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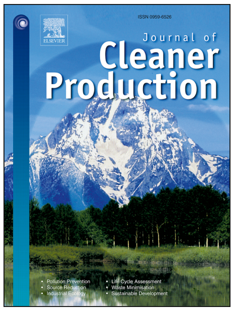

A novel selective disassembly sequence planning method for adaptive reuse of buildings

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PII: S0959-6526(18)30523-7

DOI: 10.1016/j.jclepro.2018.02.201

Reference: JCLP 12148

To appear in: *Journal of Cleaner Production*

Received Date: 30 October 2017

Revised Date: 23 January 2018

Accepted Date: 19 February 2018

Please cite this article as: Sanchez B, Haas C, A novel selective disassembly sequence planning method for adaptive reuse of buildings, *Journal of Cleaner Production* (2018), doi: 10.1016/j.jclepro.2018.02.201.

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Wordcount: Manuscript & Abstract(8,808) + Figure captions (126) + Text in figures (804) = **9,738 words**

"A novel selective disassembly sequence planning method for adaptive reuse of buildings"

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Abstract:

Adaptive reuse of buildings can be an attractive alternative to new construction in terms of sustainability and a circular economy. Achieving net benefits with adaptive reuse partly relies on efficiently planning building disassembly. The aim of this paper 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.

Keywords: disassembly planning, adaptive reuse, life cycle assessment, net environmental impacts, green design methods.

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1. 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 and Moncaster, 2017, Sassi, 2008, Smith and Hung, 2015, Volk et al., 2014). All these methods and principles have the purpose of reducing environmental impacts and increasing economic benefits in a life-cycle perspective (Smith and Hung, 2015). In particular, the End-of-Life (EoL) phase has received much attention recently in the construction and manufacturing industries (Cong et al., 2017, Sandin et al., 2014, Silvestre et al., 2014). 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 (Conejos et al., 2015, Douglas, 2006, Kibert, 2007). The potential benefits of adaptive reuse rely in 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 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 this paper 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 (Smith and Hung, 2015, Smith et al., 2012, Smith et al., 2016, Smith and 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.

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2. Literature Review – Planning and Designing for a Circular Economy in Construction

Conceptualization of the Circular Economy (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 and Rutqvist, 2015, Pomponi and Moncaster, 2017). In their work, Pomponi and Moncaster (2017) concluded that the framework encompassing green supply chains and waste reduction has been the main driver on the CE for the built environment due to the evident areas of opportunity, such as reductions in energy use, environmental impacts, and waste production. 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 have become an important part of the design process in most industries, including construction. These methods are designed to reduce environmental cost and increase economic benefits over the entire product or service lifecycle (Smith et al., 2016). Examples of green design methods are design for assembly, supply chain management, Life Cycle Assessment (LCA), design for disassembly, design for remanufacture, disassembly sequence planning and adaptive reuse. 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 and Davison, 2012, Guy and McLendon, 2000, Kokkos, 2014, Schultmann and Sunke, 2007, Silvestre et al., 2014). Adaptive reuse can be similarly attractive.

2.1. 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). Because of the great impact that the building industry has on the environment, failing to optimize buildings' useful lives can result in their residual lifecycle expectancy not being fully exploited, and with it, wasting the resources embedded. 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,

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Langston et al., 2008). Adaptive reuse takes advantage of the green design methods mentioned in the last section, in order to restore and redevelop existing buildings.

The restorative and regenerative nature of adaptive reuse of buildings is highly aligned to circular economy building principles. This is because: (1) an enormous proportion of all the materials ever extracted in human history are in today's built environment (Kibert, 2007), (2) 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), (3) the price of materials extraction is increasing as is the negative environmental impacts due to the natural constraints of the more dilute and distant stocks of ores and other resources (Kibert, 2007), (4) understanding the real value of the built environment in terms of circular economy through merging cutting-edge Building Information Modeling (BIM) technology with the most updated, complete, and realistic databases of the existing building stock is improving (Langston, 2013, Ortlepp et al., 2016, Stephan and Athanassiadis, 2017), and (5) the accurate monetization of environmental impacts through technological development and research in the field is improving (Shindell, 2015, Viscusi, 2005, Yeung, 2016).

The decision-making processes associated with adaptive reuse of building projects are diverse and dynamic. The complexity lies in the different challenges and opportunities that must be taken into account simultaneously, such as the technical implications, economic concerns, environmental impacts implicated, etc. For this reason, little research has been done on developing methodologies for improving the performance of adaptive reuse of buildings. The current implementations of adaptive reuse rely in descriptive approaches with little objective measurement that depends on the intuition and experience of practitioners (Highfield and Gorse, 2009). Such is the case with the Adaptive Reuse Potential model (Langston, 2012), the adaptSTAR model (Conejos et al., 2015, Conejos et al., 2014), and the Smart codes (Cantell, 2005, DHUD, 2001). Intuitive planning procedures are easy to apply but often lead to suboptimal plans (Lin and Haas, 1996).

The ARP model predicts useful life as a function of physical life and obsolescence. In consequence, an estimated timing for future adaptive reuse can be predicted (Conejos et al., 2015). The adaptSTAR model is a decision-making tool that provides a weighted checklist of design strategies that assists in the development of new buildings that can be adaptively reused in the future (Conejos et al., 2015). The adaptSTAR model is based on survey results collected from selected practitioners in construction. Smart codes is the term used to describe building codes that encourage the alteration and reuse of existing buildings (DHUD, 2001). These regulations are guidelines with best practices for reusing an existing asset. Examples of smart codes are the Uniform Code for Existing Buildings (UCEB) in 2000, the International Existing Building Code (IEBC) in 1999, and the National Fire Protection Association 5000 building code (NFPA 5000) in 1999, among others. Even though the methods and regulations mentioned above 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 process in terms of life cycle.

2.2. 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 (Smith and Hung, 2015). Disassembly planning consists of finding an optimal and feasible path for disassembly under given constraints. Fig. 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, Smith and Hung, 2015). In spite of the advances in this matter, there is a lack of knowledge on disassembly planning for buildings. In this study, we set the framework for analysis and integration of the topics related to disassembly planning for adaptive reuse of buildings (see Fig. 1). Then, we develop a feasible solution for the sequential disassembly for building assemblages as part of the first steps for solving inefficiencies during the process of adaptive reuse of buildings.

For the purposes of this study, 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. Fig 1. shows the disassembly planning methods for products and buildings, as well as the processes involved in the adaptive reuse of an existing building.

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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 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 manufacturing 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 works 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.

2.3. Knowledge Gap

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. Fig. 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.

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3. Disassembly Planning Approach for Buildings

Disassembly planning consists of creating a disassembly model and then generating disassembly sequences (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.

3.1 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. Fig. 3 shows the configuration of the final 6D BIM prototype under study.

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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 Fig. 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.

3.2 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 Fig. 4 is.

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

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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 works 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 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, Fig. 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 Fig. 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*).

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 Fig. 4, $CF_1 = 3$ and $CF_3 = 2$.

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 works 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 $MF = 0$.

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-

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level-working-space parts. The approach of this study uses the *PC* matrix to choose optimized part disassembly directions.

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. Fig. 5 shows the hierarchical liaison graph for the assembly prototype under study.

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 Fig. 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.

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 $LC_7 = [f_8, f_9]$.

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*).

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®, thinkstep® & Autodesk®, 2015). 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 Fig. 4 is.

$$EnvC = \begin{bmatrix} EnvC_1 \\ EnvC_2 \\ EnvC_3 \\ EnvC_4 \\ EnvC_5 \\ EnvC_6 \\ EnvC_7 \\ EnvC_8 \\ EnvC_9 \\ EnvC_{10} \end{bmatrix} = \begin{array}{c} \begin{array}{cc} \textbf{GWP} & \textbf{PED} \end{array} \\ \left[\begin{array}{rr} 805.43 & 6{,}416.06 \\ 805.43 & 6{,}416.06 \\ 805.43 & 6{,}416.06 \\ 228.94 & 3{,}124.31 \\ 202.74 & 1{,}568.91 \\ 202.74 & 1{,}568.91 \\ 174.34 & 2{,}516.24 \\ 485.25 & 3{,}733.11 \\ 12.47 & 185.29 \\ 21.93 & 301.00 \end{array}\right] \end{array} \tag{2}$$

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

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individual demolition/disassembly cost for each component meant to be part of the same assemblage. The component cost for these works 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 Fig. 4 is.

$$EC = \begin{bmatrix} EC_1 \\ EC_2 \\ EC_3 \\ EC_4 \\ EC_5 \\ EC_6 \\ EC_7 \\ EC_8 \\ EC_9 \\ EC_{10} \end{bmatrix} = \begin{bmatrix} \$438.25 \\ \$438.25 \\ \$438.25 \\ \$86.75 \\ \$71.61 \\ \$71.61 \\ \$86.75 \\ \$174.73 \\ \$67.29 \\ \$40.12 \end{bmatrix} \begin{array}{l} S.Demolition \\ S.Demolition \\ S.Demolition \\ S.Disassembly \\ S.Disassembly \\ S.Disassembly \\ S.Disassembly \\ S.Demolition \\ S.Disassembly \\ S.Disassembly \end{array} \qquad (3)$$

3.3 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 works). 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 works, 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 (Smith and Hung, 2015, Smith et al., 2012, Smith et al., 2016, Smith and 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 (Smith and Hung, 2015, Smith et al., 2012, Smith et al., 2016, Smith and Chen, 2011). This

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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 works.

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.

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 (Smith et al., 2012). Similar to previous studies for manufacturing products' disassembly (Smith and Hung, 2015, Smith et al., 2012, Smith et al., 2016, Smith and 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 works. 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 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 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 the other expert rules. Fig. 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.

4.2 Disassembly Sequence Planning Algorithms

Algorithm 1 in Table 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

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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 2 in Table 2 shows the steps for creating the *EVM* matrix. This matrix contains the numerical quantification of the accumulated cost associated with all 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 3 in Table 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.

Table 1

Algorithm for creating a combined matrix MF_{HC} for the first expert rule

```
Step  Algorithm 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 2

Algorithm for creating an *EVM* matrix for the second expert rule

```
Step  Algorithm 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
```

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

```
Step  Algorithm 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. Case study

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

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 Fig. 4 and 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. Fig. 7 shows the 19-part assembly prototype under study. If an enumeration method is used, there are $19! = 1.22 \cdot 10^{17}$ 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.

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 Fig. 4, the best directions for removing components c_7 and c_5 are $-y$ and $+x$ directions respectively. Fig. 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

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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.

5.2. Example 2

Fig. 9 and 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 Fig. 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.

6. Conclusions and future work

This paper establishes the reference framework of the key role that adaptive reuse of buildings has inside the circular economy 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 the paper, 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 lifecycle 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.

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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.

As future research, the new approach has to incorporate more than a single method of disassembly or deconstruction according to the most common practices in this matter. For the purposes of this study, 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 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.

In other topics, 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.

Acknowledgements

The authors would like to thank the energy Council of Canada (ECC) and the Waterloo Institute for Sustainable Energy (WISE) for providing support for this research paper.

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Figure Caption

Fig. 1. Disassembly planning categories for buildings and products.

Fig. 2. The role of green design methods in the reduction of environmental burdens for building stock renovation

Fig. 3. 6D BIM building frame structure prototype.

Fig. 4. Two-dimensional representation of the assembly prototype.

Fig. 5. Hierarchical liaison graph of the assembly prototype.

Fig. 6. An Approach for Sequence Disassembly Planning for Buildings (SDPB).

Fig. 7. Assembly prototype.

Fig. 8. Automated graph generation of the single-target disassembly plans for components c_7 and c_5.

Fig. 9. Example building assembly 2.

Fig. 10. Exploded view of example building assembly 2.

Fig. 11. Automated graph generation of the single-target disassembly plan for components c_{19}.

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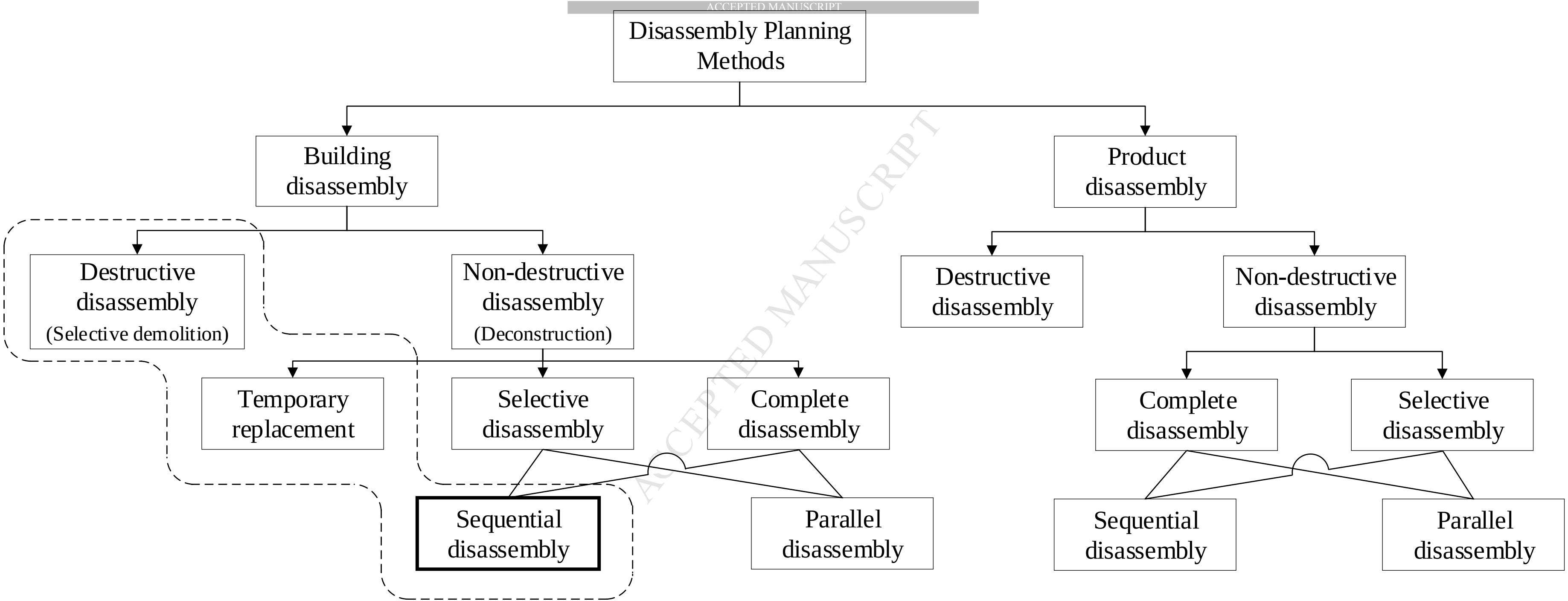

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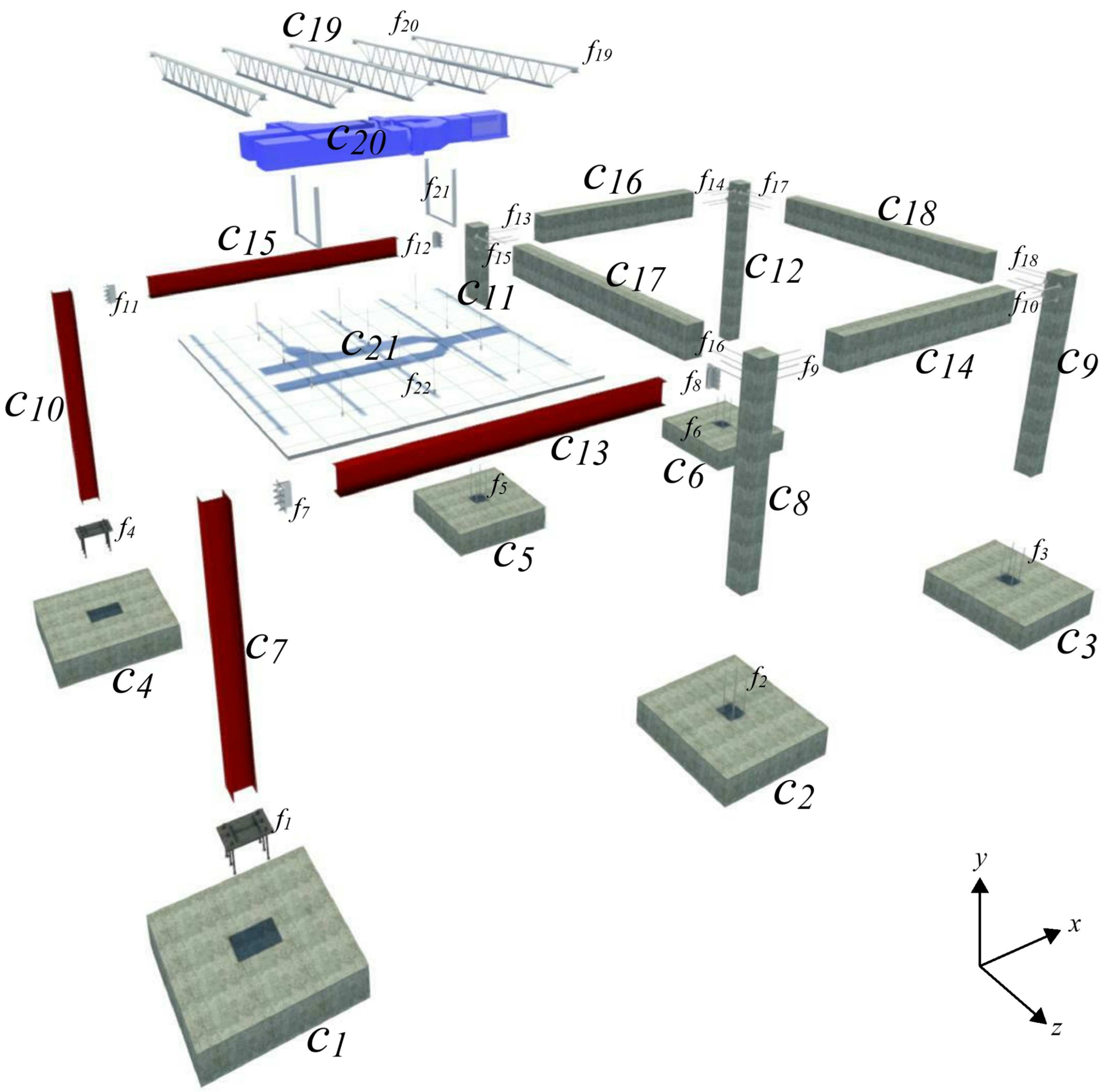

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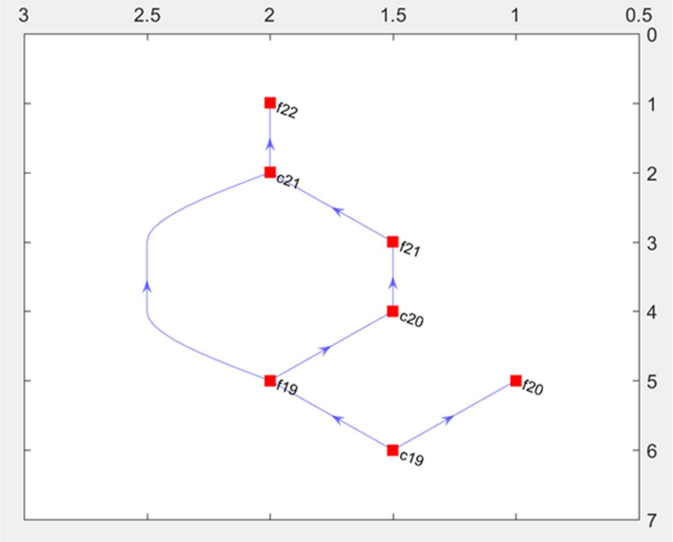

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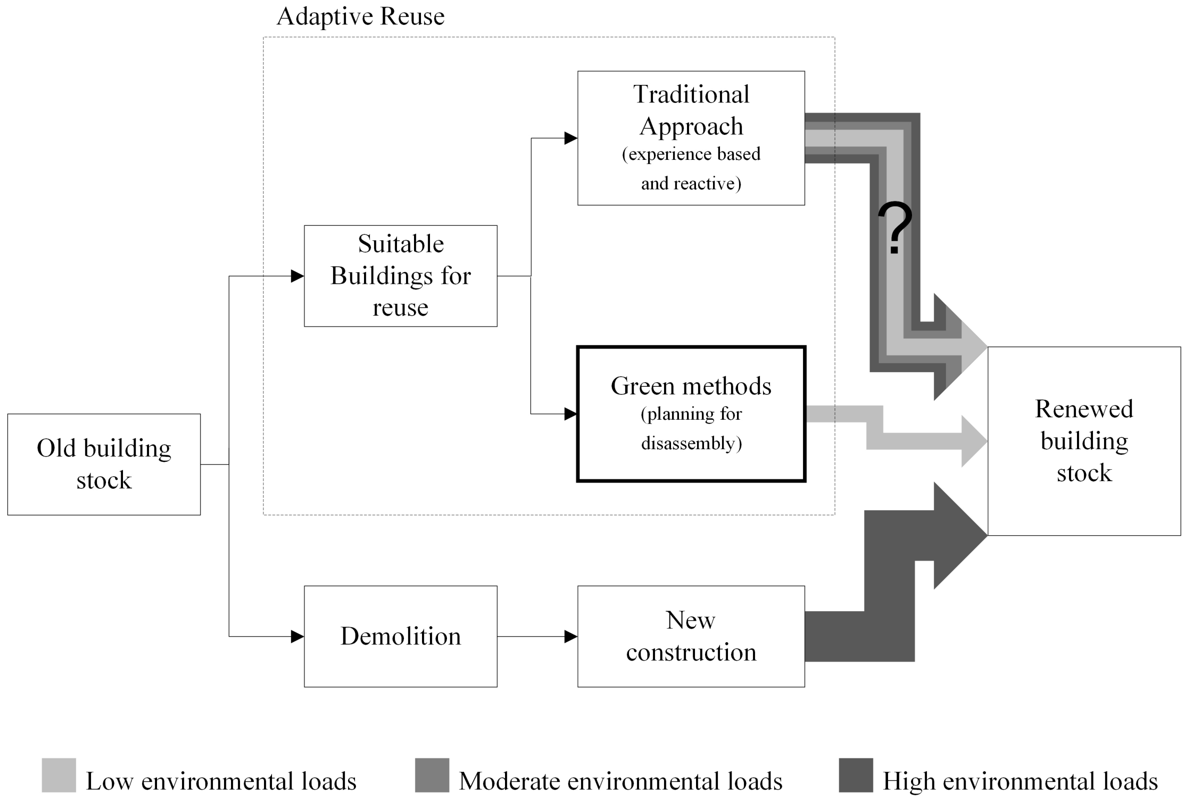

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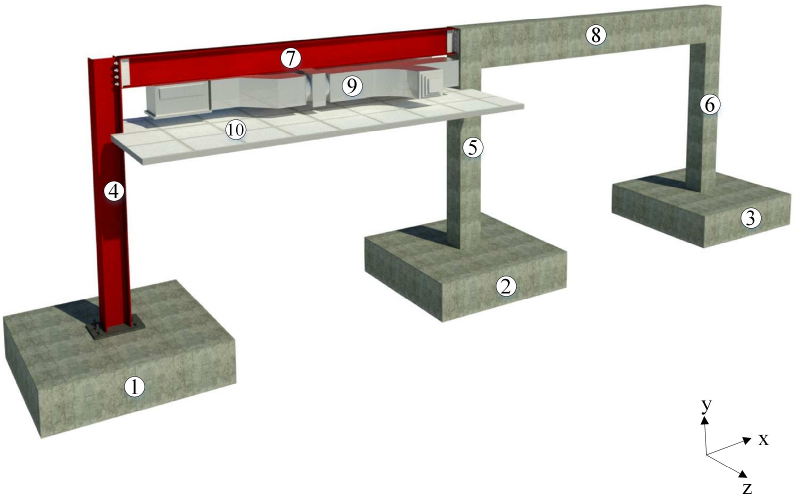

Assembly components:

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.

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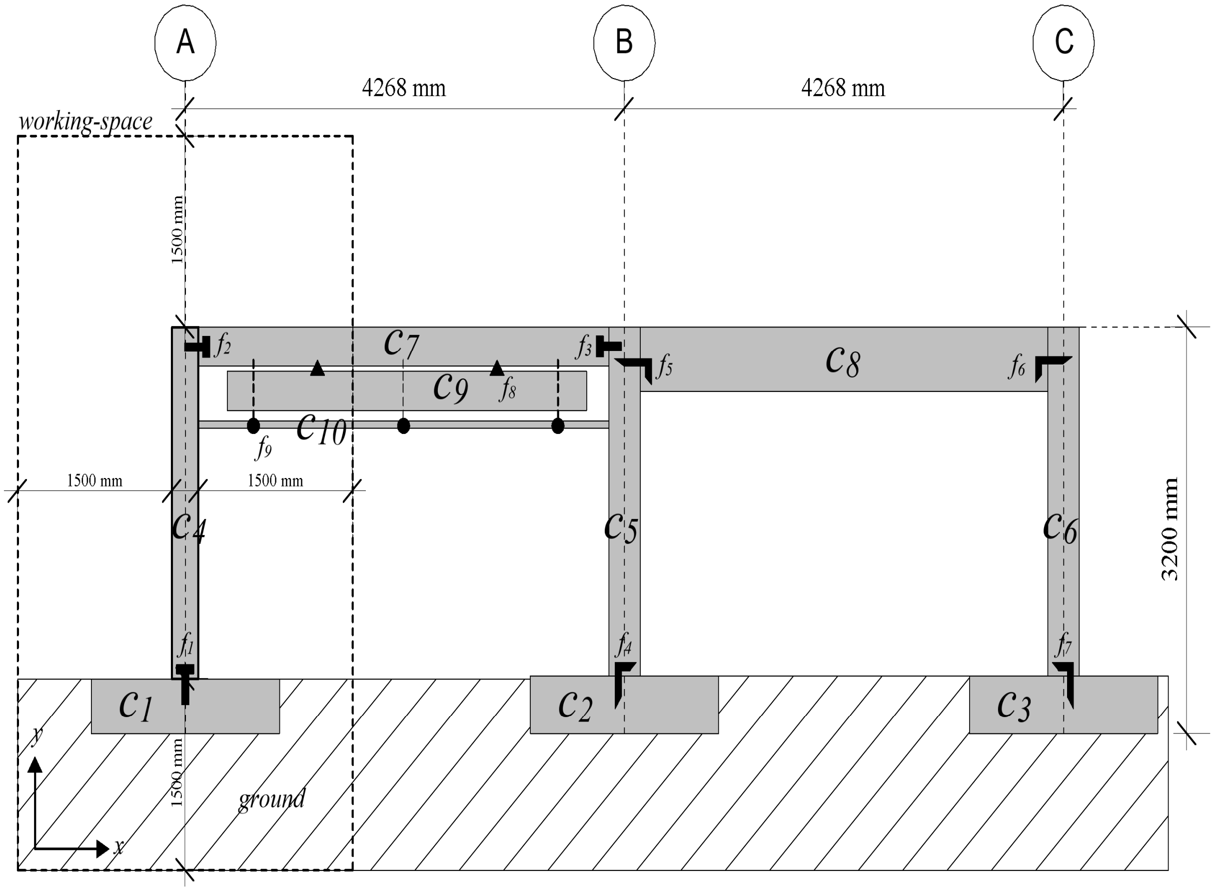

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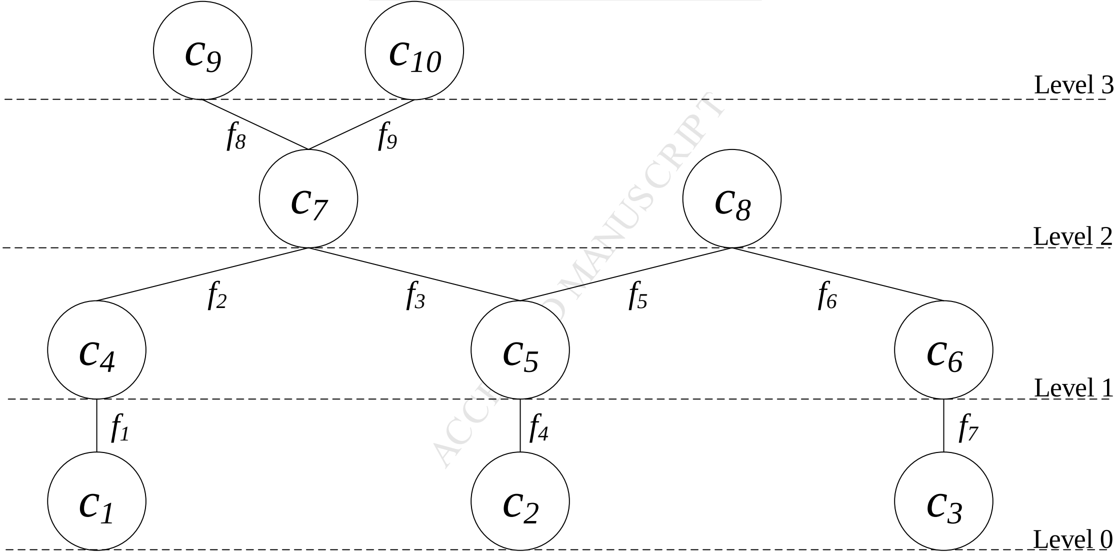

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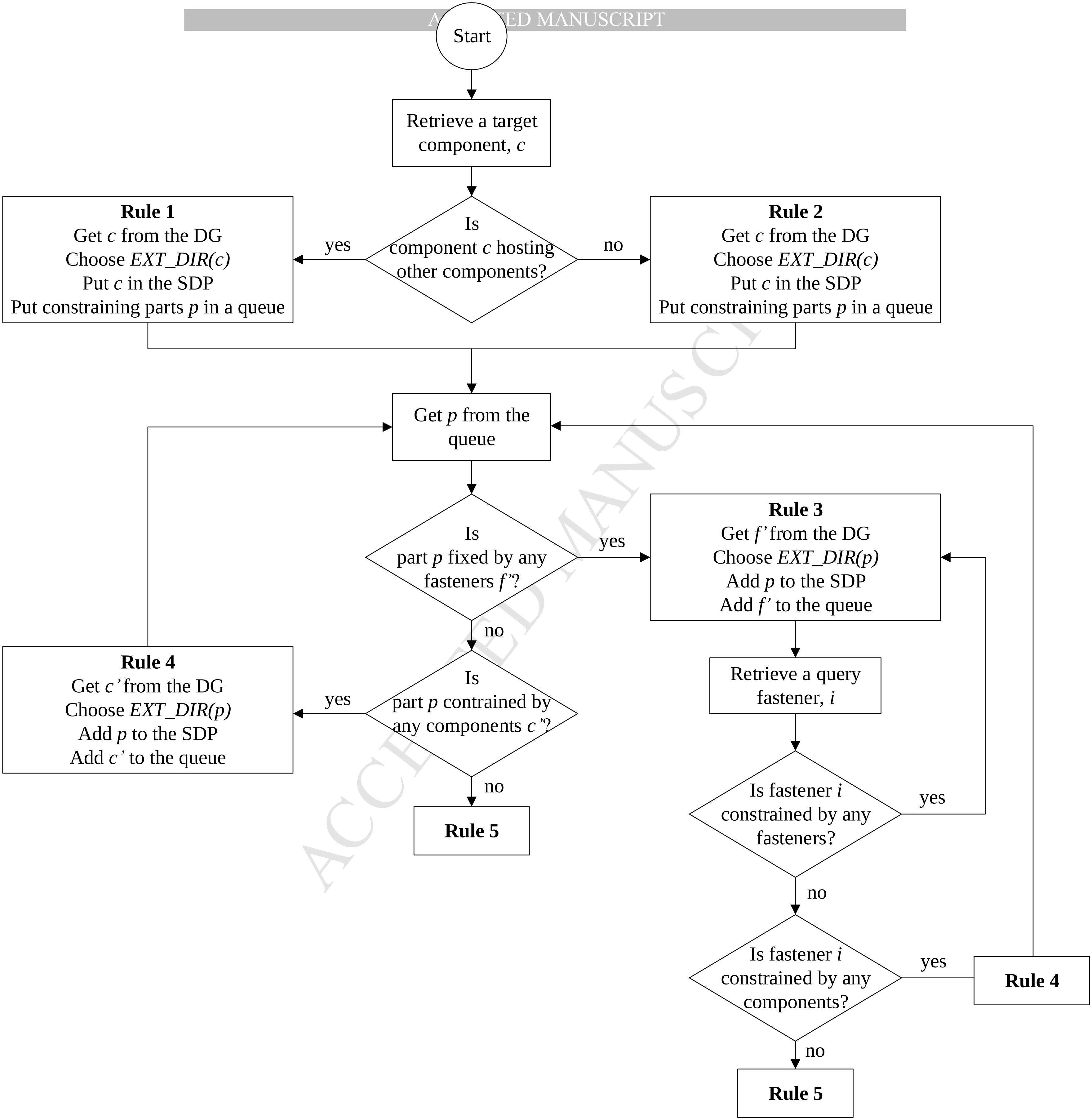

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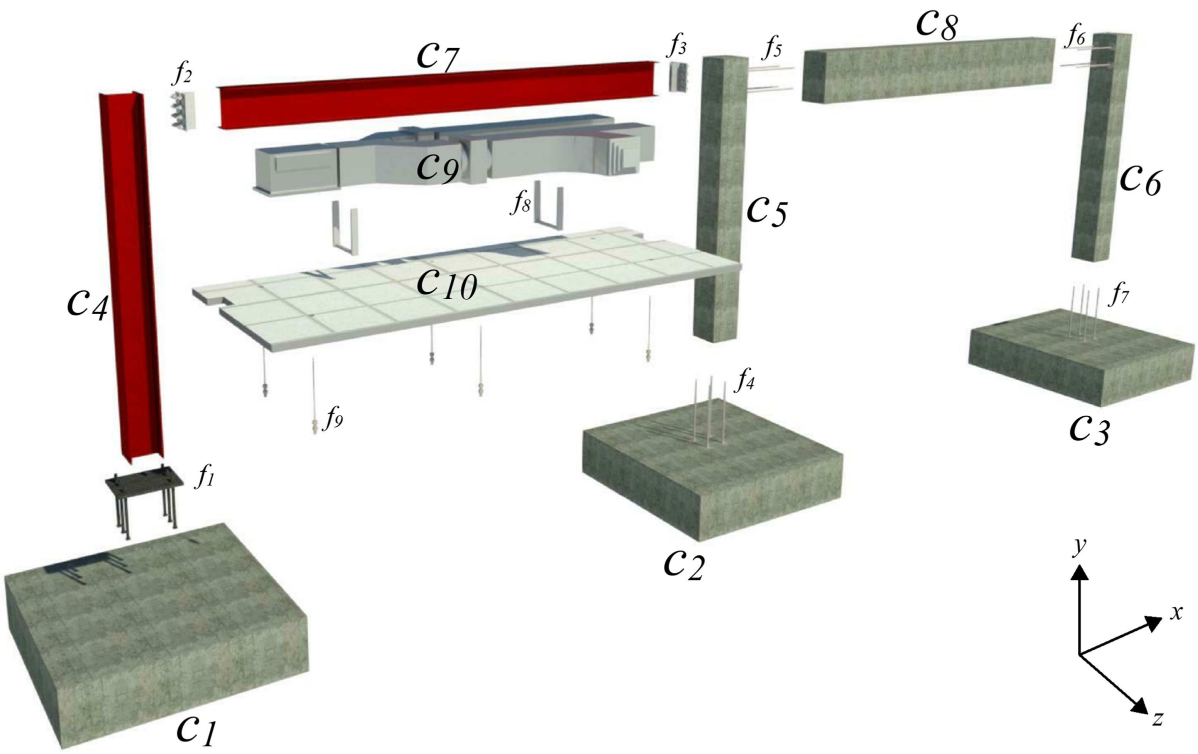

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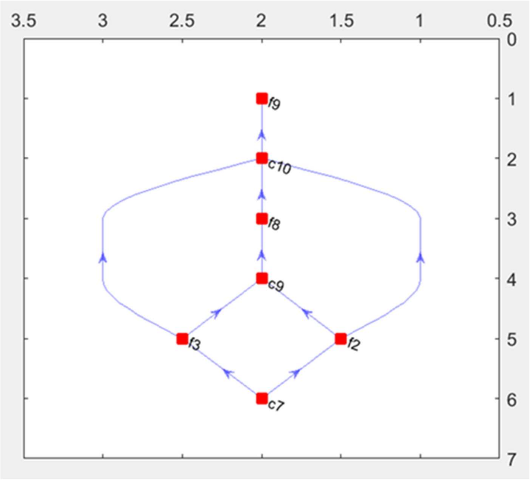

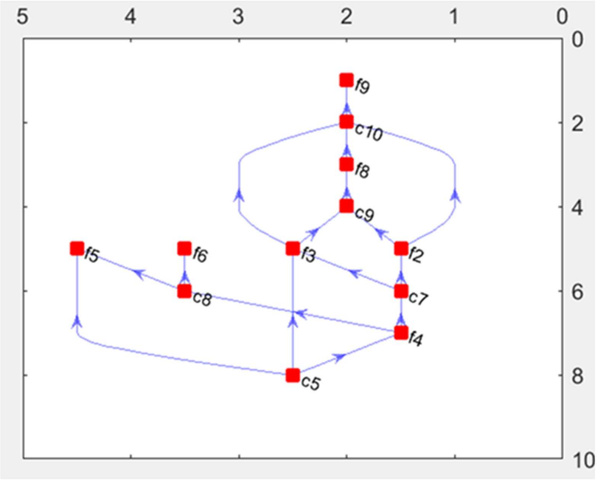

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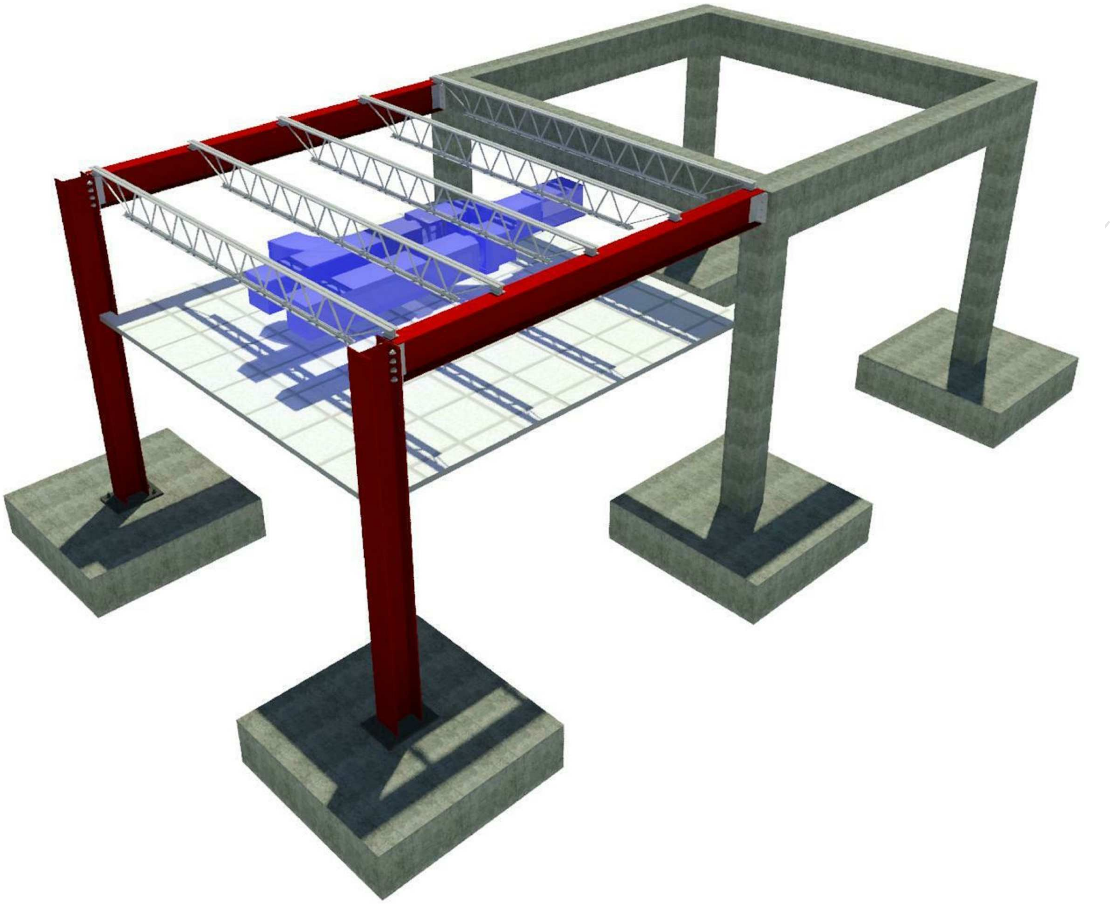

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Highlights

- 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.

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