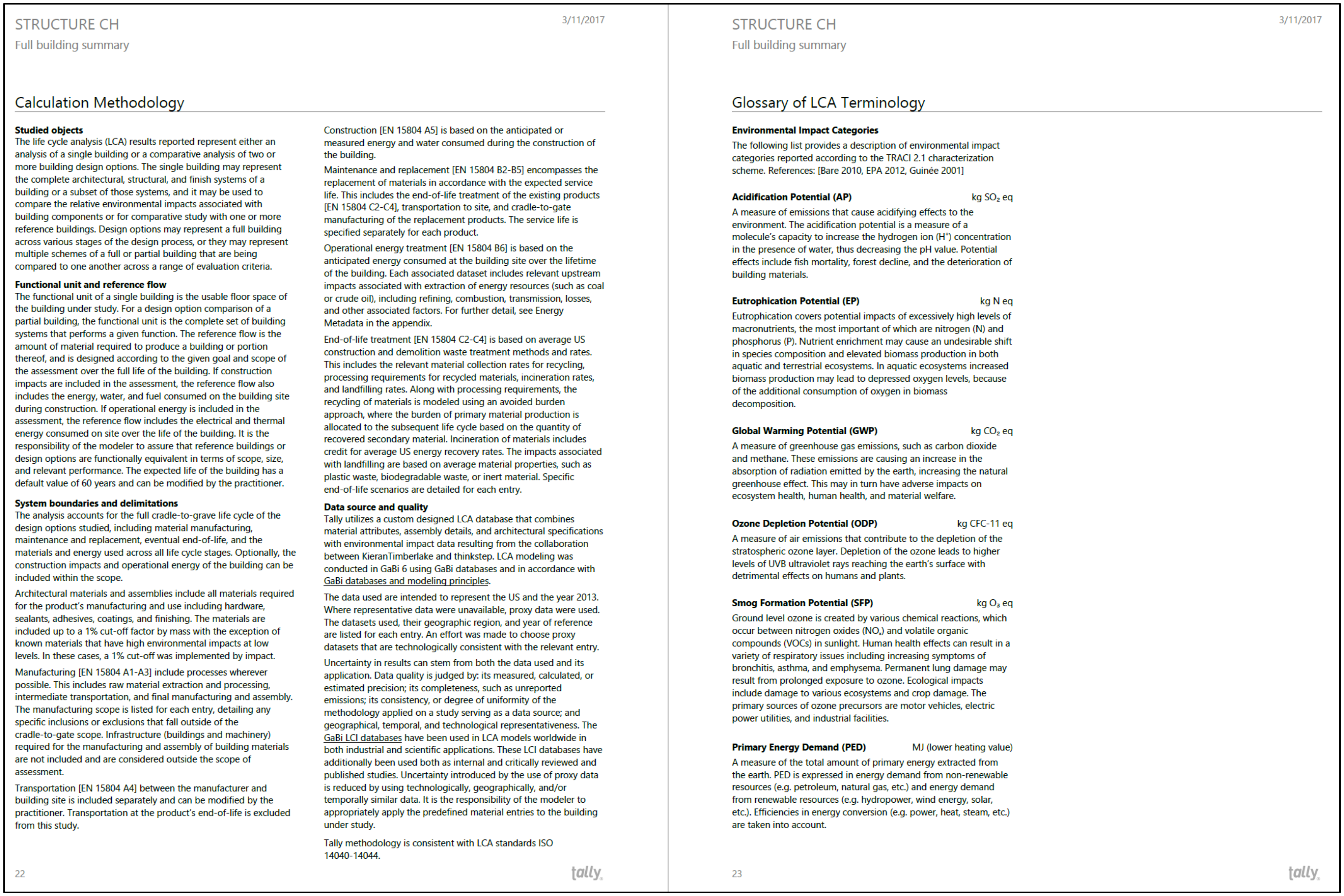
Legend

Floors

- ■ Expanded polystyrene (EPS), board
- ■ Galvanized steel form deck
- ■ Polyethelene sheet vapor barrier (HDPE)
- ■ Steel, reinforcing rod
- ■ Structural concrete, 3000 psi, 30% fly ash

Structure

- ■ Hot rolled structural steel



Calculation Methodology

Studied objects
The life cycle analysis (LCA) results reported represent either an analysis of a single building or a comparative analysis of two or more building design options. The single building may represent the complete architectural, structural, and finish systems of a building or a subset of those systems, and it may be used to compare the relative environmental impacts associated with building components or for comparative study with one or more reference buildings. Design options may represent a full building across various stages of the design process, or they may represent multiple schemes of a full or partial building that are being compared to one another across a range of evaluation criteria.

Functional unit and reference flow
The functional unit of a single building is the usable floor space of the building under study. For a design option comparison of a partial building, the functional unit is the complete set of building systems that performs a given function. The reference flow is the amount of material required to produce a building or portion thereof, and is designed according to the given goal and scope of the assessment over the full life of the building. If construction impacts are included in the assessment, the reference flow also includes the energy, water, and fuel consumed on the building site during construction. If operational energy is included in the assessment, the reference flow includes the electrical and thermal energy consumed on site over the life of the building. It is the responsibility of the modeler to assure that reference buildings or design options are functionally equivalent in terms of scope, size, and relevant performance. The expected life of the building has a default value of 60 years and can be modified by the practitioner.

System boundaries and delimitations
The analysis accounts for the full cradle-to-grave life cycle of the design options studied, including material manufacturing, maintenance and replacement, eventual end-of-life, and the materials and energy used across all life cycle stages. Optionally, the construction impacts and operational energy of the building can be included within the scope.

Architectural materials and assemblies include all materials required for the product's manufacturing and use including hardware, sealants, adhesives, coatings, and finishing. The materials are included up to a 1% cut-off factor by mass with the exception of known materials that have high environmental impacts at low levels. In these cases, a 1% cut-off was implemented by impact.

Manufacturing [EN 15804 A1-A3] include processes wherever possible. This includes raw material extraction and processing, intermediate transportation, and final manufacturing and assembly. The manufacturing scope is listed for each entry, detailing any specific inclusions or exclusions that fall outside of the cradle-to-gate scope. Infrastructure (buildings and machinery) required for the manufacturing and assembly of building materials are not included and are considered outside the scope of assessment.

Transportation [EN 15804 A4] between the manufacturer and building site is included separately and can be modified by the practitioner. Transportation at the product's end-of-life is excluded from this study.

Construction [EN 15804 A5] is based on the anticipated or measured energy and water consumed during the construction of the building.

Maintenance and replacement [EN 15804 B2-B5] encompasses the replacement of materials in accordance with the expected service life. This includes the end-of-life treatment of the existing products [EN 15804 C2-C4], transportation to site, and cradle-to-gate manufacturing of the replacement products. The service life is specified separately for each product.

Operational energy treatment [EN 15804 B6] is based on the anticipated energy consumed at the building site over the lifetime of the building. Each associated dataset includes relevant upstream impacts associated with extraction of energy resources (such as coal or crude oil), including refining, combustion, transmission, losses, and other associated factors. For further detail, see Energy Metadata in the appendix.

End-of-life treatment [EN 15804 C2-C4] is based on average US construction and demolition waste treatment methods and rates. This includes the relevant material collection rates for recycling, processing requirements for recycled materials, incineration rates, and landfilling rates. Along with processing requirements, the recycling of materials is modeled using an avoided burden approach, where the burden of primary material production is allocated to the subsequent life cycle based on the quantity of recovered secondary material. Incineration of materials includes credit for average US energy recovery rates. The impacts associated with landfilling are based on average material properties, such as plastic waste, biodegradable waste, or inert material. Specific end-of-life scenarios are detailed for each entry.

Data source and quality
Tally utilizes a custom designed LCA database that combines material attributes, assembly details, and architectural specifications with environmental impact data resulting from the collaboration between KieranTimberlake and thinkstep. LCA modeling was conducted in GaBi 6 using GaBi databases and in accordance with GaBi databases and modeling principles.

The data used are intended to represent the US and the year 2013. Where representative data were unavailable, proxy data were used. The datasets used, their geographic region, and year of reference are listed for each entry. An effort was made to choose proxy datasets that are technologically consistent with the relevant entry.

Uncertainty in results can stem from both the data used and its application. Data quality is judged by: its measured, calculated, or estimated precision; its completeness, such as unreported emissions; its consistency, or degree of uniformity of the methodology applied on a study serving as a data source; and geographical, temporal, and technological representativeness. The GaBi LCI databases have been used in LCA models worldwide in both industrial and scientific applications. These LCI databases have additionally been used both as internal and critically reviewed and published studies. Uncertainty introduced by the use of proxy data is reduced by using technologically, geographically, and/or temporally similar data. It is the responsibility of the modeler to appropriately apply the predefined material entries to the building under study.

Tally methodology is consistent with LCA standards ISO 14040-14044.

Glossary of LCA Terminology

Environmental Impact Categories
The following list provides a description of environmental impact categories reported according to the TRACI 2.1 characterization scheme. References: [Bare 2010, EPA 2012, Guinée 2001]

Acidification Potential (AP) kg SO_2 eq
A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline, and the deterioration of building materials.

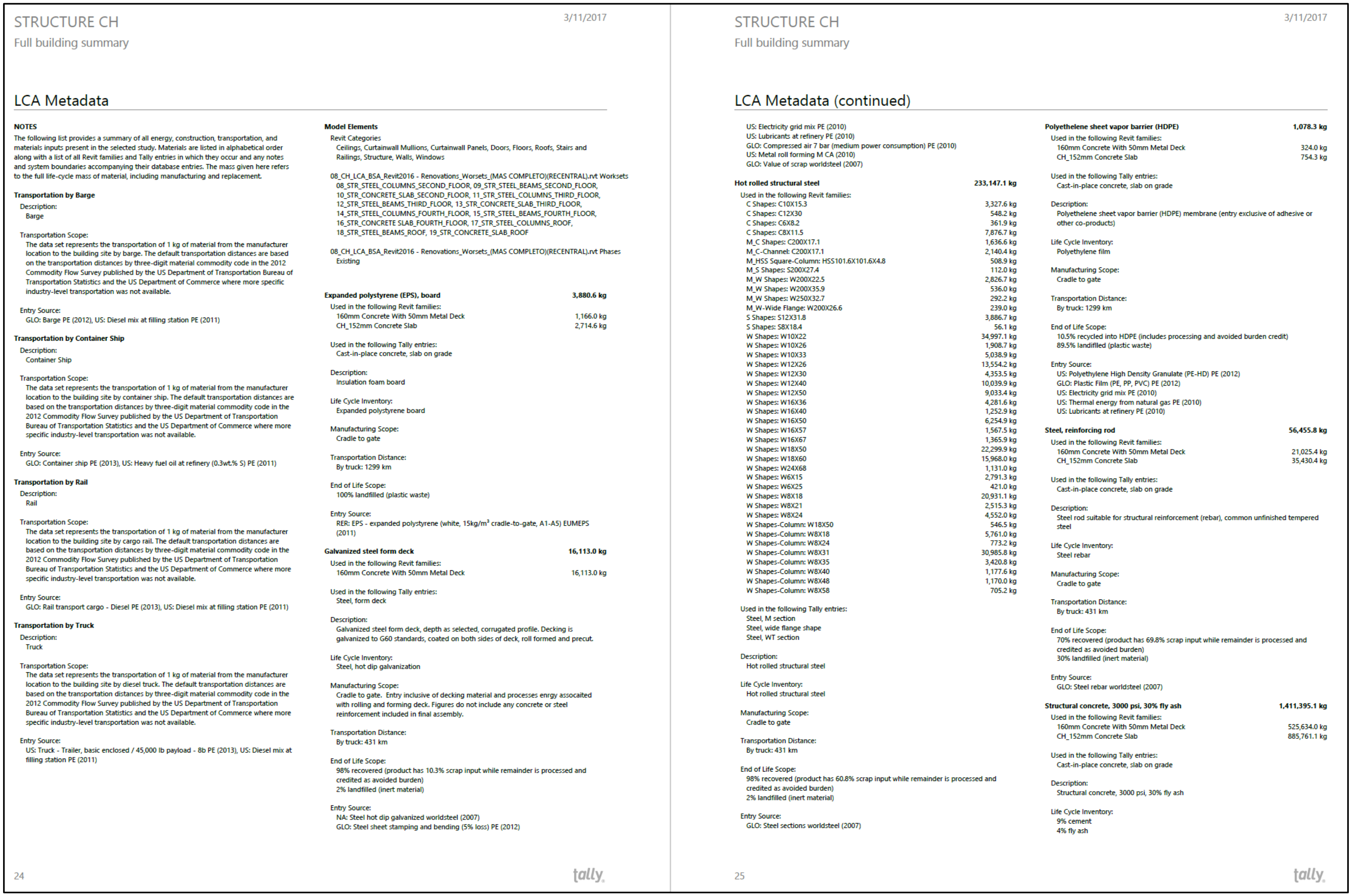
Eutrophication Potential (EP) kg N eq
Eutrophication covers potential impacts of excessively high levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.

Global Warming Potential (GWP) kg CO_2 eq
A measure of greenhouse gas emissions, such as carbon dioxide and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health, and material welfare.

Ozone Depletion Potential (ODP) kg CFC-11 eq
A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants.

Smog Formation Potential (SFP) kg O_3 eq
Ground level ozone is created by various chemical reactions, which occur between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in sunlight. Human health effects can result in a variety of respiratory issues including increasing symptoms of bronchitis, asthma, and emphysema. Permanent lung damage may result from prolonged exposure to ozone. Ecological impacts include damage to various ecosystems and crop damage. The primary sources of ozone precursors are motor vehicles, electric power utilities, and industrial facilities.

Primary Energy Demand (PED) MJ (lower heating value)
A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) and energy demand from renewable resources (e.g. hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.



STRUCTURE CH
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LCA Metadata

NOTES

The following list provides a summary of all energy, construction, transportation, and materials inputs present in the selected study. Materials are listed in alphabetical order along with a list of all Revit families and Tally entries in which they occur and any notes and system boundaries accompanying their database entries. The mass given here refers to the full life-cycle mass of material, including manufacturing and replacement.

Transportation by Barge

Description:
Barge

Transportation Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by barge. The default transportation distances are based on the transportation distances by three-digit material commodity code in the 2012 Commodity Flow Survey published by the US Department of Transportation Bureau of Transportation Statistics and the US Department of Commerce where more specific industry-level transportation was not available.

Entry Source:
GLO: Barge PE (2012), US: Diesel mix at filling station PE (2011)

Transportation by Container Ship

Description:
Container Ship

Transportation Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by container ship. The default transportation distances are based on the transportation distances by three-digit material commodity code in the 2012 Commodity Flow Survey published by the US Department of Transportation Bureau of Transportation Statistics and the US Department of Commerce where more specific industry-level transportation was not available.

Entry Source:
GLO: Container ship PE (2013), US: Heavy fuel oil at refinery (0.3wt.% S) PE (2011)

Transportation by Rail

Description:
Rail

Transportation Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by cargo rail. The default transportation distances are based on the transportation distances by three-digit material commodity code in the 2012 Commodity Flow Survey published by the US Department of Transportation Bureau of Transportation Statistics and the US Department of Commerce where more specific industry-level transportation was not available.

Entry Source:
GLO: Rail transport cargo - Diesel PE (2013), US: Diesel mix at filling station PE (2011)

Transportation by Truck

Description:
Truck

Transportation Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by diesel truck. The default transportation distances are based on the transportation distances by three-digit material commodity code in the 2012 Commodity Flow Survey published by the US Department of Transportation Bureau of Transportation Statistics and the US Department of Commerce where more specific industry-level transportation was not available.

Entry Source:
US: Truck - Trailer, basic enclosed / 45,000 lb payload - 8b PE (2013), US: Diesel mix at filling station PE (2011)

Model Elements

Revit Categories
Ceilings, Curtainwall Mullions, Curtainwall Panels, Doors, Floors, Roofs, Stairs and Railings, Structure, Walls, Windows

08_CH_LCA_BSA_Revit2016 - Renovations_Worsets_(MAS COMPLETO)(RECENTRAL).rvt Worksets
08_STR_STEEL_COLUMNS_SECOND_FLOOR, 09_STR_STEEL_BEAMS_SECOND_FLOOR, 10_STR_CONCRETE_SLAB_SECOND_FLOOR, 11_STR_STEEL_COLUMNS_THIRD_FLOOR, 12_STR_STEEL_BEAMS_THIRD_FLOOR, 13_STR_CONCRETE_SLAB_THIRD_FLOOR, 14_STR_STEEL_COLUMNS_FOURTH_FLOOR, 15_STR_STEEL_BEAMS_FOURTH_FLOOR, 16_STR_CONCRETE SLAB_FOURTH_FLOOR, 17_STR_STEEL_COLUMNS_ROOF, 18_STR_STEEL_BEAMS_ROOF, 19_STR_CONCRETE_SLAB_ROOF

08_CH_LCA_BSA_Revit2016 - Renovations_Worsets_(MAS COMPLETO)(RECENTRAL).rvt Phases
Existing

Expanded polystyrene (EPS), board	**3,880.6 kg**
Used in the following Revit families:	
160mm Concrete With 50mm Metal Deck	1,166.0 kg
CH_152mm Concrete Slab	2,714.6 kg

Used in the following Tally entries:
Cast-in-place concrete, slab on grade

Description:
Insulation foam board

Life Cycle Inventory:
Expanded polystyrene board

Manufacturing Scope:
Cradle to gate

Transportation Distance:
By truck: 1299 km

End of Life Scope:
100% landfilled (plastic waste)

Entry Source:
RER: EPS - expanded polystyrene (white, 15kg/m³ cradle-to-gate, A1-A5) EUMEPS (2011)

Galvanized steel form deck	**16,113.0 kg**
Used in the following Revit families:	
160mm Concrete With 50mm Metal Deck	16,113.0 kg

Used in the following Tally entries:
Steel, form deck

Description:
Galvanized steel form deck, depth as selected, corrugated profile. Decking is galvanized to G60 standards, coated on both sides of deck, roll formed and precut.

Life Cycle Inventory:
Steel, hot dip galvanization

Manufacturing Scope:
Cradle to gate. Entry inclusive of decking material and processes enrgy assocaited with rolling and forming deck. Figures do not include any concrete or steel reinforcement included in final assembly.

Transportation Distance:
By truck: 431 km

End of Life Scope:
98% recovered (product has 10.3% scrap input while remainder is processed and credited as avoided burden)
2% landfilled (inert material)

Entry Source:
NA: Steel hot dip galvanized worldsteel (2007)
GLO: Steel sheet stamping and bending (5% loss) PE (2012)

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LCA Metadata (continued)

US: Electricity grid mix PE (2010)
US: Lubricants at refinery PE (2010)
GLO: Compressed air 7 bar (medium power consumption) PE (2010)
US: Metal roll forming M CA (2010)
GLO: Value of scrap worldsteel (2007)

Hot rolled structural steel	**233,147.1 kg**
Used in the following Revit families:	
C Shapes: C10X15.3	3,327.6 kg
C Shapes: C12X30	548.2 kg
C Shapes: C6X8.2	361.9 kg
C Shapes: C8X11.5	7,876.7 kg
M_C Shapes: C200X17.1	1,636.6 kg
M_C-Channel: C200X17.1	2,140.4 kg
M_HSS Square-Column: HSS101.6X101.6X4.8	508.9 kg
M_S Shapes: S200X27.4	112.0 kg
M_W Shapes: W200X22.5	2,826.7 kg
M_W Shapes: W200X35.9	536.0 kg
M_W Shapes: W250X32.7	292.2 kg
M_W-Wide Flange: W200X26.6	239.0 kg
S Shapes: S12X31.8	3,886.7 kg
S Shapes: S8X18.4	56.1 kg
W Shapes: W10X22	34,997.1 kg
W Shapes: W10X26	1,908.7 kg
W Shapes: W10X33	5,038.9 kg
W Shapes: W12X26	13,554.2 kg
W Shapes: W12X30	4,353.5 kg
W Shapes: W12X40	10,039.9 kg
W Shapes: W12X50	9,033.4 kg
W Shapes: W16X36	4,281.6 kg
W Shapes: W16X40	1,252.9 kg
W Shapes: W16X50	6,254.9 kg
W Shapes: W16X57	1,567.5 kg
W Shapes: W16X67	1,365.9 kg
W Shapes: W18X50	22,299.9 kg
W Shapes: W18X60	15,968.0 kg
W Shapes: W24X68	1,131.0 kg
W Shapes: W6X15	2,791.3 kg
W Shapes: W6X25	421.0 kg
W Shapes: W8X18	20,931.1 kg
W Shapes: W8X21	2,515.3 kg
W Shapes: W8X24	4,552.0 kg
W Shapes-Column: W18X50	546.5 kg
W Shapes-Column: W8X18	5,761.0 kg
W Shapes-Column: W8X24	773.2 kg
W Shapes-Column: W8X31	30,985.8 kg
W Shapes-Column: W8X35	3,420.8 kg
W Shapes-Column: W8X40	1,177.6 kg
W Shapes-Column: W8X48	1,170.0 kg
W Shapes-Column: W8X58	705.2 kg

Used in the following Tally entries:
Steel, M section
Steel, wide flange shape
Steel, WT section

Description:
Hot rolled structural steel

Life Cycle Inventory:
Hot rolled structural steel

Manufacturing Scope:
Cradle to gate

Transportation Distance:
By truck: 431 km

End of Life Scope:
98% recovered (product has 60.8% scrap input while remainder is processed and credited as avoided burden)
2% landfilled (inert material)

Entry Source:
GLO: Steel sections worldsteel (2007)

Polyethelene sheet vapor barrier (HDPE)	**1,078.3 kg**
Used in the following Revit families:	
160mm Concrete With 50mm Metal Deck	324.0 kg
CH_152mm Concrete Slab	754.3 kg

Used in the following Tally entries:
Cast-in-place concrete, slab on grade

Description:
Polyethelene sheet vapor barrier (HDPE) membrane (entry exclusive of adhesive or other co-products)

Life Cycle Inventory:
Polyethylene film

Manufacturing Scope:
Cradle to gate

Transportation Distance:
By truck: 1299 km

End of Life Scope:
10.5% recycled into HDPE (includes processing and avoided burden credit)
89.5% landfilled (plastic waste)

Entry Source:
US: Polyethylene High Density Granulate (PE-HD) PE (2012)
GLO: Plastic Film (PE, PP, PVC) PE (2012)
US: Electricity grid mix PE (2010)
US: Thermal energy from natural gas PE (2010)
US: Lubricants at refinery PE (2010)

Steel, reinforcing rod	**56,455.8 kg**
Used in the following Revit families:	
160mm Concrete With 50mm Metal Deck	21,025.4 kg
CH_152mm Concrete Slab	35,430.4 kg

Used in the following Tally entries:
Cast-in-place concrete, slab on grade

Description:
Steel rod suitable for structural reinforcement (rebar), common unfinished tempered steel

Life Cycle Inventory:
Steel rebar

Manufacturing Scope:
Cradle to gate

Transportation Distance:
By truck: 431 km

End of Life Scope:
70% recovered (product has 69.8% scrap input while remainder is processed and credited as avoided burden)
30% landfilled (inert material)

Entry Source:
GLO: Steel rebar worldsteel (2007)

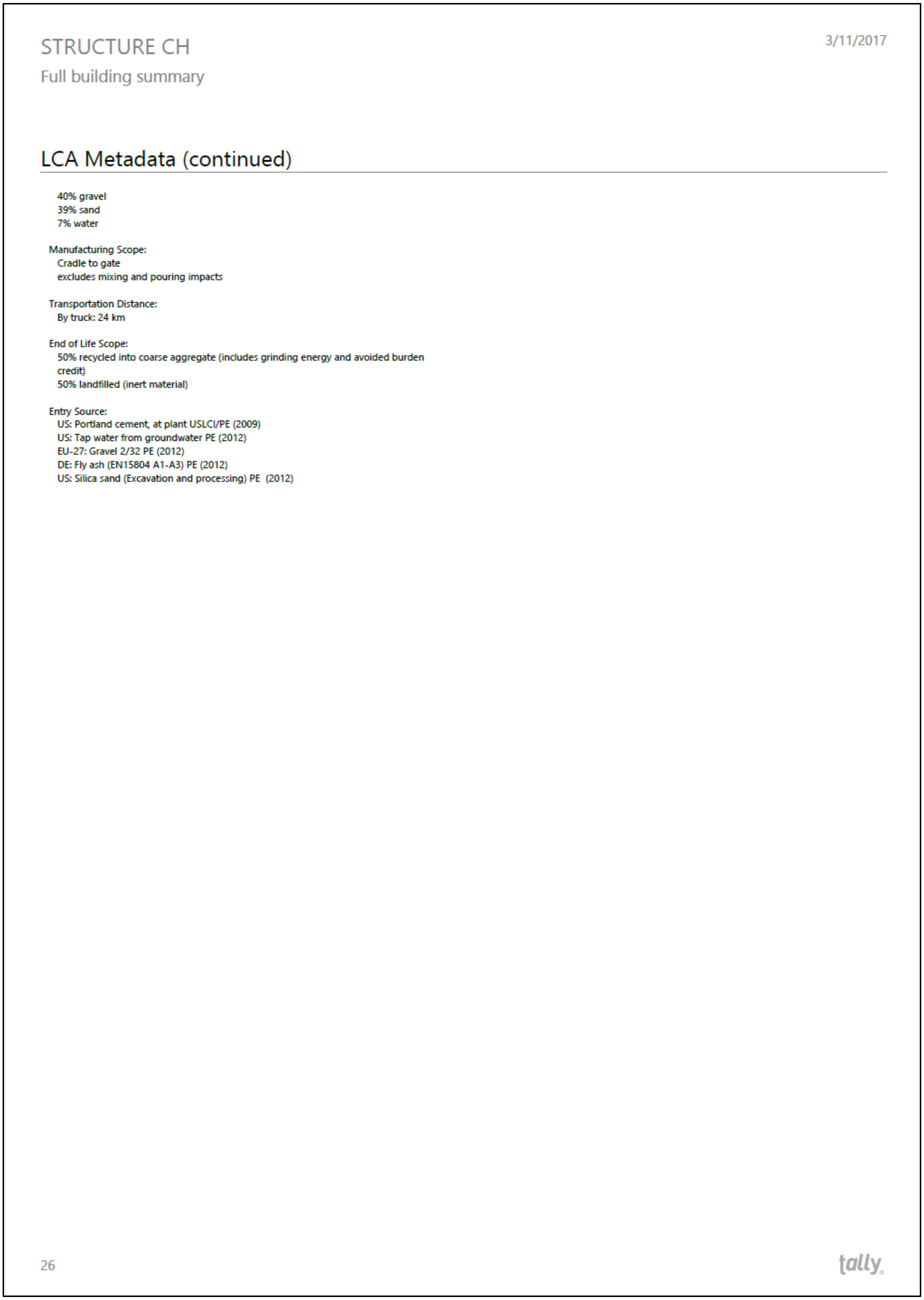
Structural concrete, 3000 psi, 30% fly ash	**1,411,395.1 kg**
Used in the following Revit families:	
160mm Concrete With 50mm Metal Deck	525,634.0 kg
CH_152mm Concrete Slab	885,761.1 kg

Used in the following Tally entries:
Cast-in-place concrete, slab on grade

Description:
Structural concrete, 3000 psi, 30% fly ash

Life Cycle Inventory:
9% cement
4% fly ash

25



LCA Metadata (continued)

40% gravel
39% sand
7% water

Manufacturing Scope:
Cradle to gate
excludes mixing and pouring impacts

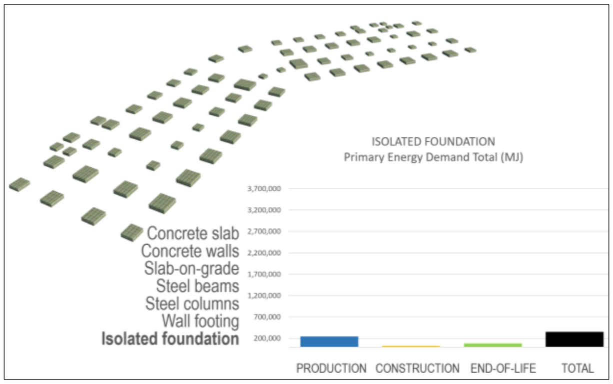
Transportation Distance:
By truck: 24 km

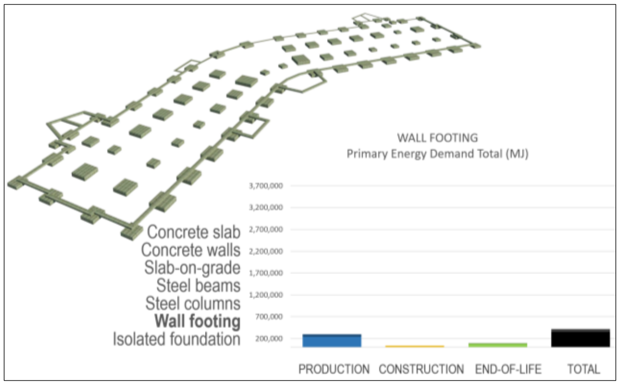
End of Life Scope:
50% recycled into coarse aggregate (includes grinding energy and avoided burden credit)
50% landfilled (inert material)

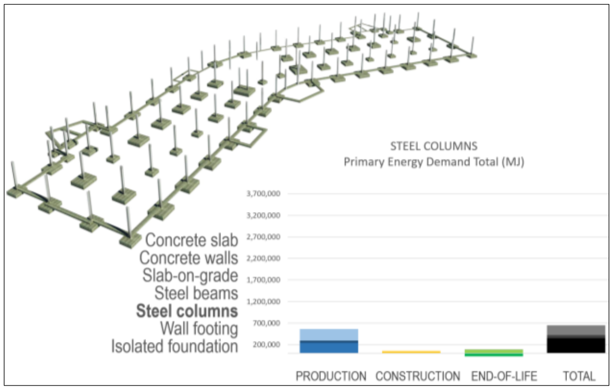
Entry Source:
US: Portland cement, at plant USLCI/PE (2009)
US: Tap water from groundwater PE (2012)
EU-27: Gravel 2/32 PE (2012)
DE: Fly ash (EN15804 A1-A3) PE (2012)
US: Silica sand (Excavation and processing) PE (2012)

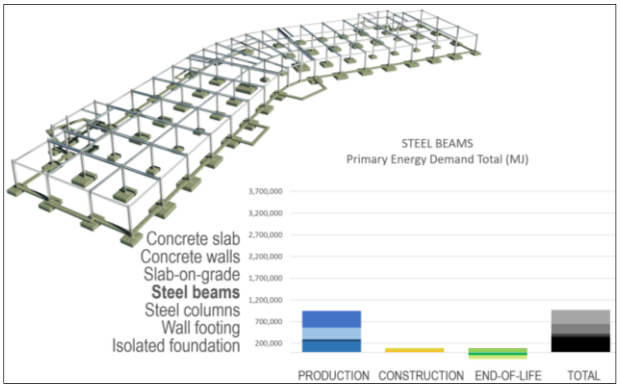
Appendix C: Waterloo county courthouse cenovations - BIM model subsets and partial LCA results

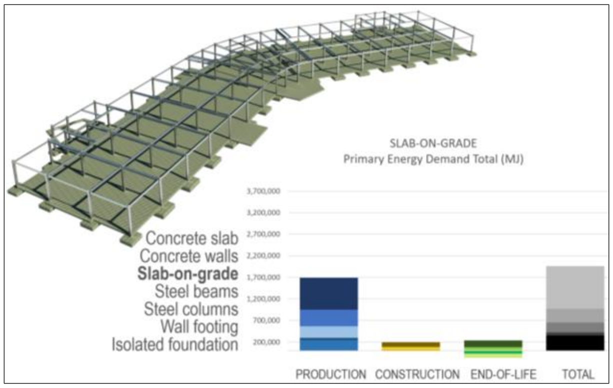
Scenario 1 Baseline: LCA of existing substructure and complete demolition

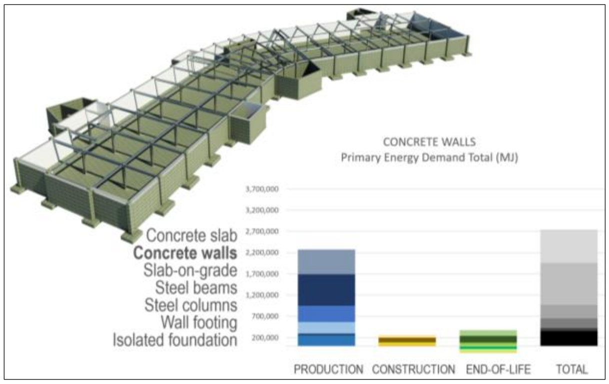


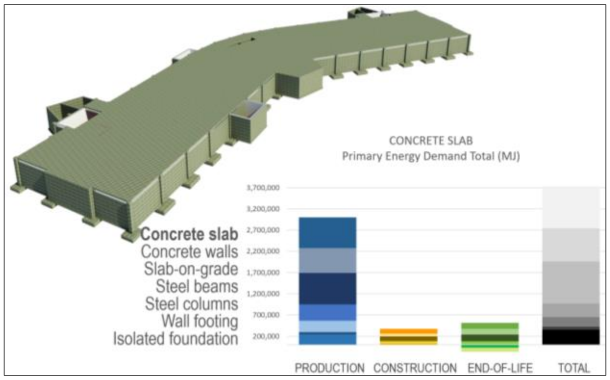


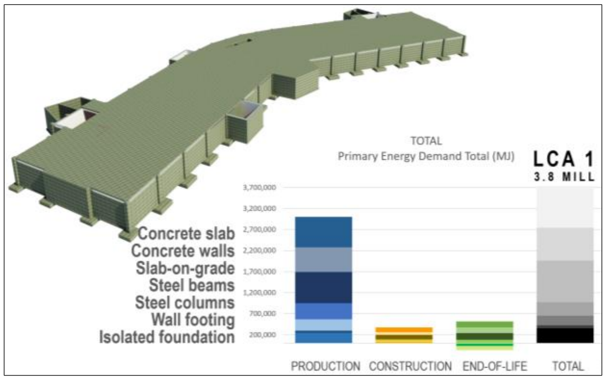




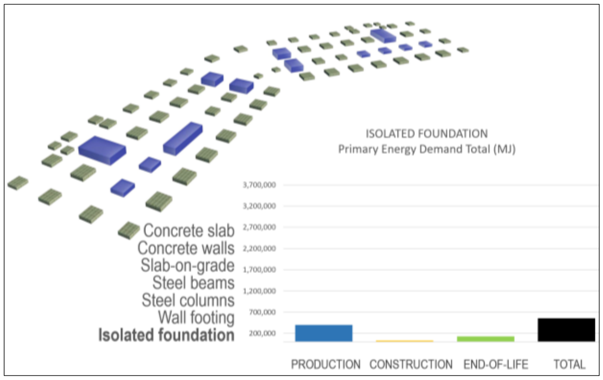


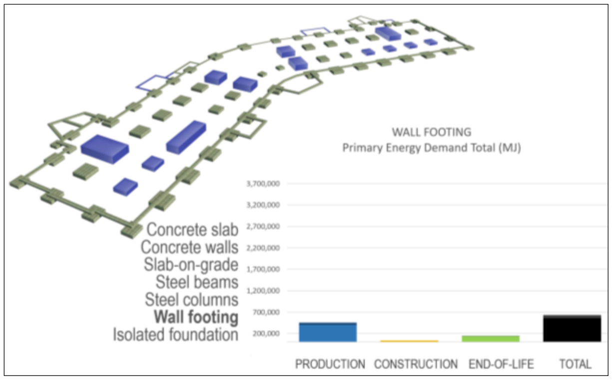


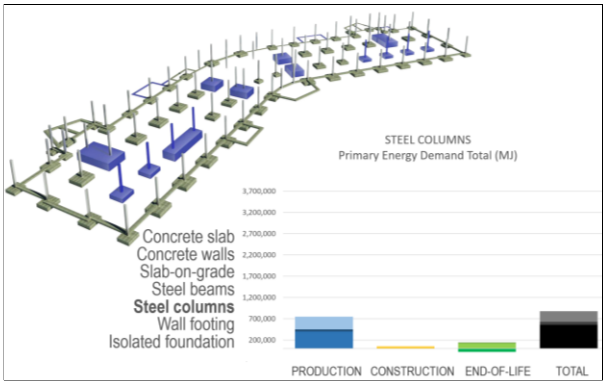


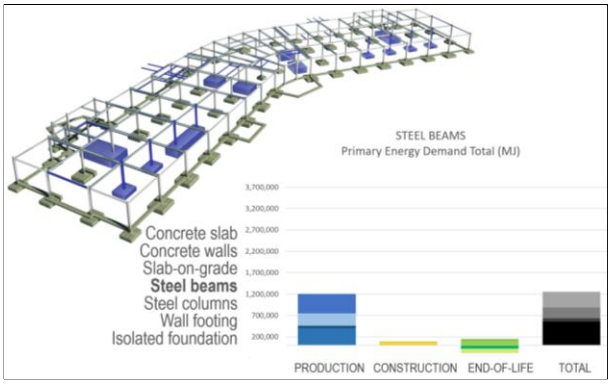


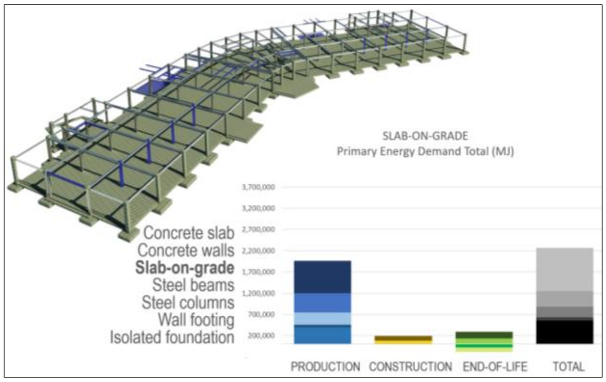
Scenario 1 Baseline: LCA of the new substructure design and complete demolition

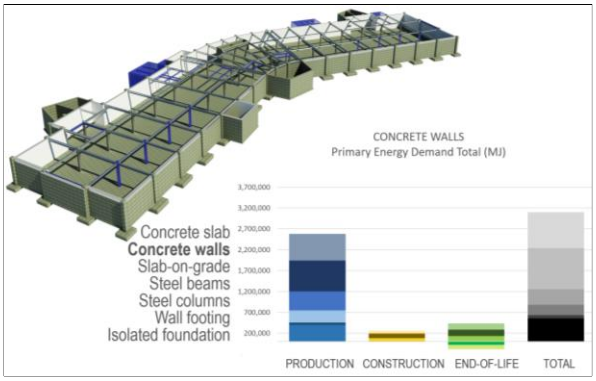


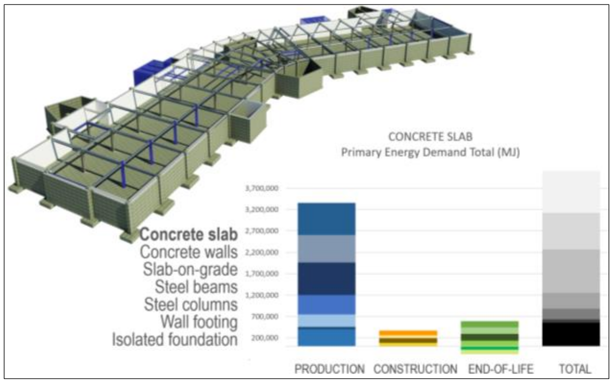


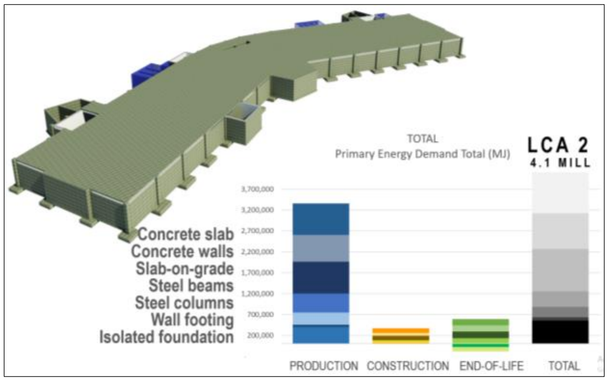




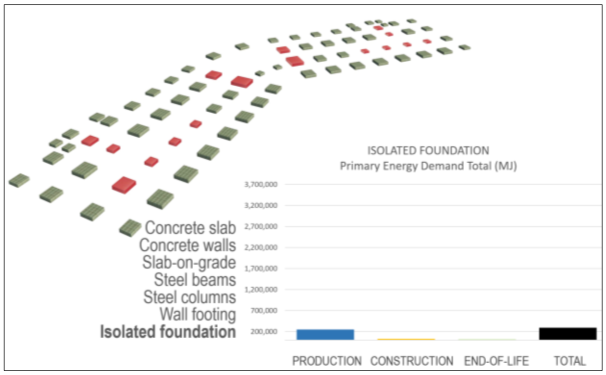


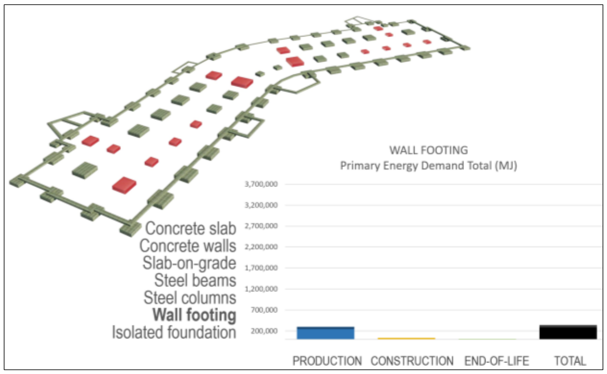


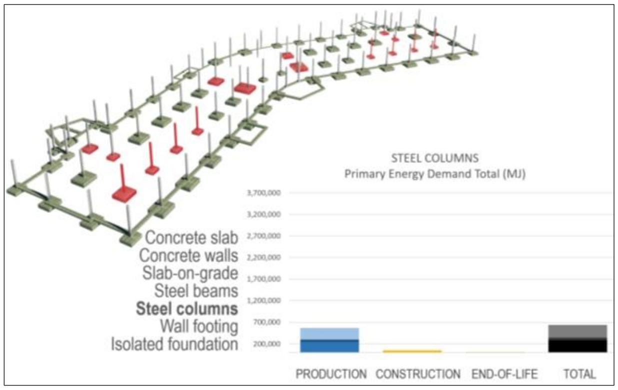


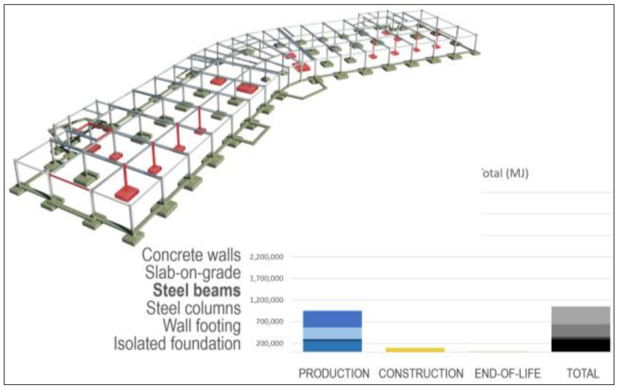


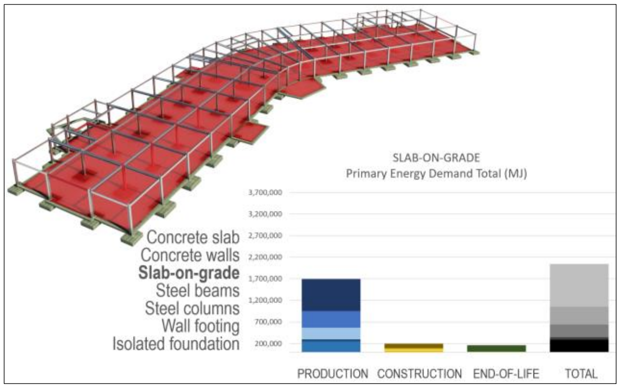
Scenario 2 Adaptive Reuse: LCA of existing substructure and selective demolition

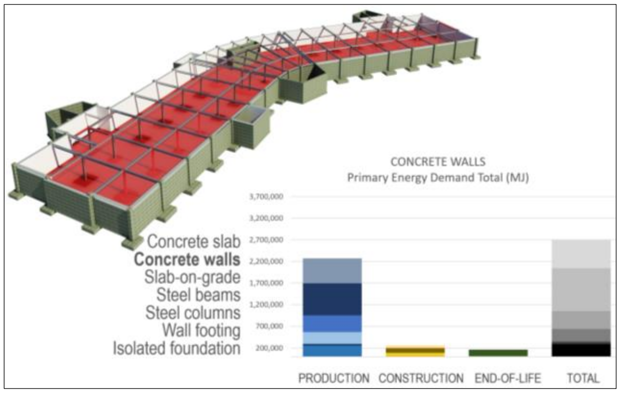


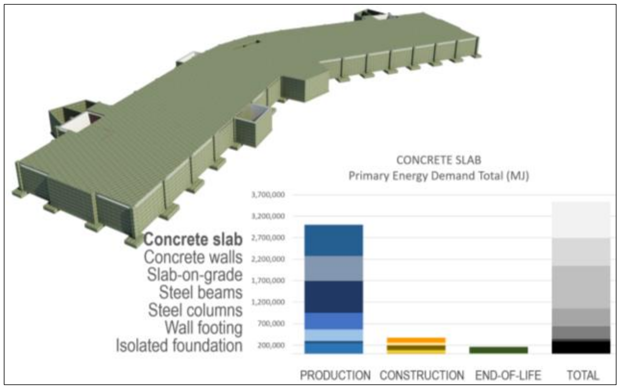


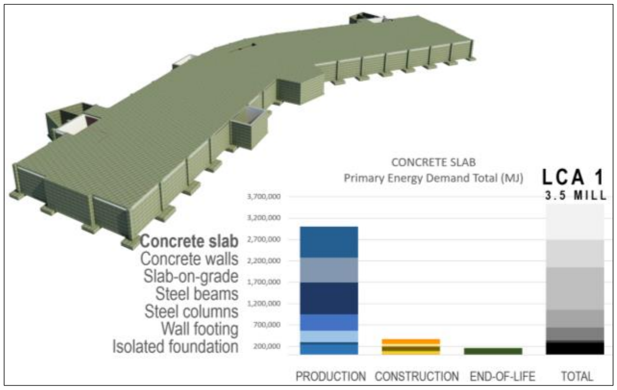

STEEL COLUMNS
Primary Energy Demand Total (MJ)
3,700,000
3,200,000
2,700,000
2,200,000
1,700,000
1,200,000
700,000
200,000
Concrete slab
Concrete walls
Slab-on-grade
Steel beams
Steel columns
Wall footing
Isolated foundation
PRODUCTION
CONSTRUCTION
END-OF-LIFE
TOTAL


'otal (MJ)
2,200,000
1,700,000
1,200,000
700,000
200,000
Concrete walls
Slab-on-grade
Steel beams
Steel columns
Wall footing
Isolated foundation
PRODUCTION
CONSTRUCTION
END-OF-LIFE
TOTAL

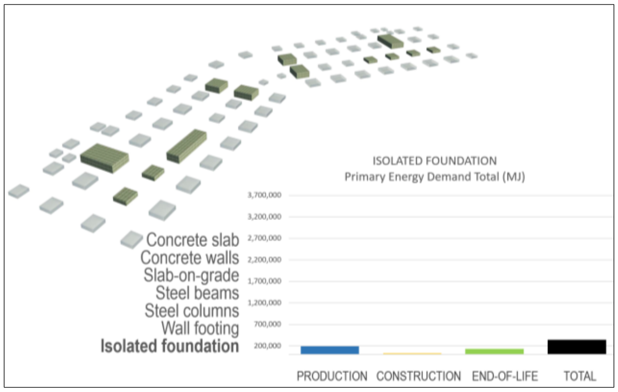

SLAB-ON-GRADE
Primary Energy Demand Total (MJ)
3,700,000
3,200,000
2,700,000
2,200,000
1,700,000
1,200,000
700,000
200,000
Concrete slab
Concrete walls
Slab-on-grade
Steel beams
Steel columns
Wall footing
Isolated foundation
PRODUCTION
CONSTRUCTION
END-OF-LIFE
TOTAL

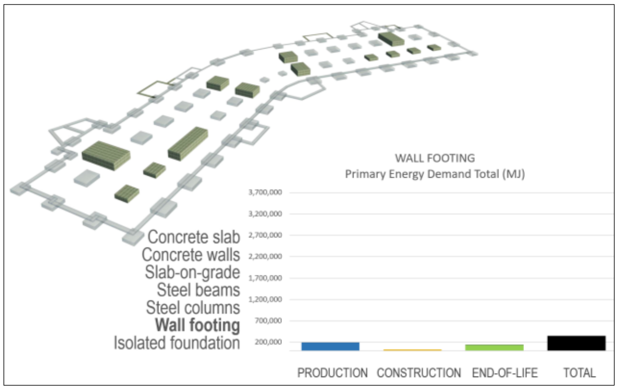

CONCRETE WALLS
Primary Energy Demand Total (MJ)
3,700,000
3,200,000
2,700,000
2,200,000
1,700,000
1,200,000
700,000
200,000
Concrete slab
Concrete walls
Slab-on-grade
Steel beams
Steel columns
Wall footing
Isolated foundation
PRODUCTION
CONSTRUCTION
END-OF-LIFE
TOTAL

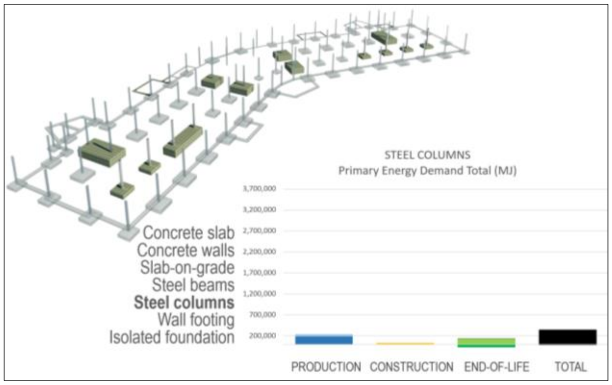

CONCRETE SLAB
Primary Energy Demand Total (MJ)
3,700,000
3,200,000
2,700,000
2,200,000
1,700,000
1,200,000
700,000
200,000
Concrete slab
Concrete walls
Slab-on-grade
Steel beams
Steel columns
Wall footing
Isolated foundation
PRODUCTION
CONSTRUCTION
END-OF-LIFE
TOTAL

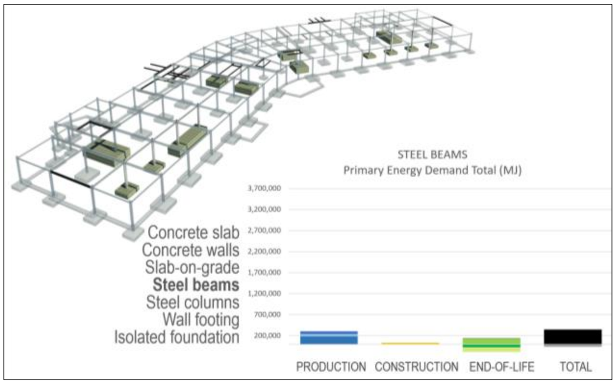

CONCRETE SLAB
Primary Energy Demand Total (MJ)
LCA 1
3.5 MILL
3,700,000
3,200,000
2,700,000
2,200,000
1,700,000
1,200,000
700,000
200,000
Concrete slab
Concrete walls
Slab-on-grade
Steel beams
Steel columns
Wall footing
Isolated foundation
PRODUCTION
CONSTRUCTION
END-OF-LIFE
TOTAL

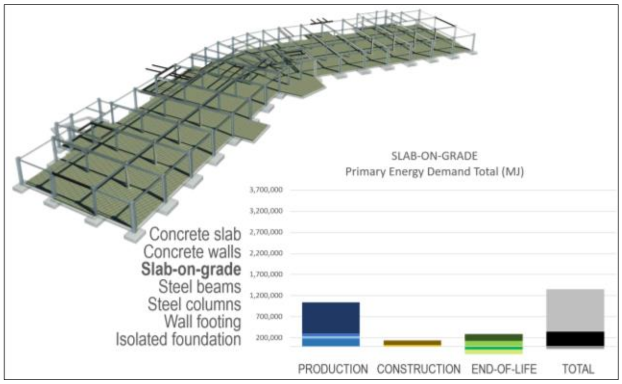
Scenario 2 Adaptive Reuse: LCA of the redeveloped substructure and complete demolition

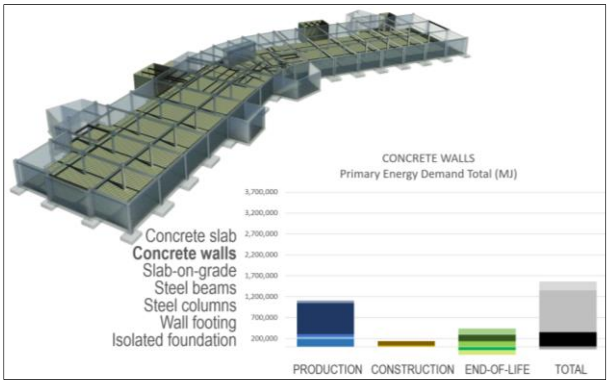


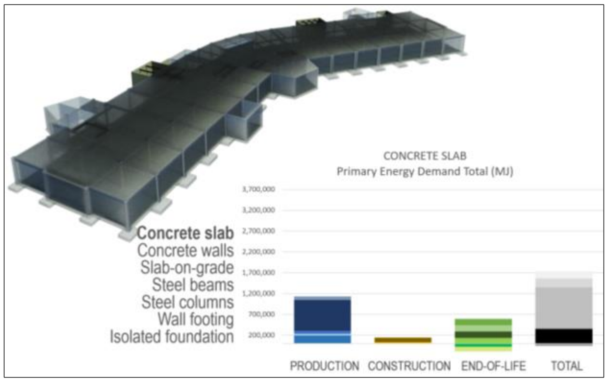


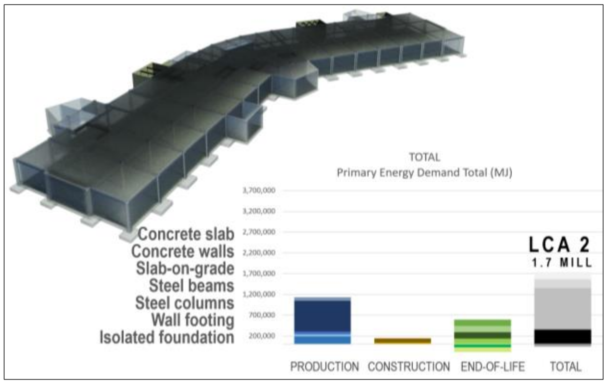




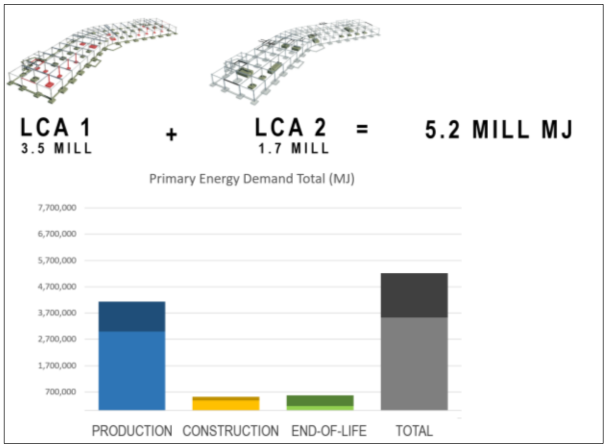


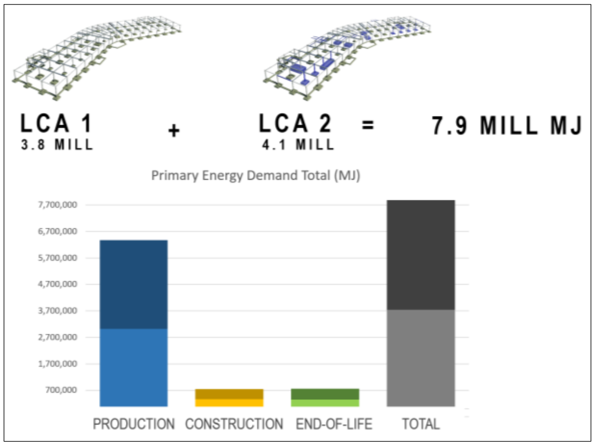


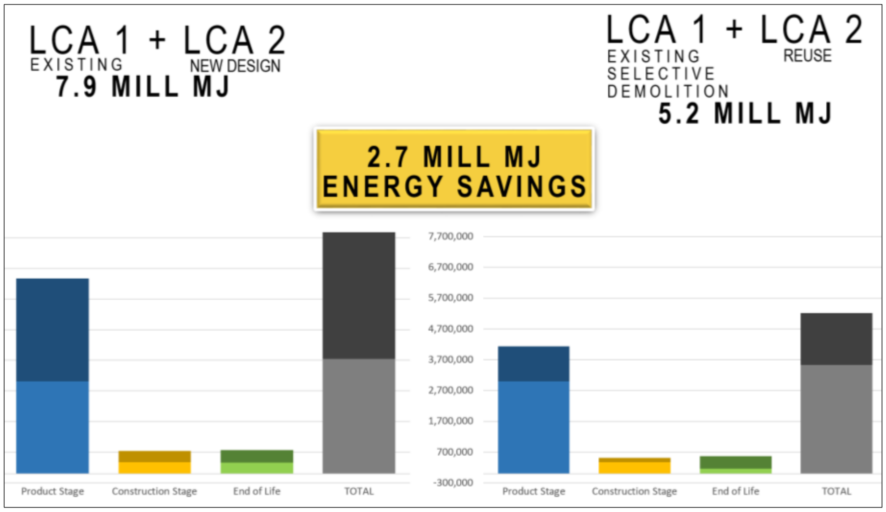




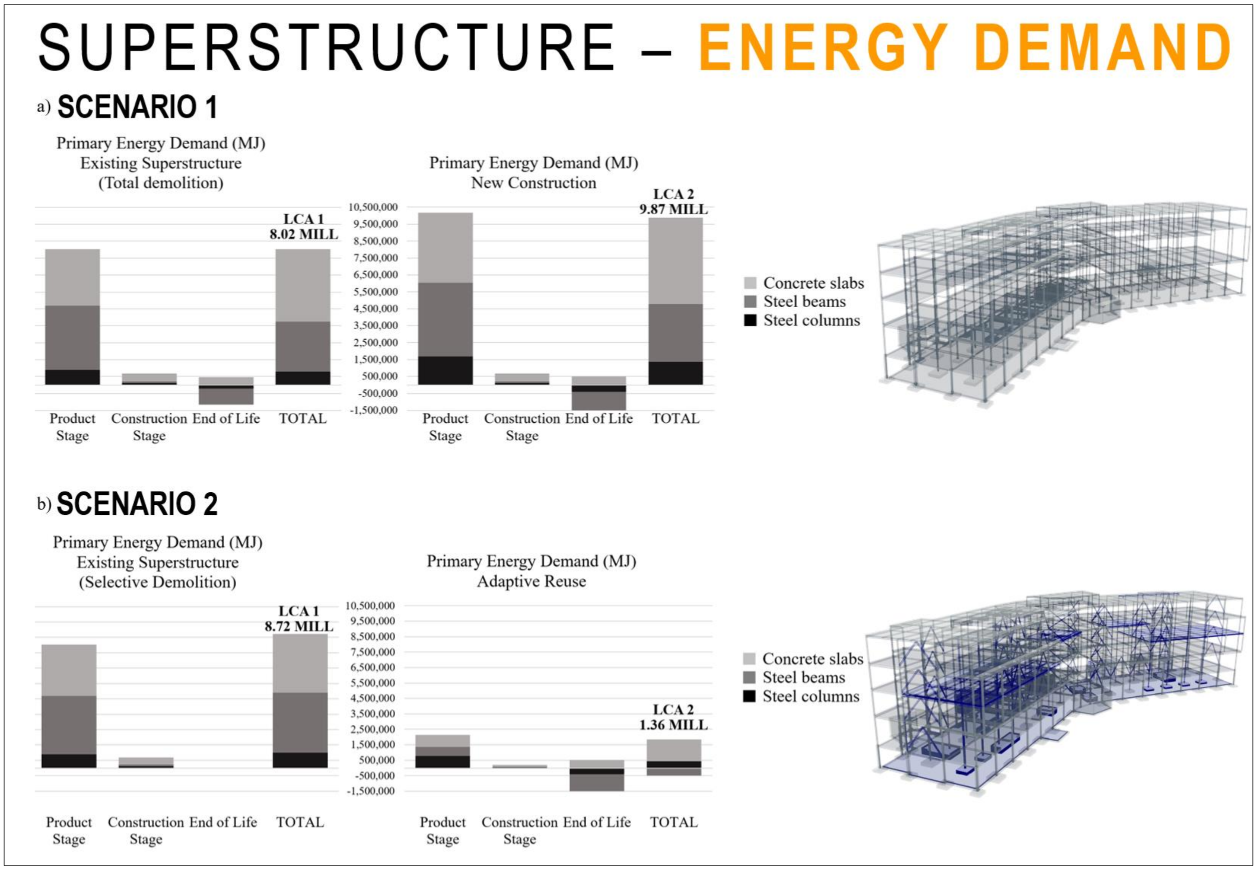
Final comparison - Substructure:







Final comparison - Superstructure:



Appendix D: Disassembly sequence planning algorithms

Algorithm 5-1: Algorithm for creating a combined matrix MF-HC for the first expert rule

```
sizeMF=size(MF);
sizeHM=size(HM);
sizeHM_COMPONENT_UNDER_STUDY=size(HM_COMPONENT_UNDER_STUDY);
sizeLM=size(LM);
sizeMF_FASTENER_UNDER_STUDY=size(MF_FASTENER_UNDER_STUDY);
MF_HM = cell(sizeMF);

for i=1:sizeMF(1,1)
    sizeHM_i=size(HM{i,1});
    if sizeHM_i(1,2) == 1
        for n=1:sizeHM_COMPONENT_UNDER_STUDY(1,1)
            if HM{i,1} == HM_COMPONENT_UNDER_STUDY{n,1}
                FINAL_VALUE_MF_HM = HM{n,1};
                for k=1:sizeMF(1,1)
                    if LM{i,1} == MF_FASTENER_UNDER_STUDY{k,1}
                        MF_HM{k,1}  = FINAL_VALUE_MF_HM + MF{i,1};
                    else
                    end
                end
            else
                if HM{i,1} == 0
                    MF_HM{i,1} = MF{i,1};
                else
                end
            end
        end
    else
        HM_i = HM{i,1};
        sizeLM_i=size(LM{i,1});
        for n=1:sizeHM_COMPONENT_UNDER_STUDY(1,1)
            for m=1:sizeHM_i(1,2)
                if HM_i(1,m) == HM_COMPONENT_UNDER_STUDY{n,1}
                    FINAL_VALUE_MF_HM = HM{n,1};
                    for k=1:sizeMF(1,1)
                        LM_i=LM{i,1};
                        if LM_i(1,m) == MF_FASTENER_UNDER_STUDY{k,1}
                            MF_HM{k,1}  = FINAL_VALUE_MF_HM + MF{i,1};
                        else
                        end
                    end
                else
                end
            end
        end
    end
end
```

Algorithm 5-2: Algorithm for creating an EVM matrix for the second expert rule

```
%It generates the EVM - Environmental Value Matrix (CO2eq)
EVM_VALUES = [805.43 805.43 805.43 228.94 202.74 202.74 174.34 485.25 12.47
21.93];
EVM = zeros(sizeMC);
for i=1:sizeMC(1,1)
    for j=1:sizeMC(1,2)
        sizeMCn_m=size(MC{i,j});
        for n=1:sizeMCn_m(1,2)
            for k=1:sizeCOMPONENTS(1,2)
               if MC{i,j}(1,n) == COMPONENTS(1,k)
                  EVM(i,j) = EVM(i,j)+EVM_VALUES(1,k);
               end
            end
        end
    end
end
```

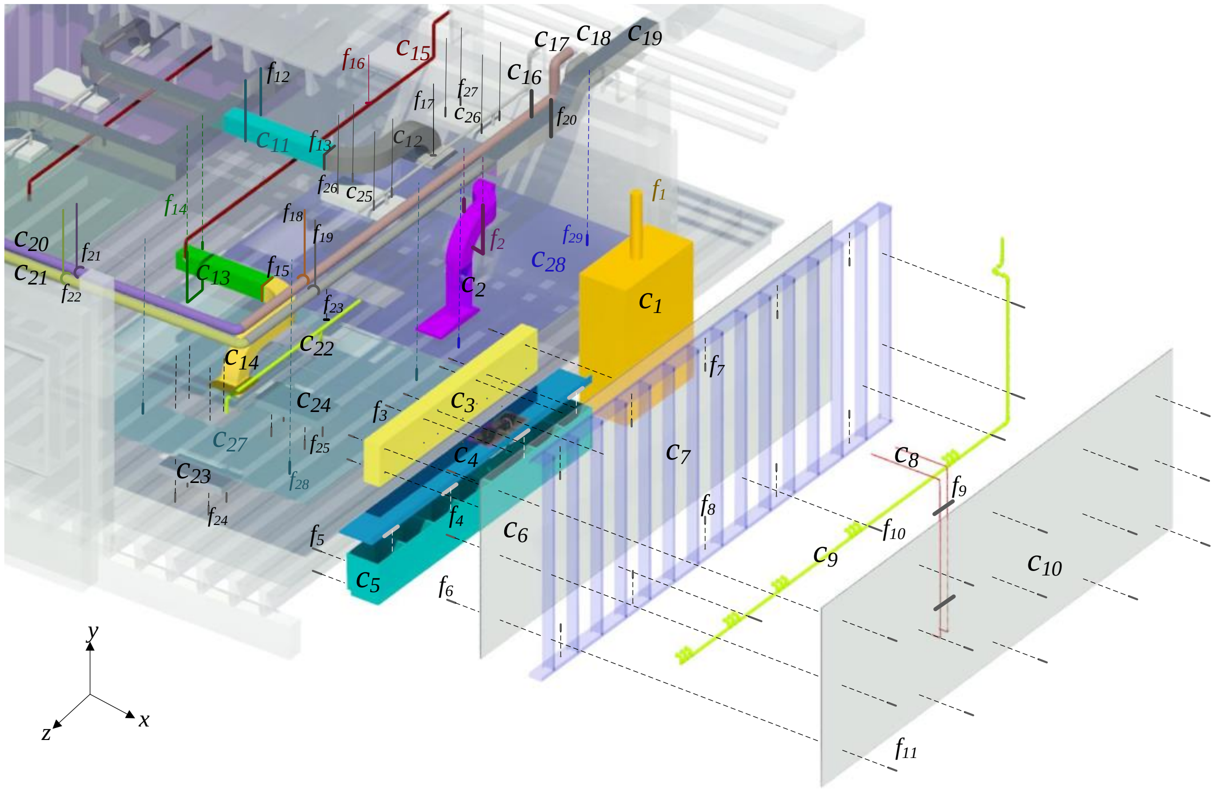
Algorithm 5-3: Workflow and algorithms for creating an optimized disassembly sequence planning for building assemblages

SDPB Function “extraction_vector_n” for choosing the best extraction direction per building component

```
function
[COUNTER,C_objective,EXTRACTION_VECTOR,EXTRACTION_ELEMENTS_UNDER_STUDY,EXTRAC
TION_ELEMENTS_UNDER_STUDY_WITHOUT_QUEUE,QUEUE_VECTOR,FINAL_EXTRACCTION_VECTOR
] = ...
    extraction_vector_n
(COUNTER,MC,HM_COMPONENT_UNDER_STUDY,C_objective,HM,COMPONENTS,EVM,MF_FASTENE
R_UNDER_STUDY,MF_HM,QUEUE_VECTOR,EXTRACTION_ELEMENTS_UNDER_STUDY,EXTRACTION_V
ECTOR,EXTRACTION_ELEMENTS_UNDER_STUDY_WITHOUT_QUEUE,FINAL_EXTRACCTION_VECTOR)

sizeMC=size(MC);
if find([HM_COMPONENT_UNDER_STUDY{:}]==C_objective) ~= 0
    ROW_INDEX_COMPONENT=find([HM_COMPONENT_UNDER_STUDY{:}] == C_objective);
    sizeHM_objective=size(HM{ROW_INDEX_COMPONENT,1});
    HM_VECTOR_OBJECTIVE=(HM{ROW_INDEX_COMPONENT,1});
    COMPONENT_COUNTER=0;
    if HM{ROW_INDEX_COMPONENT,1} ~= 0
        for i=1:sizeMC(1,2);
            COMPONENT_COUNTER=0;
            VECTOR_UNDER_STUDY=(MC{ROW_INDEX_COMPONENT,i});
            sizeMC_VECTOR_UNDER_STUDY=size(MC{ROW_INDEX_COMPONENT,i});
            for j=1:sizeMC_VECTOR_UNDER_STUDY(1,2)
                for k=1:sizeHM_objective(1,2)
                    if VECTOR_UNDER_STUDY(1,j) == HM_VECTOR_OBJECTIVE(1,k)
                        COMPONENT_COUNTER = COMPONENT_COUNTER+1;
                        RECORD_NUMBER_OF_HOSTED_COMP(1,i) =
COMPONENT_COUNTER;
                    else
                    end
                end
            end
        end
        [maxVal, position] = max(RECORD_NUMBER_OF_HOSTED_COMP);
        EXTRACTION_DIRECTION = position;
    else
        sizeCOMPONENTS=size(COMPONENTS);
        for i=1:sizeCOMPONENTS(1,2)
            if COMPONENTS(1,i) == C_objective
                EVM_ROW_UNDER_STUDY = EVM(i,:);
                [minVal, position] = min(EVM_ROW_UNDER_STUDY);
                EXTRACTION_DIRECTION = position;
                ROW_INDEX_COMPONENT = i;
            else
            end
        end
    end
    EXTRACTION_ELEMENTS_UNDER_STUDY =
MC{ROW_INDEX_COMPONENT,EXTRACTION_DIRECTION};
    EXTRACTION_VECTOR = [C_objective,EXTRACTION_ELEMENTS_UNDER_STUDY];
```

```
size_EXTRACTION_ELEMENTS_UNDER_STUDY=size(EXTRACTION_ELEMENTS_UNDER_STUDY);
    QUEUE_VECTOR = [];
    for i=1:size_EXTRACTION_ELEMENTS_UNDER_STUDY(1,2)
        ROW_INDEX_FASTENER=find([MF_FASTENER_UNDER_STUDY{:}] ==
EXTRACTION_ELEMENTS_UNDER_STUDY(1,i));
        if ROW_INDEX_FASTENER~= 0
            QUEUE_VECTOR = union(QUEUE_VECTOR,MF_HM{ROW_INDEX_FASTENER,1});
        else
        end
    end
    QUEUE_VECTOR = transpose(QUEUE_VECTOR);
    tf = ismember(EXTRACTION_ELEMENTS_UNDER_STUDY,QUEUE_VECTOR);
    EXTRACTION_ELEMENTS_UNDER_STUDY_WITHOUT_QUEUE =
EXTRACTION_ELEMENTS_UNDER_STUDY(~tf);

size_EXTRACTION_ELEMENTS_UNDER_STUDY_WITHOUT_QUEUE=size(EXTRACTION_ELEMENTS_U
NDER_STUDY_WITHOUT_QUEUE);
    FINAL_EXTRACCTION_VECTOR =
[C_objective,EXTRACTION_ELEMENTS_UNDER_STUDY_WITHOUT_QUEUE];
    size_FINAL_EXTRACCTION_VECTOR=size(FINAL_EXTRACCTION_VECTOR);
    C_objective=EXTRACTION_ELEMENTS_UNDER_STUDY_WITHOUT_QUEUE(1,COUNTER);
    COUNTER=COUNTER+1;
else
    F_objective=C_objective;

ROW_INDEX_FASTENER_UNDER_ANALYSIS=find([MF_FASTENER_UNDER_STUDY{:}]==F_object
ive);
    if QUEUE_VECTOR ~= 0
        tf =
ismember(MF_HM{ROW_INDEX_FASTENER_UNDER_ANALYSIS,1},QUEUE_VECTOR);
        QUEUE_VECTOR = EXTRACTION_ELEMENTS_UNDER_STUDY(~tf);
    end

EXTRACTION_ELEMENTS_UNDER_STUDY_WITHOUT_QUEUE=MF_HM{ROW_INDEX_FASTENER_UNDER_
ANALYSIS,1};
    C_objective=F_objective;
    size_FINAL_EXTRACCTION_VECTOR=size(FINAL_EXTRACCTION_VECTOR);
    if size_FINAL_EXTRACCTION_VECTOR(1,2) > COUNTER
        C_objective=EXTRACTION_ELEMENTS_UNDER_STUDY(1,COUNTER);
    end
    COUNTER=COUNTER+1;
end
end
```

Example: Building model under study



Input data for the building model under study

```
%Initial Matrices - Manual input (NOTE: "ground" represents the "limits of
design")
function [OBJ_DISASSEMBY_VECTOR,EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR] =
extraction_cn_multitarget ()
clc
clear
syms c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c16 c17 c18 c19
c20 c21 c22 c23 c24 c25 c26 c27 c28 cx cy cz cw f1 f2 f3 f4 f5 f6 f7 f8 f9
f10 f11 f12 f13 f_14 f15 f16 f17 f18 f19 f20 f21 f22 f23 f24 f25 f26 f27 f28
f29 ground roof demolition disassembly;

%MC- Motion Constraint Matrix
MC1_1 = [f1,c6];
MC1_2 = [f1,c28];
MC1_3 = [f1,ground];
MC1_4 = [f1,ground];

MC2_1 = [f2,c6];
MC2_2 = [f2,c28];
MC2_3 = [f2,ground];
MC2_4 = [f2,c1];

MC3_1 = [f3,c6];
```

```
MC3_2 = [f3];
MC3_3 = [f3,ground];
MC3_4 = [f3];

MC4_1 = [f4,c6];
MC4_2 = [f4];
MC4_3 = [f4];
MC4_4 = [f4,c5];

MC5_1 = [f5,c6];
MC5_2 = [f5];
MC5_3 = [f5,c4];
MC5_4 = [f5,ground];

MC6_1 = [f6,c7];
MC6_2 = [f6,c1,c2,c3,c4,c5];
MC6_3 = [f6,ground];
MC6_4 = [f6,ground];

MC7_1 = [f7,f8,c9];
MC7_2 = [f7,f8,c6];
MC7_3 = [f7,f8,ground];
MC7_4 = [f7,f8,ground];

MC8_1 = [f9,c10];
MC8_2 = [f9,c9];
MC8_3 = [f9,ground];
MC8_4 = [f9,ground];

MC9_1 = [f10,c8];
MC9_2 = [f10,c7];
MC9_3 = [f10,ground];
MC9_4 = [f10,ground];

MC10_1 = [f11];
MC10_2 = [f11,c8];
MC10_3 = [f11,ground];
MC10_4 = [f11,ground];

MC11_1 = [f12,c12];
MC11_2 = [f12,ground];
MC11_3 = [f12,ground];
MC11_4 = [f12,c15,c28];

MC12_1 = [f13,c16,c17,c18,c28];
MC12_2 = [f13,c11,c15,c28];
MC12_3 = [f13,ground];
MC12_4 = [f13,c25,c28];

MC13_1 = [f_14,c14,c22];
MC13_2 = [f_14,ground];
MC13_3 = [f_14,ground];
MC13_4 = [f_14,c15,c27];

MC14_1 = [f15,c17,c18,c22,c28];
MC14_2 = [f15,c13,c15,c28];
MC14_3 = [f15,ground];
```

```
MC14_4 = [f15,c24,c27];

MC15_1 = [f16];
MC15_2 = [f16];
MC15_3 = [f16,c11,c13,ground];
MC15_4 = [f16,c27,c28];

MC16_1 = [f17];
MC16_2 = [f17];
MC16_3 = [f17,ground];
MC16_4 = [f17,c25,c26,c28];

MC17_1 = [f18,c2,c8,c18];
MC17_2 = [f18,c12,c14,c16,c22];
MC17_3 = [f18,ground];
MC17_4 = [f18,c27,c28];

MC18_1 = [f19,c8];
MC18_2 = [f19,c12,c14,c16,c17,c22];
MC18_3 = [f19,ground];
MC18_4 = [f19,c27,c28];

MC19_1 = [f20,c6];
MC19_2 = [f20,c16,c17,c18];
MC19_3 = [f20,ground];
MC19_4 = [f20,c1,c28];

MC20_1 = [f21,c7];
MC20_2 = [f21,ground];
MC20_3 = [f21,ground];
MC20_4 = [f21,c27];

MC21_1 = [f22,c7];
MC21_2 = [f22,ground];
MC21_3 = [f22,ground];
MC21_4 = [f22,c27];

MC22_1 = [f23];
MC22_2 = [f23,c14];
MC22_3 = [f23,ground];
MC22_4 = [f23,c23,c24,c27];

MC23_1 = [f24,c7];
MC23_2 = [f24,c27];
MC23_3 = [f24,ground];
MC23_4 = [f24];

MC24_1 = [f25,c7];
MC24_2 = [f25,c27];
MC24_3 = [f25,ground];
MC24_4 = [f25];

MC25_1 = [f26,c28];
MC25_2 = [f26,c28];
MC25_3 = [f26,ground];
MC25_4 = [f26];
```

```
MC26_1 = [f27,c28];
MC26_2 = [f27,c28];
MC26_3 = [f27,ground];
MC26_4 = [f27];

MC27_1 = [f28,c7,c14,c23,c24];
MC27_2 = [f28,c14,c23,c24,ground];
MC27_3 = [f28,c13,c14,c15,c17,c18,c22,ground];
MC27_4 = [f28];

MC28_1 = [f29,c1,c2,c7,c12,c25,c26];
MC28_2 = [f29,c12,c25,c26,ground];
MC28_3 = [f29,c11,c12,c15,c16,c17,c18,c19,ground];
MC28_4 = [f29];

MC={MC1_1,MC1_2,MC1_3,MC1_4;...
    MC2_1,MC2_2,MC2_3,MC2_4;...
    MC3_1,MC3_2,MC3_3,MC3_4;...
    MC4_1,MC4_2,MC4_3,MC4_4;...
    MC5_1,MC5_2,MC5_3,MC5_4;...
    MC6_1,MC6_2,MC6_3,MC6_4;...
    MC7_1,MC7_2,MC7_3,MC7_4;...
    MC8_1,MC8_2,MC8_3,MC8_4;...
    MC9_1,MC9_2,MC9_3,MC9_4;...
    MC10_1,MC10_2,MC10_3,MC10_4;...
    MC11_1,MC11_2,MC11_3,MC11_4;...
    MC12_1,MC12_2,MC12_3,MC12_4;...
    MC13_1,MC13_2,MC13_3,MC13_4;...
    MC14_1,MC14_2,MC14_3,MC14_4;...
    MC15_1,MC15_2,MC15_3,MC15_4;...
    MC16_1,MC16_2,MC16_3,MC16_4;...
    MC17_1,MC17_2,MC17_3,MC17_4;...
    MC18_1,MC18_2,MC18_3,MC18_4;...
    MC19_1,MC19_2,MC19_3,MC19_4;...
    MC20_1,MC20_2,MC20_3,MC20_4;...
    MC21_1,MC21_2,MC21_3,MC21_4;...
    MC22_1,MC22_2,MC22_3,MC22_4;...
    MC23_1,MC23_2,MC23_3,MC23_4;...
    MC24_1,MC24_2,MC24_3,MC24_4;...
    MC25_1,MC25_2,MC25_3,MC25_4;...
    MC26_1,MC26_2,MC26_3,MC26_4;...
    MC27_1,MC27_2,MC27_3,MC27_4;...
    MC28_1,MC28_2,MC28_3,MC28_4};

FASTENERS =[f1 f2 f3 f4 f5 f6 f7 f8 f9 f10 f11 f12 f13 f_14 f15 f16 f17 f18
f19 f20 f21 f22 f23 f24 f25 f26 f27 f28 f29];
sizeMC=size(MC);
COMPONENTS = [c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
c19 c20 c21 c22 c23 c24 c25 c26 c27 c28 ground];
sizeCOMPONENTS=size(COMPONENTS);

%PC - Projection constraint matrix for components
PC1_1 = [f1,c6,c7,c9,c10];
PC1_2 = [f1];
PC1_3 = [f1,ground];
PC1_4 = [f1,ground];
```

```
PC2_1 = [f2,c6,c7,c10];
PC2_2 = [f2];
PC2_3 = [f2,ground];
PC2_4 = [f2,c1];

PC3_1 = [f3,c6,c7,c8,c10];
PC3_2 = [f3];
PC3_3 = [f3,ground];
PC3_4 = [f3];

PC4_1 = [f4,c6,c7,c8,c10];
PC4_2 = [f4];
PC4_3 = [f4];
PC4_4 = [f4,c5];

PC5_1 = [f5,c6,c7,c8,c10];
PC5_2 = [f5];
PC5_3 = [f5,c4];
PC5_4 = [f5,ground];

PC6_1 = [f6,c7,c8,c9,c10];
PC6_2 = [f6,c1,c2,c3,c4,c5];
PC6_3 = [f6,ground];
PC6_4 = [f6,ground];

PC7_1 = [f7,f8,c8,c9,c10];
PC7_2 = [f7,f8,c1,c2,c3,c4,c5,c6];
PC7_3 = [f7,f8,ground];
PC7_4 = [f7,f8,ground];

PC8_1 = [f9,c10];
PC8_2 = [f9,c3,c4,c5,c6];
PC8_3 = [f9,ground];
PC8_4 = [f9,c3,ground];

PC9_1 = [f10,c10];
PC9_2 = [f10,c1,c6];
PC9_3 = [f10,ground];
PC9_4 = [f10,ground];

PC10_1 = [f11];
PC10_2 = [f11,c1,c2,c3,c4,c5,c6,c7,c8,c9];
PC10_3 = [f11,ground];
PC10_4 = [f11,ground];

PC11_1 = [f12,c12];
PC11_2 = [f12,ground];
PC11_3 = [f12,ground];
PC11_4 = [f12,c15,c28];

PC12_1 = [f13,c16,c17,c18,c28];
PC12_2 = [f13,c11,c15,c28];
PC12_3 = [f13,ground];
PC12_4 = [f13,c25,c28];

PC13_1 = [f_14,c14];
PC13_2 = [f_14,ground];
```

```
PC13_3 = [f_14,ground];
PC13_4 = [f_14,c15,c27];

PC14_1 = [f15,c17,c18,c22,c28];
PC14_2 = [f15,c13,c15,c28];
PC14_3 = [f15,ground];
PC14_4 = [f15,c24,c27];

PC15_1 = [f16];
PC15_2 = [f16];
PC15_3 = [f16,c11,c13,ground];
PC15_4 = [f16,c27,c28];

PC16_1 = [f17];
PC16_2 = [f17];
PC16_3 = [f17,ground];
PC16_4 = [f17,c25,c26,c28];

PC17_1 = [f18,c2,c8,c18,c19];
PC17_2 = [f18,c12,c14,c16,c22];
PC17_3 = [f18,ground];
PC17_4 = [f18,c27,c28];

PC18_1 = [f19,c2,c8,c19];
PC18_2 = [f19,c12,c14,c16,c17,c22];
PC18_3 = [f19,ground];
PC18_4 = [f19,c27,c28];

PC19_1 = [f20,c6];
PC19_2 = [f20,c16,c17,c18];
PC19_3 = [f20,ground];
PC19_4 = [f20,c1,c28];

PC20_1 = [f21,c7];
PC20_2 = [f21,ground];
PC20_3 = [f21,ground];
PC20_4 = [f21,c27];

PC21_1 = [f22,c7];
PC21_2 = [f22,ground];
PC21_3 = [f22,ground];
PC21_4 = [f22,c27];

PC22_1 = [f23];
PC22_2 = [f23,c14];
PC22_3 = [f23,ground];
PC22_4 = [f23,c23,c24,c27];

PC23_1 = [f24,c7];
PC23_2 = [f24,c27];
PC23_3 = [f24,ground];
PC23_4 = [f24];

PC24_1 = [f25,c7];
PC24_2 = [f25,c27];
PC24_3 = [f25,ground];
PC24_4 = [f25];
```

```
PC25_1 = [f26,c28];
PC25_2 = [f26,c28];
PC25_3 = [f26,ground];
PC25_4 = [f26];

PC26_1 = [f27,c28];
PC26_2 = [f27,c28];
PC26_3 = [f27,ground];
PC26_4 = [f27];

PC27_1 = [f28,c7,c14,c23,c24];
PC27_2 = [f28,c14,c23,c24,ground];
PC27_3 = [f28,c13,c14,c15,c17,c18,c22,ground];
PC27_4 = [f28];

PC28_1 = [f29,c1,c2,c7,c12,c25,c26];
PC28_2 = [f29,c12,c25,c26,ground];
PC28_3 = [f29,c11,c12,c15,c16,c17,c18,c19,ground];
PC28_4 = [f29];

PC={PC1_1,PC1_2,PC1_3,PC1_4;...
    PC2_1,PC2_2,PC2_3,PC2_4;...
    PC3_1,PC3_2,PC3_3,PC3_4;...
    PC4_1,PC4_2,PC4_3,PC4_4;...
    PC5_1,PC5_2,PC5_3,PC5_4;...
    PC6_1,PC6_2,PC6_3,PC6_4;...
    PC7_1,PC7_2,PC7_3,PC7_4;...
    PC8_1,PC8_2,PC8_3,PC8_4;...
    PC9_1,PC9_2,PC9_3,PC9_4;...
    PC10_1,PC10_2,PC10_3,PC10_4;...
    PC11_1,PC11_2,PC11_3,PC11_4;...
    PC12_1,PC12_2,PC12_3,PC12_4;...
    PC13_1,PC13_2,PC13_3,PC13_4;...
    PC14_1,PC14_2,PC14_3,PC14_4;...
    PC15_1,PC15_2,PC15_3,PC15_4;...
    PC16_1,PC16_2,PC16_3,PC16_4;...
    PC17_1,PC17_2,PC17_3,PC17_4;...
    PC18_1,PC18_2,PC18_3,PC18_4;...
    PC19_1,PC19_2,PC19_3,PC19_4;...
    PC20_1,PC20_2,PC20_3,PC20_4;...
    PC21_1,PC21_2,PC21_3,PC21_4;...
    PC22_1,PC22_2,PC22_3,PC22_4;...
    PC23_1,PC23_2,PC23_3,PC23_4;...
    PC24_1,PC24_2,PC24_3,PC24_4;...
    PC25_1,PC25_2,PC25_3,PC25_4;...
    PC26_1,PC26_2,PC26_3,PC26_4;...
    PC27_1,PC27_2,PC27_3,PC27_4;...
    PC28_1,PC28_2,PC28_3,PC28_4};
sizePC=size(PC);

%CF - Contact Constraint Matrix for Fasteners +x = 1; -x=2; +y=3; -y=4
CF = [2;4;2;2;2;2;4;3;1;1;1;4;4;4;4;4;4;4;4;4;4;4;4;4;4;4;4;4];

%MF - Motion Constraint Matrix for Fasteners
```

```
MF_FASTENER_UNDER_STUDY =
{f1;f2;f3;f4;f5;f6;f7;f8;f9;f10;f11;f12;f13;f_14;f15;f16;f17;f18;f19;f20;f21;
f22;f23;f24;f25;f26;f27;f28;f29};
MF = {0;c1;0;0;0;[c1 c2 c3 c4 c5];0;0;c10;c10;0;c28;c25;c27;c24;[c27
c28];c28;[c27 c28];[c27 c28];c28;c27;c27;c27;0;0;0;0;0;0};

%HM - Hosting Constraint Matrix
HM_COMPONENT_UNDER_STUDY =
{c1;c2;c3;c4;c5;c6;c7;c8;c9;c10;c11;c12;c13;c14;c15;c16;c17;c18;c19;c20;c21;c
22;c23;c24;c25;c26;c27;c28};
HM =
{0;0;0;0;c4;[c3,c5];[c6,c8,c9,c10];0;0;0;c12;0;c14;0;0;[c25,c26];0;0;0;0;0;[c
23,c24];0;0;0;0;0;0};

%LM - Liaison Matrix of Hosting Components
LM =
{0;0;0;0;f4;[f3,f5];[f6,f9,f10,f11];0;0;0;f13;0;f15;0;0;[f26,f27];0;0;0;0;0;[
f24,f25];0;0;0;0;0;0};

%MF_HM
MF_HM =
{0;c1;0;0;c4;[c1,c2,c3,c4,c5];[c6,c8,c9,c10];[c6,c8,c9,c10];c10;c10;0;c28;c25
;c27;c24;[c27,c28];c28;[c27,c28];[c27,c28];c28;c27;c27;c27;0;0;0;0;0;0};

%%%%%%ALGORITHM 2
%It generates the EVM - Environmental Value Matrix (CO2eq)
EVM_VALUES = [307.14 102.38 167.74 254.44 167.74 129.07 146.75 7.12 22.97
129.07 81.90 102.38 81.90 102.38 21.36 11.49 64.09 64.09 163.81 64.09 64.09
11.49 102.38 102.38 102.38 102.38 167.79 167.79 1000];
EVM = zeros(sizePC);
for i=1:sizePC(1,1)
    for j=1:sizePC(1,2)
        sizeMCn_m=size(PC{i,j});
        for n=1:sizeMCn_m(1,2)
            for k=1:sizeCOMPONENTS(1,2)
               if PC{i,j}(1,n) == COMPONENTS(1,k)
                  EVM(i,j) = EVM(i,j)+EVM_VALUES(1,k);
               end
            end
        end
    end
end
```

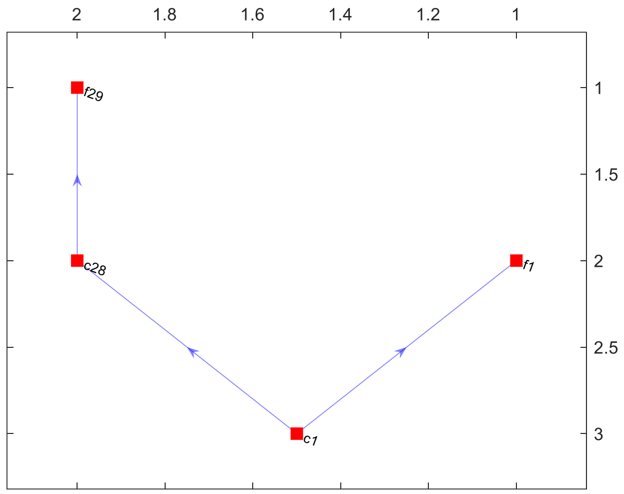
SDPB - Algorithm for creating an optimized disassembly sequence planning for building assemblages

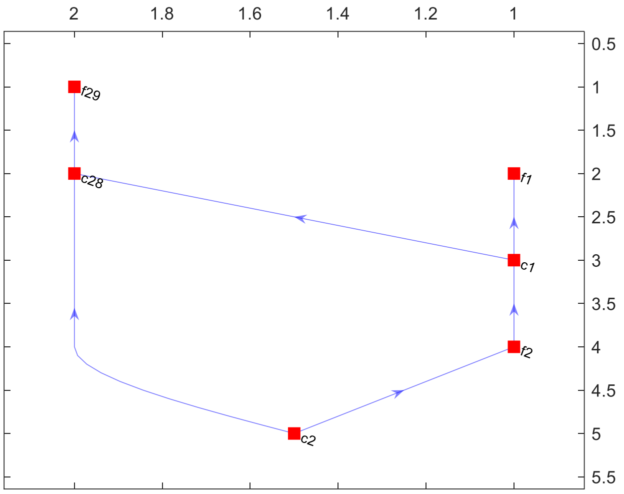
```
C_objective = input ('What is the target component? ');
C_objective_Under_Study_Initial = C_objective;
OBJ_DISASSEMBY_VECTOR = [];
COUNTER_WHILE = 1;
LIMIT = 5;
NUMBER_OF_VECTORS=1;
OBJ_DISASSEMBY_VECTOR_TOTAL = [];
EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL = [];
NEW_C_objective = 0;
NEXT_COMPS = [];
PAST_COMPS = [];
COUNTER_NEXT_COMPS = 1;
while C_objective_Under_Study_Initial == C_objective
    OBJ_DISASSEMBY_VECTOR = [];
    COUNTER_WHILE = 1;
    while C_objective_Under_Study_Initial == C_objective |
sum(ismember(OBJ_DISASSEMBY_VECTOR,COMPONENTS)) == 1
        C_objective = C_objective_Under_Study_Initial;
        QUEUE_VECTOR = [0];
        EXTRACTION_ELEMENTS_UNDER_STUDY=[0];
        EXTRACTION_VECTOR=[0];
        EXTRACTION_ELEMENTS_UNDER_STUDY_WITHOUT_QUEUE=[0];
        FINAL_EXTRACCTION_VECTOR=[0];
        clearvars OBJ_DISASSEMBY_VECTOR
        OBJ_DISASSEMBY_VECTOR(1,1) = C_objective;
        COUNTER=1;
        for i=1:COUNTER_WHILE
            COUNTER_ANTERIOR=i;

[COUNTER,C_objective,EXTRACTION_VECTOR,EXTRACTION_ELEMENTS_UNDER_STUDY,EXTRAC
TION_ELEMENTS_UNDER_STUDY_WITHOUT_QUEUE,QUEUE_VECTOR,FINAL_EXTRACCTION_VECTOR
] =
extraction_vector_n(COUNTER,MC,HM_COMPONENT_UNDER_STUDY,C_objective,HM,COMPON
ENTS,EVM,MF_FASTENER_UNDER_STUDY,MF_HM,QUEUE_VECTOR,EXTRACTION_ELEMENTS_UNDER
_STUDY,EXTRACTION_VECTOR,EXTRACTION_ELEMENTS_UNDER_STUDY_WITHOUT_QUEUE,FINAL_
EXTRACCTION_VECTOR);

EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR{i,1}=EXTRACTION_ELEMENTS_UNDER_STUDY_W
ITHOUT_QUEUE;
            QUEUE_DISASSEMBY_DISASSEMBY_VECTOR{i,1}=QUEUE_VECTOR;
            OBJ_DISASSEMBY_VECTOR(COUNTER,1) = C_objective;
            size_OBJ_DISASSEMBY_VECTOR=size(OBJ_DISASSEMBY_VECTOR);
            size_FINAL_EXTRACCTION_VECTOR=size(FINAL_EXTRACCTION_VECTOR);
            if size_FINAL_EXTRACCTION_VECTOR(1,2) <
size_OBJ_DISASSEMBY_VECTOR(1,1)
                OBJ_DISASSEMBY_VECTOR(COUNTER) = [];
                break
            end
        end
        OBJ_DISASSEMBY_VECTOR_1=OBJ_DISASSEMBY_VECTOR;

EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_1=EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECT
OR;
        COUNTER_WHILE = COUNTER_WHILE + 1;
```

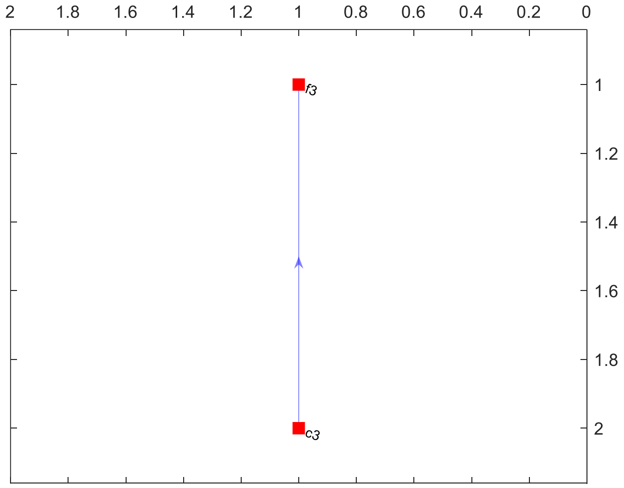
```
        if COUNTER_WHILE > LIMIT
            break
        end
    end
    OBJ_DISASSEMBY_VECTOR_TOTAL =
[OBJ_DISASSEMBY_VECTOR_TOTAL;OBJ_DISASSEMBY_VECTOR];
    EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL =
[EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL;EXT_EL_WITHOUT_QUEUE_DISASSEMBY
_VECTOR];
    size_OBJ_DISASSEMBY_VECTOR_TOTAL = size(OBJ_DISASSEMBY_VECTOR_TOTAL);
    size_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL =
size(EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL);
    if size_OBJ_DISASSEMBY_VECTOR_TOTAL(1,1) <
size_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL(1,1)
        TEMPORAL_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL = {};
        for i=1:size_OBJ_DISASSEMBY_VECTOR_TOTAL(1,1)
            TEMPORAL_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL{i,1} =
EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL{i,1};
        end
        EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL =
TEMPORAL_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL;
    end
    NEXT_COMPS = union (NEXT_COMPS , setxor(NEXT_COMPS ,
intersect(horzcat(EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR{:}),COMPONENTS)));
    PAST_COMPS = [PAST_COMPS ; C_objective_Under_Study_Initial];
    NEXT_COMPS = setdiff(NEXT_COMPS , PAST_COMPS);
    size_NEXT_COMPS = size(NEXT_COMPS);
    if size_NEXT_COMPS(1,2) == 0
        break
    end
    if size_NEXT_COMPS(1,1) == 0
        break
    end
    NEW_C_objective = NEXT_COMPS(1,1);
    C_objective = NEW_C_objective;
    C_objective_Under_Study_Initial = C_objective;
end
OBJ_DISASSEMBY_VECTOR = OBJ_DISASSEMBY_VECTOR_TOTAL;
EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR =
EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR_TOTAL;
size_OBJ_DISASSEMBY_VECTOR=size(OBJ_DISASSEMBY_VECTOR);
OBJ_DISASSEMBY_VECTOR_NO_REPS=OBJ_DISASSEMBY_VECTOR;
COUNTER=1;
ROWS_TO_DELETE = [];
for i=1:size_OBJ_DISASSEMBY_VECTOR(1,1)
    C_under_analysis = OBJ_DISASSEMBY_VECTOR(i,1);
    VECTOR_ROW_INDEX_REPEATED =
find(OBJ_DISASSEMBY_VECTOR==C_under_analysis);
    size_VECTOR_ROW_INDEX_REPEATED=size(VECTOR_ROW_INDEX_REPEATED);
    if size_VECTOR_ROW_INDEX_REPEATED(1,1) > 1
        if
intersect(OBJ_DISASSEMBY_VECTOR_TOTAL(VECTOR_ROW_INDEX_REPEATED(1,1)+1 , 1) ,
COMPONENTS) ~= 0
            for b=1:size_VECTOR_ROW_INDEX_REPEATED(1,1)-1;
                DELETE = VECTOR_ROW_INDEX_REPEATED(b,1);
                OBJ_DISASSEMBY_VECTOR_NO_REPS(DELETE) = 0;
                ROWS_TO_DELETE(COUNTER) = [VECTOR_ROW_INDEX_REPEATED(b,1)];
```

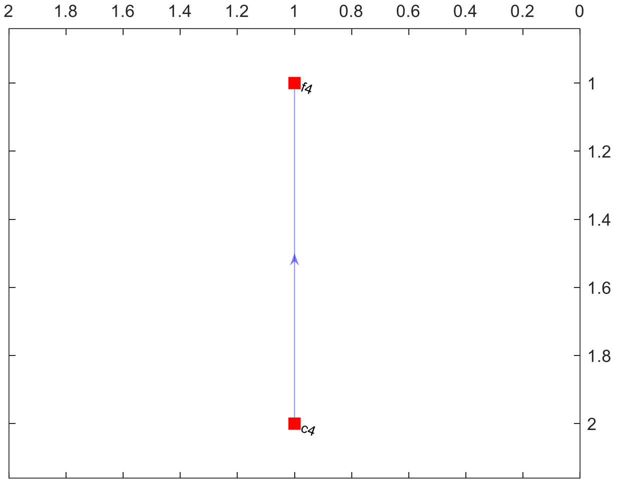
```
                COUNTER = COUNTER +1;
            end
        else
            for b=2:size_VECTOR_ROW_INDEX_REPEATED(1,1);
                DELETE = VECTOR_ROW_INDEX_REPEATED(b,1);
                OBJ_DISASSEMBY_VECTOR_NO_REPS(DELETE) = 0;
                ROWS_TO_DELETE(COUNTER) = [VECTOR_ROW_INDEX_REPEATED(b,1)];
                COUNTER = COUNTER +1;
            end
        end

    end
end
if size(ROWS_TO_DELETE) ~= 0
    ROWS_TO_DELETE=unique(ROWS_TO_DELETE);
    OBJ_DISASSEMBY_VECTOR(ROWS_TO_DELETE)=[];
end
size_OBJ_DISASSEMBY_VECTOR = size(OBJ_DISASSEMBY_VECTOR);
size_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR =
size(EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR);
if size_OBJ_DISASSEMBY_VECTOR(1,1) <
size_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR(1,1)
    EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR(ROWS_TO_DELETE)=[];
else
end
size_OBJ_DISASSEMBY_VECTOR=size(OBJ_DISASSEMBY_VECTOR);
SOURCE = [0];
TARGET = [0];
names = {};
COUNTER_SOURSE=1;
for i=1:size_OBJ_DISASSEMBY_VECTOR(1,1)
    names{1,i}=char(OBJ_DISASSEMBY_VECTOR(i,1));
    VECTOR_UNDER_ANALISYS=EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR{i,1};
    size_VECTOR_UNDER_ANALISYS=size(VECTOR_UNDER_ANALISYS);
    for j=1:size_VECTOR_UNDER_ANALISYS(1,2)
        ROW_INDEX_TARGET =
find(OBJ_DISASSEMBY_VECTOR==VECTOR_UNDER_ANALISYS(1,j));
        if ROW_INDEX_TARGET ~= 0
            SOURCE(1,COUNTER_SOURSE) = i;
            TARGET(1,COUNTER_SOURSE) = ROW_INDEX_TARGET;
            COUNTER_SOURSE=COUNTER_SOURSE+1;
        end
    end
end
D=digraph(SOURCE,TARGET,0,names);
h=plot(D,'EdgeColor','b','NodeColor','r','MarkerSize',7,'Marker','s');
camroll(-180)
```

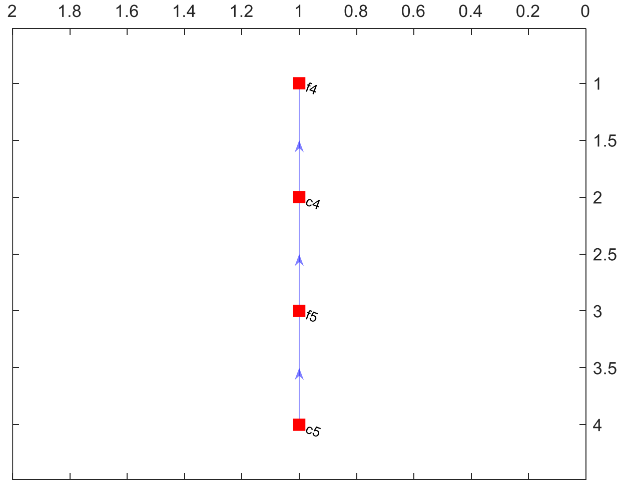
SDPB Graphical output for different targeted components to retrieve from the building model under study

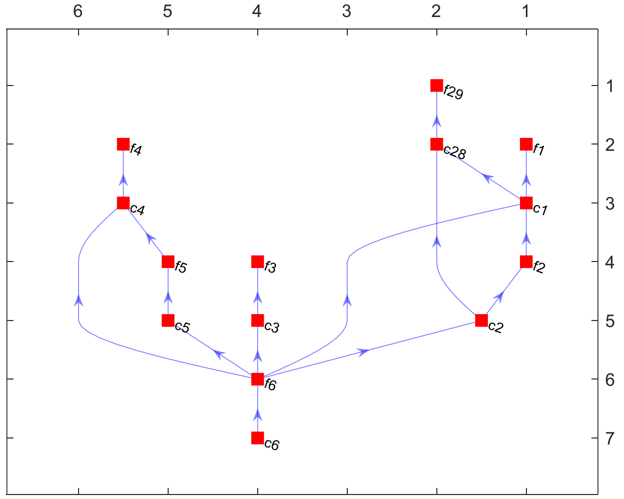


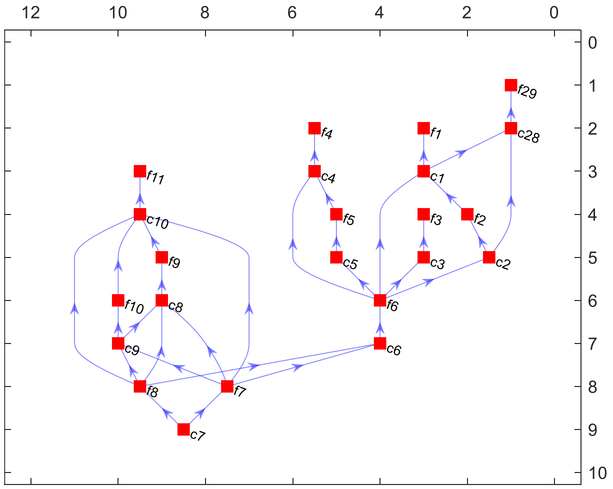








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2
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5
6
7
8
9
10
f29
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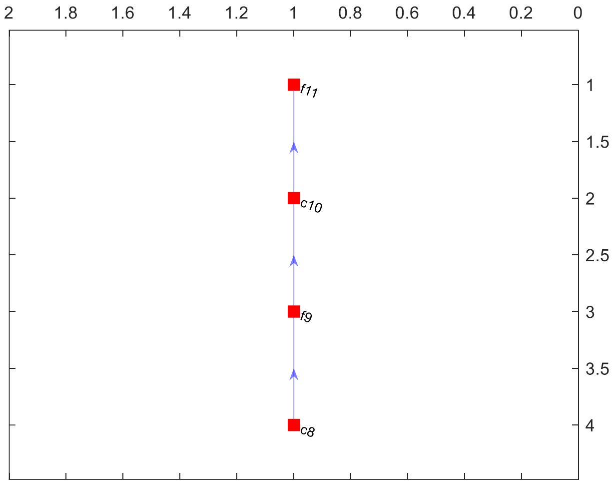
f1
c4
c1
f11
f5
f3
f2
c10
f9
c5
c3
c2
f10
c8
f6
c9
c6
f8
f7
c7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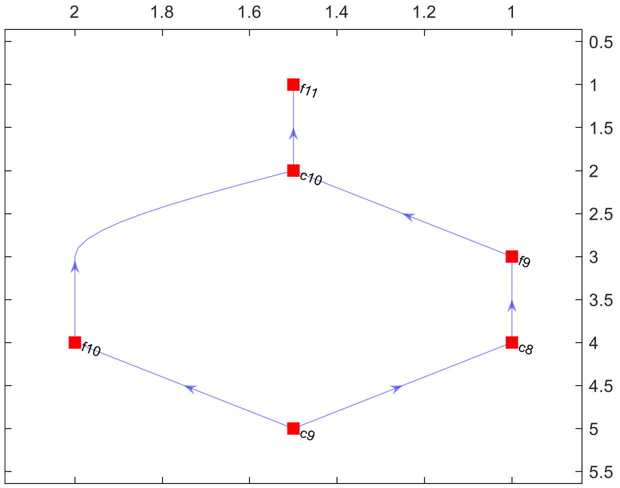
3
3.5
4
f11
c10
f9
c8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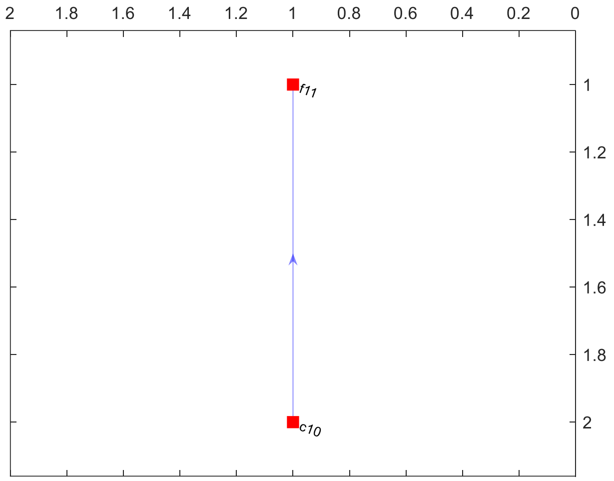
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1.4
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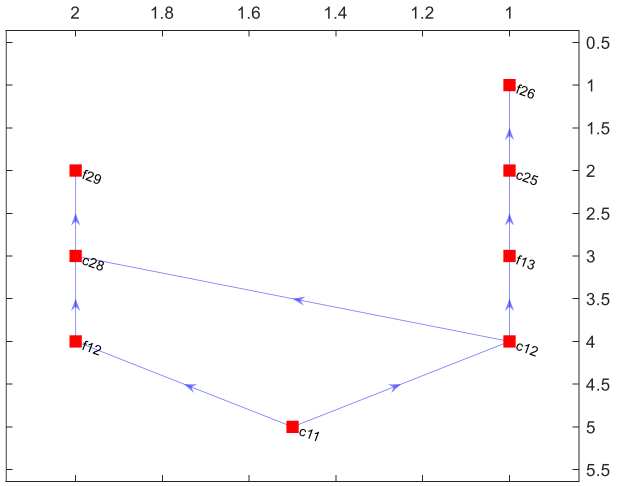
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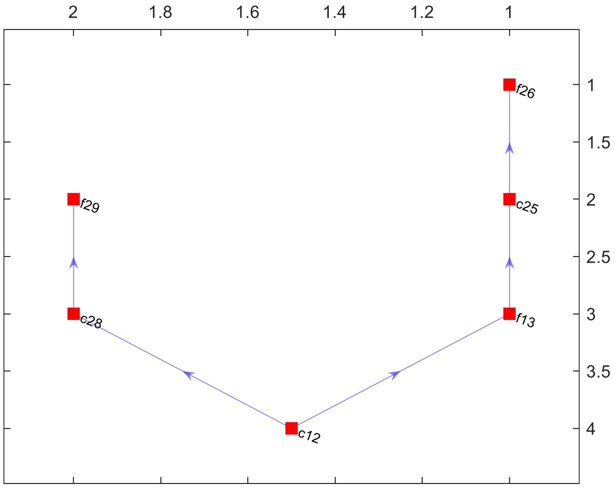
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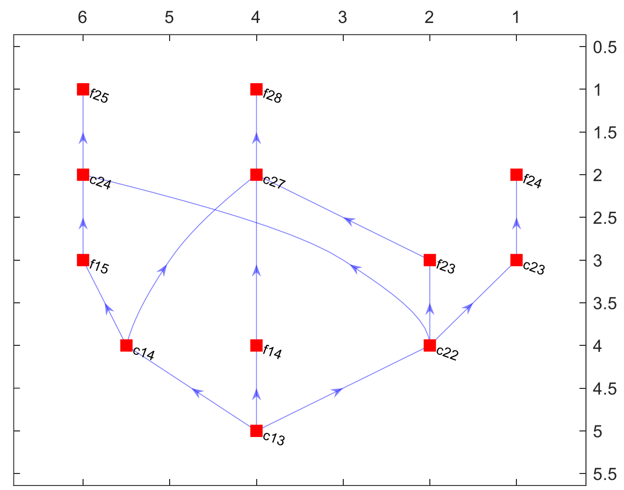
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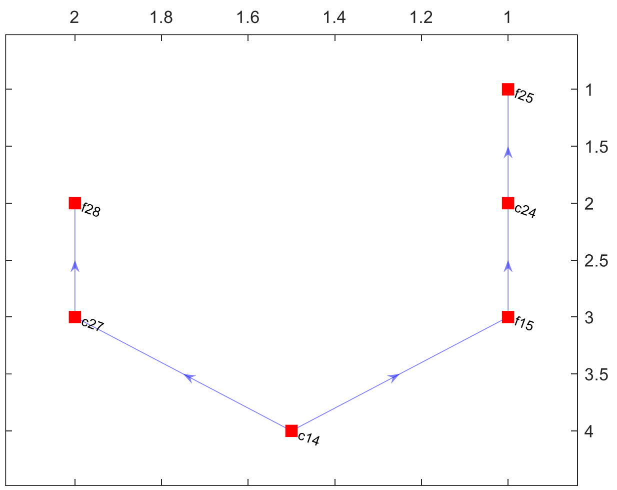
c13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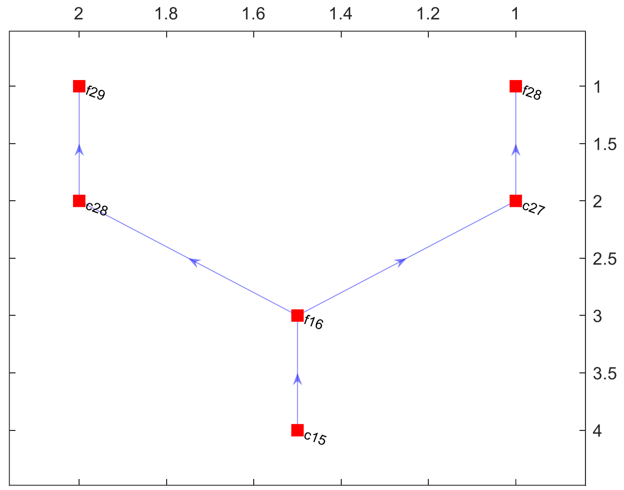
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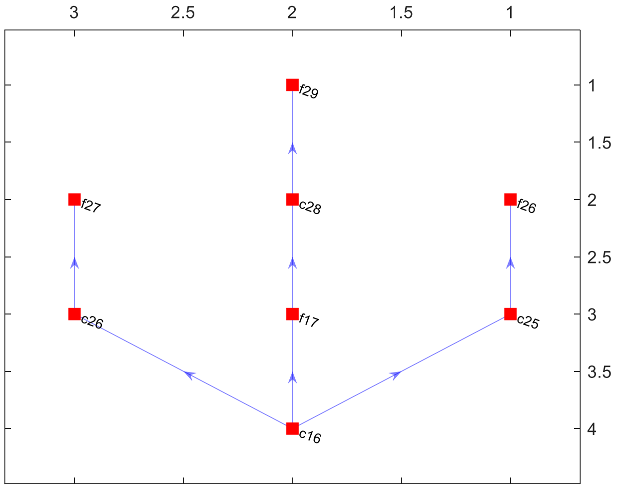
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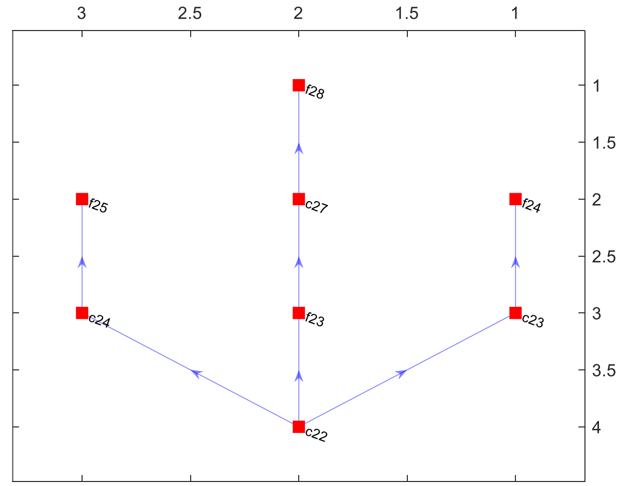
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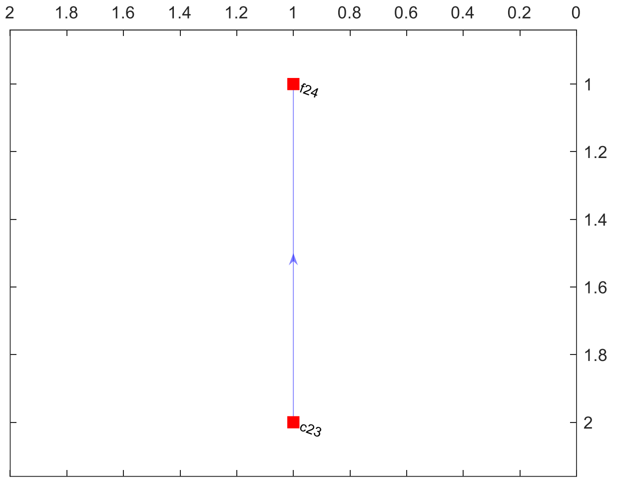
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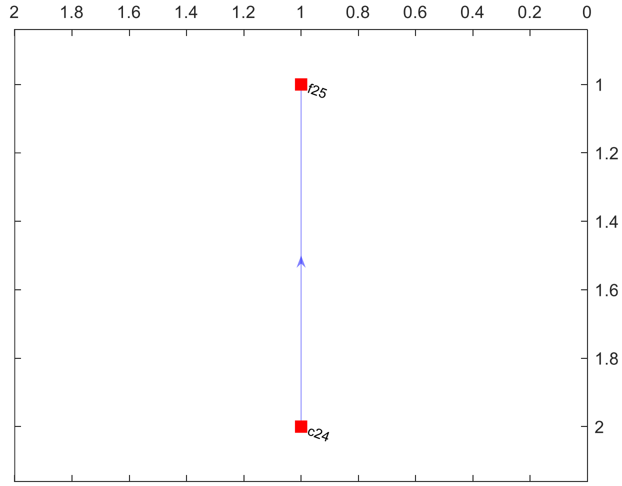
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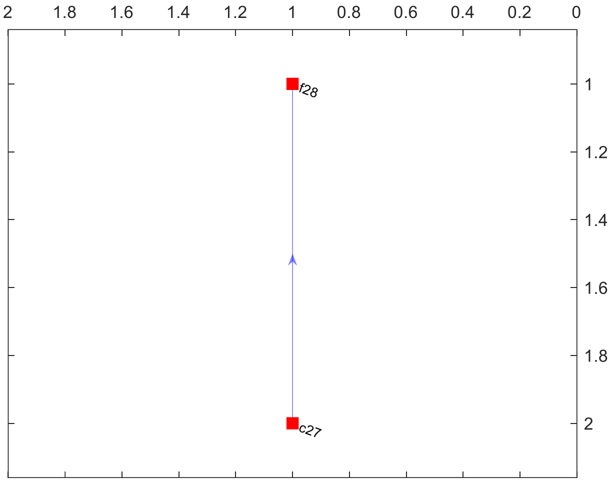
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1.8
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Appendix E: An algorithm for creating a multiple-target sequential disassembly planning (SDP) model for buildings

```
clc
clear
prompt = 'Do you want to select multiple-targeted components? Y/N [Y]: ';
answer = input(prompt,'s');
counter = 0;
CELLARRAY_OBJ_DISASSEMBY_VECTOR={};
CELLARRAY_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR={};
while answer == 'Y';
    counter = counter+1;
    extraction ='extraction_';
    [OBJ_DISASSEMBY_VECTOR,EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR] =
extraction_cn_multitarget();
    CELLARRAY_OBJ_DISASSEMBY_VECTOR{counter,1}=OBJ_DISASSEMBY_VECTOR;

CELLARRAY_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR{counter,1}=EXT_EL_WITHOUT_QU
EUE_DISASSEMBY_VECTOR;
    prompt = 'Do you want to select another component? Y/N [Y]: ';
    answer = input(prompt,'s');
end
for i=1:counter;
    OBJ_DISASSEMBY_VECTOR_SIZE{i,1} =
size(CELLARRAY_OBJ_DISASSEMBY_VECTOR{i,1});
    OBJ_DISASSEMBY_VECTOR_COUNT(i,1) = max(OBJ_DISASSEMBY_VECTOR_SIZE{i,1});
end
[MAX,INDEX_MAX] = max(OBJ_DISASSEMBY_VECTOR_COUNT);
 REF_VECTOR = CELLARRAY_OBJ_DISASSEMBY_VECTOR{INDEX_MAX,1};
 REF_QUEUE = CELLARRAY_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR{INDEX_MAX,1};
 OBJ_DISASSEMBY_VECTOR = REF_VECTOR;
 EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR = REF_QUEUE;
for i=1:counter;
    SECONDARY_VECTOR = CELLARRAY_OBJ_DISASSEMBY_VECTOR{i,1};
    SECONDARY_QUEUE = CELLARRAY_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR{i,1};
    REPEATED_PARTS = intersect(REF_VECTOR,SECONDARY_VECTOR);
    if size(REPEATED_PARTS) == size(SECONDARY_VECTOR);
        REPEATED_PARTS_SIZE = size(REPEATED_PARTS);
        REF_VECTOR_SIZE = size(REF_VECTOR);
        if  REPEATED_PARTS_SIZE(1,1 )~= REF_VECTOR_SIZE(1,1)
            CELLARRAY_OBJ_DISASSEMBY_VECTOR{i,1} = 0;
            CELLARRAY_EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR{i,1} = 0;
        end
    else
        OBJ_DISASSEMBY_VECTOR = [OBJ_DISASSEMBY_VECTOR;SECONDARY_VECTOR];
        EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR =
[EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR;SECONDARY_QUEUE];
    end
end
size_OBJ_DISASSEMBY_VECTOR=size(OBJ_DISASSEMBY_VECTOR);
SOURCE = [0];
TARGET = [0];
names = {};
COUNTER_SOURSE=1;
for i=1:size_OBJ_DISASSEMBY_VECTOR(1,1)
    names{1,i}=char(OBJ_DISASSEMBY_VECTOR(i,1));
```

```
    VECTOR_UNDER_ANALISYS=EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR{i,1};
    size_VECTOR_UNDER_ANALISYS=size(VECTOR_UNDER_ANALISYS);
    for j=1:size_VECTOR_UNDER_ANALISYS(1,2)
        ROW_INDEX_TARGET =
find(OBJ_DISASSEMBY_VECTOR==VECTOR_UNDER_ANALISYS(1,j));
        if ROW_INDEX_TARGET ~= 0
            SOURCE(1,COUNTER_SOURSE) = i;
            TARGET(1,COUNTER_SOURSE) = ROW_INDEX_TARGET;
            COUNTER_SOURSE=COUNTER_SOURSE+1;
        end
    end

end
D=digraph(SOURCE,TARGET,0,names);
plot(D,'EdgeColor','b','NodeColor','r','MarkerSize',7,'Marker','s')
camroll(-180)
hold on
%%%MS PROJECT
ACTIVITIES = flip(OBJ_DISASSEMBY_VECTOR);
PREDECESORS = flip(EXT_EL_WITHOUT_QUEUE_DISASSEMBY_VECTOR);
sizeACTIVITIES=size(ACTIVITIES);
for i=1:sizeACTIVITIES(1,1);
    sizePREDECESORS_VECTOR_UNDER_STUDY=size(PREDECESORS{i,1});
    for k=1:sizeACTIVITIES(1,1);
            for j=1:sizePREDECESORS_VECTOR_UNDER_STUDY(1,2);
                if ACTIVITIES(k,1) == PREDECESORS{i,1}(1,j);
                    PREDECESORS{i,1}(1,j)=k;
                else
                end
            end
    end
end
```