Multi-objective Optimization Analysis for Selective Disassembly Planning of Buildings

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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. In this paper we provide a framework for the multi-objective analysis to obtain several effective selective disassembly plans through the combination of different deconstruction methods. The analysis is delineated in terms of the physical, environmental, and economic constraints of the deconstruction methods per building component. Then, a weighted multi-objective optimization analysis is incorporated to generate the set of noninferior solutions that minimizes environmental impacts and building cost. 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).

Keywords –

multi-objective optimization, selective disassembly, adaptive reuse, Circular Economy, green design.

1 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. Adaptive reuse is considered a disruptive practice in the current capital project delivery model for the renewal of today's built environment [1,2]. 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 analyses for the optimization of environmental and financial benefits. The aim of this study is to develop the framework for 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 [3,4], 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 study shows that different complete disassembly plans exist for all 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 implementation of this approach could 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.

2 Background

Over the last two decades, environmental concerns have driven the research of construction projects' life cycle performance towards a holistic approach to sustainability [5-8]. 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 [3,9,10]. 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.

2.1 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 [3]. Green design methods are intended to reduce environmental cost and increase economic benefits over the entire product or service lifecycle [11]. 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 [12]. 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 [13,14]. 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 [3] developed the first-in-its-class selective disassembly sequence planning method for adaptive reuse of buildings. The method seeks to minimize environmental impact and cost of the selective disassembly of building components to retrieve, based upon physical, environmental, and economic constraints. As an extension of this work, Sanchez, Rausch, and Haas [4] developed a multiple-target sequential disassembly planning model for buildings, as well as a novel approach for deconstruction programming for adaptive reuse of buildings.

2.2 Multi-objective Optimization Analysis for Selective Disassembly

According to Revelle & Whitlach [15], 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. 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. We might seek to evaluate environmental quality and economic efficiency trade-offs along 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 works. The conflict or trade-off between the mentioned objectives is found in the incommensurable differences between the environmental value and removal cost of different selective disassembly plans for components.

2.3 The Knowledge Gap

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 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 through the combination of different deconstruction methods.

3 Methodology

The proposed methodology for a multiple objective optimization analysis is incorporated into the framework of selective deconstruction project planning by using

BIM-based phase planning presented in a previous work [4]. 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, environmental, and economic constraints per building component and by using just one deconstruction method per building component, which is "selective 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 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 1, this becomes an iterative process whereby if the project needs are not fulfilled, the adaptive reuse design should be changed by the designers.

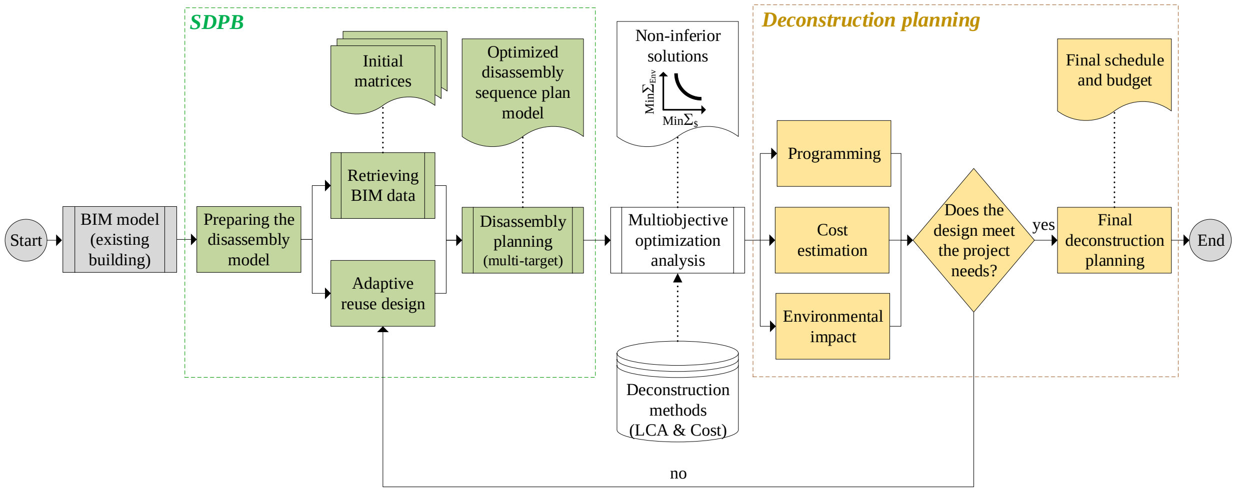

Figure 1. Multiple objective optimization analysis for selective deconstruction project planning

3.1 The Disassembly Sequence Plan Model for Adaptive Reuse of Buildings

This study is built on previous works related to selective disassembly planning for adaptive reuse [3,4]. 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 *p*, in this case, can be a component *c* (building component) or a fastener *f* (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, or functional. 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 [3,16]. Finally, the approach uses expert rules to improve solution quality, minimize graph complexity, and reduce searching time for finding optimized disassembly sequence plans [3,11,16]. 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 works.

Figure 2 shows as an example the multi-target SDPB for a building assembly subset which was part of an adaptive reuse project of the "Engineering 2" (E2) building at the University of Waterloo campus. Figure 2 shows the 57-part assembly model under study. The SDPB method creates optimized single-target disassembly sequences 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 2 also shows a multiple-target disassembly plan (inverted tree) for components c_7 and c_{13}. For the disassembly plan in Figure 2, n_t are the number of targeted components; and n_c, n_f, and n_p are the number of components, fasteners, and parts in the disassembly plan, respectively.

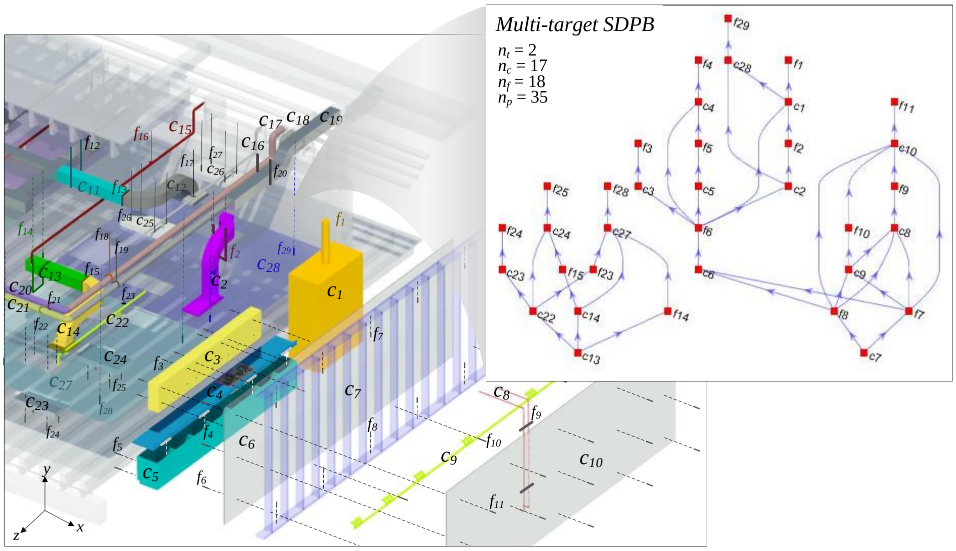

Figure 2. Automated generation of the multiple-target SDPB for components c_7 and c_{13}

3.2 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 [3]. The 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 [17] 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 (1)-(3).

$$LCA^a_{jm} = EI^{a,production}_{jm} + EI^{a,construction}_{j} + EI^{a,EoL}_{jm} \tag{1}$$

$$\begin{aligned} EI^{a,production}_{jm} &= EI^{a,raw\ materials\ supply}_{jm} \\ &\quad + EI^{a,transport}_{j} \\ &\quad + EI^{a,manufacturing}_{jm} \end{aligned} \tag{2}$$

$$\begin{aligned} EI^{a,construction}_{j} &= EI^{a,transport}_{j} \\ &\quad + EI^{a,installation\ process}_{j} \end{aligned} \tag{3}$$

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 [18]. The LCA for selective demolition was calculated per component using the commercial 6D BIM software Revit® and Tally®.

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 [19].

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 (4)-(6):

$$EI^{a,production}_{j,sel.demolition} = EI^{a,raw\ materials\ supply}_{j,sel.demolition} + EI^{a,transport}_{j} + EI^{a,manufacturing}_{j,sel.demolition} \tag{4}$$

$$EI^{a,production}_{j,destruct.disassembly} = EI^{a,raw\ materials\ supply}_{j,destruct.disassembly} + EI^{a,transport}_{j} + EI^{a,manufacturing}_{j,destruct.disassembly} \tag{5}$$

$$EI^{a,production}_{j,perfect\ disassembly} = EI^{a,transport}_{j} \tag{6}$$

Where:

$$EI^{a,raw\ materials\ supply}_{j,destruct.disassembly} = \left(EI^{a,raw\ materials\ supply}_{j,sel.demolition}\right)0.2 \tag{7}$$

$$EI^{a,manufacturing}_{j,destruct.disassembly} = \left(EI^{a,manufacturing}_{j,sel.demolition}\right)0.2 \tag{8}$$

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

$$EI^{a,EoL}_{sel.demolition} = EI^{a,demolition} + EI^{a,transport} + EI^{a,waste\ processing} + EI^{a,disposal} + EI^{a,recovery\ \&\ recycling\ potential} \tag{9}$$

$$EI^{a,EoL}_{destruct.dissasembly} = EI^{a,deconstruction} + EI^{a,transport} \tag{10}$$

$$EI^{a,EoL}_{perfect\ \ dissasembly} = EI^{a,deconstruction} + EI^{a,transport} \tag{11}$$

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 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 [20]. 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 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:

$$C_{j,m} = c^{materials}_{j,m} + c^{labor}_{j,m} + c^{equipment}_{j,m} \tag{12}$$

The developed form of Equation (12) for the deconstruction methods *m* are:

$$C_{j,destruct.disassembly} = c^{materials}_{j,destruct.disassembly} + c^{labor}_{j,destruct.disassembly} + c^{equipment}_{j,destruct.disassembly} \tag{13}$$

$$C_{j,sel.demolition} = \left(C_{j,destruct.disassembly}\right)0.65 \tag{14}$$

$$C_{j,perfect\ disassembly} = \left(C_{j,destruct.disassembly}\right)1.35 \tag{15}$$

3.3 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, we used the weighted method of multi-objective optimization that boasts widespread use among engineers and is acknowledged as the oldest multi-objective solution technique [15]. 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.

$$Minimize\ Z_1 = \sum_{j=1}^{J}\sum_{m=1}^{M_j} LCA^a_{jm} \tag{16}$$

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

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:

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

Subject to:

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

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

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

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

$$x_{jm} = \begin{cases} 1, & \text{if comp.}\ j\ \text{ends in deconstr.}\ m \\ 0, & else \end{cases}$$

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

4 Preliminary Experiments

For the process described in Figure 1, BIM was used as the main digital platform for the preliminary experiments. The E2 assembly building example in Figure 2 is used to demonstrate our approach for a multi-objective optimization analysis for selective disassembly planning for buildings. The software used for this purpose was Matlab®. 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 1 summarizes the result of the calculations, and Figures 3 and 4 displays in a graphical way the noninferior solutions founded with the proposed approach.

Table 1. 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)	Deconstr. Cost ($USD 2018)
1	1.0	0.0	A	120	$2,955
2	0.9	0.1	B	121	$2,930
3	0.8	0.2	C	135	$2,856
4	0.7	0.3	D	144	$2,833
5	0.6	0.4	E	330	$2,507
6	0.5	0.5	F	640	$2,117
7	0.4	0.6	G	844	$1,900
8	0.3	0.7	H	981	$1,876
9	0.2	0.8	I	1,930	$1,462
10	0.1	0.9	J	2,080	$1,430
11	0.0	1.0	K	2,199	$1,423

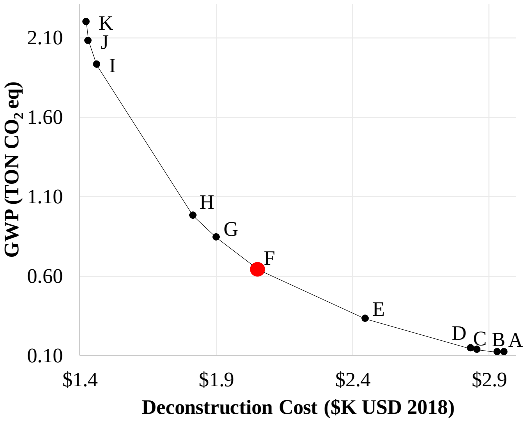

Figure 3. Pareto frontier for minimizing the Global Warming Potential and deconstruction cost of the SDPB for components c_7 and c_{13} by using different deconstruction methods

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.

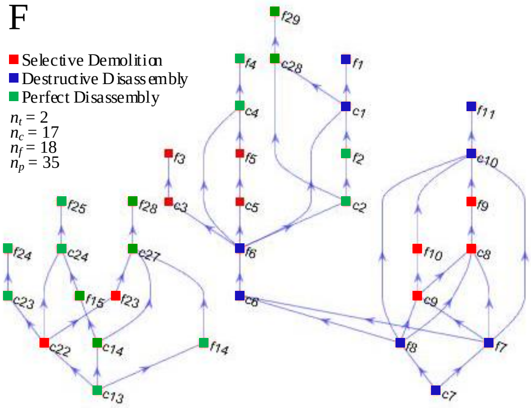

Figure 4. Graphic representation of the noninferior solution “F” for the SDPB of components c_7 and c_{13}

5 Conclusions

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 the aforementioned need, the aim of this study is to develop a multi-objective optimization analysis framework 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 focus in 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 [20].

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 through 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, we use the weighted method of multi-objective optimization 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 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 modelling, environmental assessment, and cost performance of adaptive reuse building projects.

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