Identifying key parameters for BIM-based disassembly planning

Benjamin Sanchez[1]**, Pieter Herthogs**[1] **and Rudi Stouffs**[2]

[1]Singapore-ETH Centre, Future Cities Lab Global Programme, CREATE campus, 1 CREATE Way, #06-01 CREATE Tower, Singapore 138602

[2]Department of Architecture, School of Design and Environment, National University of Singapore, Singapore 117566, Singapore

benjamin.sanchez@sec.ethz.ch, pieter.herthogs@sec.ethz.ch, stouffs@nus.edu.sg,

Abstract

Reuse of building systems and components has the potential of taking full advantage of the residual utility of building materials. In this matter, disassembly planning plays a critical role for retrieving reusable components in an optimized way. Unfortunately, the implementation of disassembly planning for buildings, at a component level, is still limited due to the lack of standardized methods and the lack of the definition of necessary characteristics (parameters) for building disassembly models. Therefore, the aim of this paper is to identify the necessary parameters for disassembly models and collate them into a framework. The approach in this study uses BIM as the main platform and graphic interface for managing the disassembly parameters for building components. First, the necessary information for building disassembly models is investigated. Then, the parameters for disassembly models are suggested and they are instrumented using BIM for a case study. The results of the enriched BIM disassembly model are verified according to the analytical solution for disassembly models for buildings.

Keywords –

Building Information Modeling; Disassembly planning; Building components reuse; Building disassembly model

1 Introduction

Reuse of building components has become a very important matter since year by year the construction industry is responsible for about 40% of the global natural resources exploitation, and 40% of waste diverted in landfills [1]. To overcome this challenge, technological advancements, such as Construction Waste Management (CWM), Materials Passports (MP), Product Recovery Management (PRM), and Life Cycle Assessment (LCA) [2], have been implemented to increase the rates of reuse and recycling of building components. However, the implementation for reuse of building components and systems is still scarce due to the lack of research about reclamation protocols [3]. In this matter, disassembly planning is a strategic approach for the recovery of building components and systems for their future reuse or recycling [4,5]. Disassembly planning is the process of recognizing the required consecutive steps for dismantling a building, defining deconstruction activities, and ordering them logically. Figure 1 shows the disassembly planning methods for buildings according to the nature, type, and mode of disassembly.

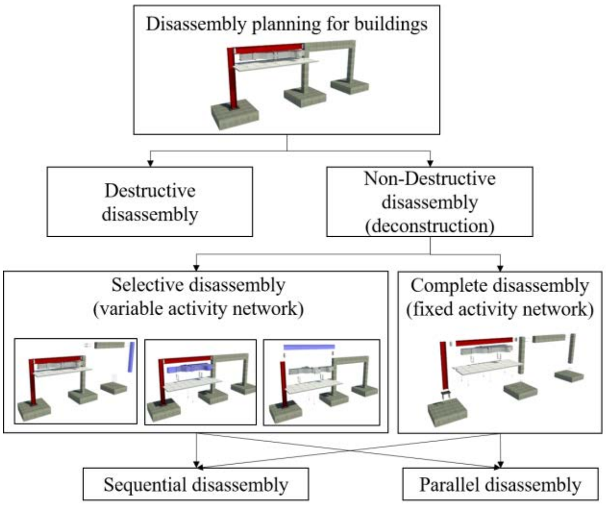


Figure 1. Disassembly planning methods for buildings

Unfortunately, disassembly planning for buildings is still underdeveloped in comparison to other industries such as manufacturing, automobile, and electronic industries [4,6]. The definitions of the characteristics (parameters) that a disassembly model should have are critical for the implementation of disassembly planning methods. This field is still underdeveloped for buildings. In the following section we identify the parameters needed for disassembly models of buildings, based on a literature review and on previous studies in this domain.

2 Required information for disassembly models of buildings

In this study we identify three consecutive disassembly modelling stages in agreement to the study presented by Zhou et al. [7] for manufacturing products. The three stages are: (1) preprocessing stage, (2) analytical disassembly model stage, and (3) performance stage. According to these stages, we present in Table 1 the parameters for disassembly planning of buildings based on (1) lessons learned from previous studies for the implementation of disassembly planning for building archetypes [6] and (2) a literature review of disassembly planning methods for buildings.

2.1 Preprocessing stage

In this stage the critical information regarding parts and the interdependency relationships among the parts of a disassembly model must be defined. Each disassembly element that is meant to be part of the disassembly model under study must have associated the relationship parameters that link it with the rest of the assembly. The *global disassembly model identifier* is the unique descriptor for identifying all the parts that conform to the same disassembly model. The identifier is an alphanumeric value (e.g., $c_{\#}$, $beam_{\#}$, $part_{\#}$). The *disassembly part type* is the classification for any disassembly part either as a component or a connection. For products' and buildings' disassembly, this classification has been standardized identifying components as *c* and connections as fasteners f [7,22]. The *disassembly part identification* assigns a numerical identifier for part types, e.g., c_1 and f_1. *Hosted components* and *hosted connections* register the parts that structurally depend on a host component.

Connection disassembly is the degree of difficulty for a connection to be disassembled usually expressed as a grade of a rating scale. This is a characteristic that has been explored deeply for manufacturing products [7,22]. In contrast, for buildings' disassembly there are just a few studies that have integrated this metric to measure the affordability for deconstruction. The main reason is the lack of studies directed specifically to the assessment of deconstructability of buildings' connections, and with it

Table 1 Required information for disassembly planning of buildings

	Preprocessing stage											Analytical disassembly model stage							Performance stage								
Source	Global disassembly model	Disassembly part type	Disassembly part	Hosted components	Hosted connections	Connection disassembly	Fastener constraint type	Physical interface	Global coordinate system	Local coordinate system	Assembly elements location	Structural composition	Graph data structure	Extraction directions	Object geometry (2D, 3D)	Physical constraints	Modular subassemblies	Working space	Disassembly tool	Disassembly method	Environmental impacts	Disassembly time	Disassembly cost	Disassembly revenue	Disassembly distance	Operation number	Disassembly energy
[6]	✓	✓	✓	✓	✓		✓		✓		✓	✓	✓	✓	✓	✓		✓			✓		✓				
[4]	✓	✓	✓	✓	✓		✓		✓		✓	✓	✓	✓	✓	✓		✓			✓	✓	✓				
[8]	✓	✓	✓	✓	✓		✓		✓		✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓			
[9]	✓	✓	✓	✓	✓		✓		✓		✓	✓	✓	✓	✓	✓		✓									
[10]	✓	✓	✓	✓		✓						✓	✓					✓				✓	✓	✓			
[11]	✓	✓	✓	✓	✓				✓				✓	✓	✓	✓				✓	✓	✓	✓				
[12]	✓	✓	✓	✓	✓	✓						✓	✓					✓			✓		✓	✓			
[13]	✓	✓	✓	✓	✓	✓						✓	✓														
[14]	✓	✓	✓	✓	✓								✓														
[15]	✓	✓	✓	✓	✓								✓				✓										
[16]	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓		✓			✓									
[17]	✓		✓			✓	✓	✓				✓	✓				✓										
[18]	✓		✓	✓	✓	✓	✓	✓	✓			✓	✓		✓		✓			✓	✓	✓	✓	✓			
[19]	✓		✓			✓	✓	✓				✓	✓				✓			✓	✓	✓	✓	✓			
[20,21]	✓	✓	✓			✓	✓					✓	✓						✓		✓	✓					

the establishment of a standardized metric. In this respect, some recent studies have proposed and implemented a BIM-based disassembly score system such as the Disassembly and Deconstruction Analytics System (D-DAS) [23] and Deconstructability Assessment Scoring (DAS) [24]. Both approaches propose innovative ways to measure deconstructability of buildings based on a qualitative description of the demountability of the building connections. Other studies have developed weighted ranking lists to score the grade of deconstructability based on the description of different types of connections and material characterization [13,25,26].

Fastener constraint type indicates the condition of a fastener being removed in either one direction or two directions. *Physical interface characterization* defines the geometrical and mechanical specifications associated to different types of connections (e.g., bolts, screws, rivets, washers, welding). None of the current approaches for disassembly planning of buildings have included this characteristic. However, the *physical interface characterization* plays a critical role for the accurate study of the disassembly properties of a connection type. We consider this characteristic of high relevance for buildings' disassembly. In comparison to manufacturing products, buildings' connections have a higher level of importance for obvious reasons. First, the structural integrity and reliability of any component (structural and non-structural) depends on the appropriate selection, design, dimensioning, and installation of its connections. Failing to achieve this might produce damages to the building and, more important, injuries to its users. Second, buildings' connections represent a higher percentage on the investment.

The *global coordinate system* defines the origin of a 3D cartesian coordinate system associated to all the parts of the disassembly model. The *local coordinate system* defines the local origin of a 3D cartesian coordinate system associated to each disassembly part. The *assembly elements location* constitutes the 3D coordinates that define the location of each disassembly part in the global coordinate system. This characteristic is exclusive for those methods in which the geometrical representation of the disassembly model is the basis for determining physical constraints among components (e.g., contact, motion, and projection constraints).

2.2 Analytical disassembly model stage

The analytical disassembly model is the mathematical representation of the disassembly model, disassembly constraints, and the disassembly precedence relationships. According to the literature review on disassembly planning for products and buildings the most studied analytical disassembly models are interference graphs, Petri nets, and constraint matrices [7]. These approaches have the objective of describing the composition of the disassembly model in a consistent data structure for its computational processing. In this respect, a *graph data structure* is necessary for establishing the mathematical configuration of the disassembly model. A graph data structure is the abstract representation of a disassembly model through nodes (vertices) and liaisons (edges). For building disassembly, some studies have implemented Graph Data Models (GDM) [10,12,13] and liaison graphs [4,6] as graph data structures for disassembly models. Other studies have used GDM to represent the connectivity between building components [14,15]. In this paper we propose an approach for determining the appropriate parameters for disassembly models at a component level, including the graph data structure. This can be achieved by registering for each component the liaison relationship(s) (fasteners f_n) with the component(s) (c_n) in the next upper level of the disassembly hierarchy (the components that are physically attached and supported by the component under study), as demonstrated in a previous study [6]. Then, in a next processing stage, the registered information for all of the components can be arranged in a matrix (liaison matrix) for the computation of the disassembly sequence.

The *structural composition relationship* is an important characteristic for disassembly models of buildings. This characteristic indicates the structural composition of components inside a disassembly model. For manufacturing products, any fastener can be removed from the disassembly model as long as the fastener is physically accessible. In comparison, in a building composition some fasteners could be physically accessible and removed but required for the structural stability of the assembly.

Extraction directions are the possible paths for removing any disassembly part. As a generality for disassembly planning methods the number of extraction directions is four in a 2D environment (+x, -x, +y, -y) and six in a 3D environment (+x, -x, +y, -y, +z, -z) [7,27,28]. The *object geometry* is the information related to the geometrical characteristics of the disassembly parts. *Physical constraints* are the physical restrictions of a disassembly part in any extraction direction (contact constraints, motion constraints, and projection constraints) [7,27,28].

Modular subassemblies is the property that form modules conformed by two or more disassembly parts which are to be retrieved together. Finally, the *working space* is an important characteristic for buildings' disassembly related to the necessary physical space for a human worker to develop disassembly works. The working space has also been explored for products' disassembly [7,29]. However, due to the significant difference of scale and the nature of the disassembly works, the implications for buildings are significantly different. For buildings it is necessary to add more detailing to the process of executing dismantling works in order to make the disassembly planning estimations significant. This includes analyzing the necessary space for manipulating disassembled components inside and outside the building, investigating the disassembly activities that need the participation of more than one human worker or mechanical manipulator (or the combination of both), and resolving resource allocation and scheduling (e.g., the possibility of developing disassembly works on different work fronts simultaneously). These are topics that have been continuously under development in Project Management (PM) for building construction. We argue the need to extend the scope of the investigations to disassembly planning of buildings.

2.3 Performance stage

This stage is related to the objectives to optimize the disassembly planning. The optimization objectives can change according to the particularities of the project and according to the goals of the stakeholders. The most common optimization objectives are low cost, low environmental impact, high revenue, and decreased time execution [7]. For a given optimization, objective specific information per disassembly part must be defined as a numerical value and unit.

Disassembly tool information establishes the instrumentation to be used for disassembly. The use of mechanical tools decreases the time for the disassembly process but increments the cost [7]. The *disassembly method* refers to the depiction of disassembly works per building component, such as perfect disassembly, destructive disassembly, and selective demolition [8]. *Environmental impacts* refer to the associated environmental impacts (e.g., Global Warming Potential [GWP], Primary Energy Demand [PED]) per building component according to the definition and scope of an LCA. *Disassembly time*, *cost*, and *revenue* are the designated amount of time, cost, and profit for disassembling a building component depending on the disassembly method and instrumentation used. The *disassembly distance* is the distance moved in disassembling a component.

The *operation number* is the total number of activities developed for the disassembly process. This domain has only been studied for the disassembly planning of manufactured products. Here, the quantified activities depend on the disassembly approach. For example, some studies have quantified the number of change of directions of a disassembly tool (manipulated by a worker) that are needed to remove fasteners [7]. Other studies have quantified the total distance traveled by a worker through different working stations in a disassembly line. Similarly, the consideration of *operation number* must be included as part of the disassembly planning for buildings in future investigations, to determine the correct approach and appropriate metrics.

Disassembly energy consumption is relevant when robotic disassembly is considered for total or partial execution of the works. It refers to the energy consumption of robots and heavy machinery in the disassembly process. It is important to mention that the last three parameters of *disassembly distance*, *operation number*, and *disassembly energy consumption* were gathered from a literature review, developed by Zhou et al. [7], of disassembly planning for manufactured products. Even though none of the approaches for buildings presented in Table 1 includes these parameters, we consider they are relevant to the disassembly of buildings and should be included, adapted, and implemented for buildings assets.

3 BIM disassembly parameters

BIM is arguably the most important technology used in the construction industry for planning and monitoring building processes along the entire life cycle of a building project [30]. BIM is a highly organized 3D model-based graphical interface for the efficient planning, designing, constructing, and management of buildings assets. In the last three decades, plenty of investigations have explored the benefits of implementing BIM in different life cycle stages of building projects, however its implementation for the End-of-Life (EoL) stage is still underdeveloped [4,6]. In this paper we argue that the current information included in BIM is incomplete and undefined for specific tasks in the EoL stage of buildings such as disassembly planning. Some of this information is indirectly embedded in BIM elements according to the Industry Foundation Classes (IFC) schema, which is the universal data format for BIM. Therefore, according to the disassembly model characteristics presented in the last section we define the BIM parameters needed for disassembly models for buildings and map the corresponding IFC entities for their definition (Table 2). These parameters can be gathered from an information model, during the planning and design stage. The parameters can be categorized according to their nature as: type parameter and instance parameter. Type parameters are the same for all the existences of BIM elements that belongs to the same family type, while instance parameters are unique to a kind of BIM object. Overall, 27 parameters (9 type parameters, 18 instance parameters) were identified (see Table 2). Figure 2 shows the mapped parameters for disassembly models into the IFC schema. The definitions of the type and instance parameters displayed in Figure 2 are a suggested first

Table 2 BIM parameters for disassembly models

Stage	Parameter	Unit	Type/instance	Available/new/retrievable
Preprocessing	Global disassembly model	Numeric	Instance	Available/read
	Disassembly part type	Binary	Instance	New/write
	Disassembly part identification	Alphanumeric	Instance	New/generate
	Hosted components	Alphanumeric	Instance	New/write
	Hosted connections	Alphanumeric	Instance	New/write
	Connection disassembly	Numeric	Type	New/write
	Fastener constraint type	Numeric	Type	New/write
	Physical interface	Numeric	Instance	Available/read
	Global coordinate system	Numeric	Type	Available/read
	Local coordinate system	Numeric	Instance	Available/read
	Assembly elements location	Numeric	Instance	New/generate
Analytical disassembly model	Structural composition	Alphanumeric	Instance	New/generate
	Graph data structure	Alphanumeric	Instance	New/generate
	Extraction directions	Numeric	Type	Available/read
	Object geometry (2D, 3D)	NA	NA	Available/read
	Physical constraints	Numeric	Instance	New/generate
	Modular subassemblies	Numeric	Type	Available/read
	Working space	Numeric	Type	New/write
Performance	Disassembly tool	Alphanumeric	Type	New/write
	Disassembly method	Alphanumeric	Type	New/write
	Environmental impacts (LCA)	Numeric	Instance	Retrievable/read
	Disassembly time	Numeric	Instance	Retrievable/read
	Disassembly cost	Numeric	Instance	Retrievable/read
	Disassembly revenue	Numeric	Instance	Retrievable/read
	Disassembly distance	Numeric	Instance	New/generate
	Operation number	Numeric	Instance	New/generate
	Disassembly energy consumption	Numeric	Instance	Retrievable/read

approach for simple BIM archetypes. This approach needs future revisions and investigations to demonstrate their functionality at a large scale for disassembly projects. As it happens for building projects, the definition of type or instance parameters for BIM elements can be customized depending on the objectives and characteristics of each project.

The parameters can be categorized according to the nature of the registered information such as *available*, *new*, and *retrievable* [31]. The *available* category is embedded information in the BIM elements that can be accessed (*read*) directly from the IFC schema. The *new* category refers to information missing in the BIM elements that can either be entered (*write*) by the user during the modeling process, or it can be estimated (*generate*) with a customized subroutine. The *retrievable* category is information that is not embedded in the BIM elements. However, the information is available in external databases and it can be accessed (*read*) and registered with an appropriate subroutine.

As it is displayed in Figure 2, we propose the mapping of the disassembly model parameters into the IFC schema. In this study, the process of retrieving, updating, and registering information in the IFC file is done through a Visual Programming Interface (VPL) in the BIM modeler Revit. In this stage of development, the whole process is manual, as a proof of concept, by entering the information of a disassembly model archetype from a previous study [6]. In future stages of development, the appropriate subroutines will be developed for the automated retrieving, updating, and registering of information in the IFC file.

4 Case study – BIM for disassembly planning

For the functional demonstration of the presented framework of assembly model characteristics and corresponding BIM parameters, we developed an information model with all the required parameters for developing the disassembly planning for retrieving targeted components. The archetype used in this demonstration comes from a previous study [6]. Similarly, the validation of the model is achieved through the comparison of the parameters included in the BIM model with the ones resolved for the analytical disassembly model of the previous study. Figure 3 shows the BIM interface with the parameters of the BIM element c_1 (structural steel column). Some of the parameters of the performance stage do not have an associated value. The reason is the lack of availability of

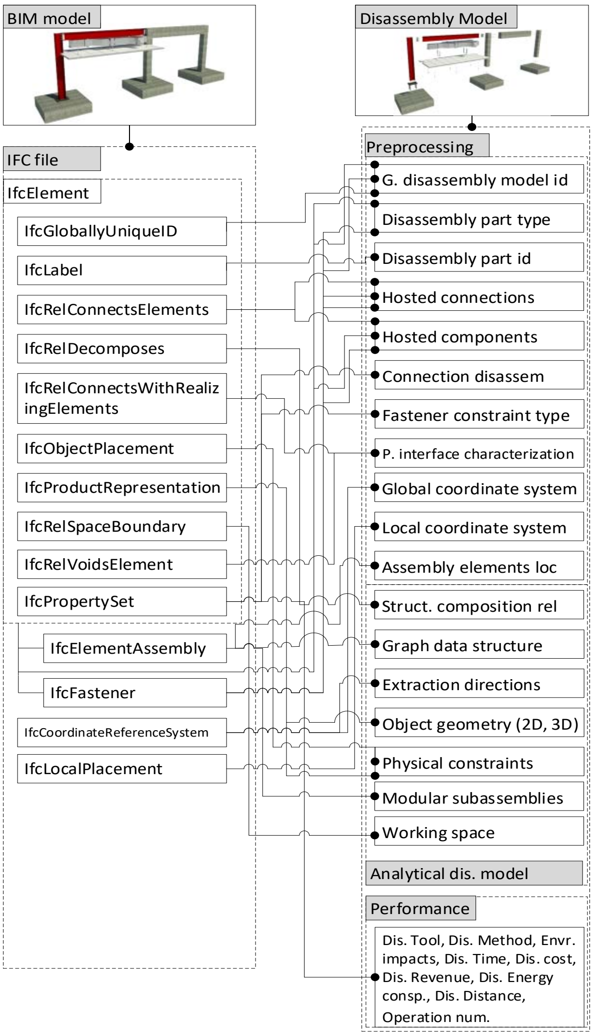
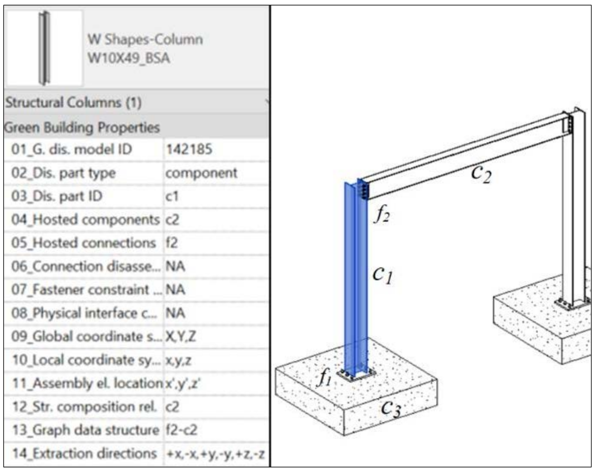


Figure 2. Mapped parameters into IFC for disassembly models


W Shapes-Column
W10X49_BSA

Structural Columns (1)

Green Building Properties

01_G. dis. model ID	142185
02_Dis. part type	component
03_Dis. part ID	c1
04_Hosted components	c2
05_Hosted connections	f2
06_Connection disasse...	NA
07_Fastener constraint ...	NA
08_Physical interface c...	NA
09_Global coordinate s...	X,Y,Z
10_Local coordinate sy...	x,y,z
11_Assembly el. location	x',y',z'
12_Str. composition rel.	c2
13_Graph data structure	f2-c2
14_Extraction directions	+x,-x,+y,-y,+z,-z

Figure 3. BIM disassembly planning parameters

reliable sources to gather such information. As discussed in subsection 2.3, that information depends on the kind of optimization assessment to perform.

5 Conclusions and future work

The results of this study demonstrate that it is possible to set the appropriate parameters for disassembly models using BIM. In this respect the IFC schema can be used to determine most of the disassembly parameters. The parameters can be retrieved directly from the IFC schema, or they can be calculated using a combination of them. It is demonstrated that it is technically feasible to develop semantically enriched BIM disassembly models using a commercial BIM software. With the disassembly BIM model ready, in the next steps it will be possible to implement any of the disassembly planning theories to develop assessments for the partial or total disassembly of the building structures. This study provides a comprehensive overview of the necessary information for disassembly models of buildings. The framework presented in this study can help to overcome the technical barriers that nowadays limit the implementation of disassembly planning in a systematic and standardized way.

A future step for this research is the development of a BIM-based automated semantic enriching engine for disassembly models. This approach will improve the generation of correct and fully semantically enriched BIM models. As discussed in Section 3, some of the proposed parameters can be retrieved from the BIM model (*available/read*), some can be entered by the users during the modelling process (*new/write*), some others can be estimated (*new/generate*), and others can be retrieved from external databases (*retrievable/read*). For any of these cases it is possible to develop the appropriate technology, e.g. Visual Programming Language (VPL) or Application Programming Interphase (API) subroutines, for the systematization and automation of the process. These techniques have become very popular in the field of open BIM in the last years. They have demonstrated efficiency for the manipulation of information in BIM environments, technical feasibility for interconnecting multiple digital technologies, and the interoperability of the processes. Therefore, the whole process of semantic enrichment of a BIM disassembly model, the verification of the completeness and correctness of the information, and the development of the disassembly assessments can be integrated in a BIM platform.

One of the limitations of the proposed approach is the elevated amount of data to integrate into a BIM model, for each one of the BIM elements (components and fasteners). This high Level of Detail (LoD) of information could be difficult to compute for large building assemblies. However, it could be possible to implement this approach for representative subassemblies to reduce the computational requirements. Also, with the development of the computational technology, in the future this kind of high LoD assessments could be possible and technically affordable. Another limitation, is the lack of available and reliable information regarding disassembly/deconstruction works. This is related to the performance stage of the proposed approach where it is necessary to have access to disassembly information for building components such as cost, time, environmental impacts, disassembly methods, among others. Nevertheless, the current reliable information in this field is very limited to the most recurrent and traditional techniques in the construction industry. This field has attracted the attention of researchers, companies, and governments in the last two decades due to the global climate emergency. Therefore, more investigations and regulations in the industry have appeared and it is expected that they will keep increasing in the coming years. The evidence shows that there is huge potential for the reuse of materials in the built environment, and the new trends of reusable buildings will lead the future for sustainable urban development.

Acknowledgements

This research was conducted at the Future Cities Lab Global at Singapore-ETH Centre. Future Cities Lab Global is supported and funded by the National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme and ETH Zurich (ETHZ), with additional contributions from the National University of Singapore (NUS), Nanyang Technological University (NTU), Singapore and the Singapore University of Technology and Design (SUTD).

References

[1] S. Badi, N. Murtagh, Green supply chain management in construction: A systematic literature review and future research agenda, Journal of Cleaner Production. 223 (2019) 312-322, https://doi.org/10.1016/j.jclepro.2019.03.132 ISSN 0959-6526.

[2] F. Jalaei, Integrate Building Information Modeling (BIM) and Sustainable Design at the Conceptual Stage of Building Projects, Doctoral Dissertation, 2015, University of Ottawa, .

[3] A. Mahpour, Prioritizing barriers to adopt circular economy in construction and demolition waste management, Resources, Conservation and Recycling. 134 (2018) 216-227.

[4] B. Sanchez, C. Rausch, C. Haas, Deconstruction programming for adaptive reuse of buildings, Automation in Construction. 107 (2019) 102921, https://doi.org/10.1016/j.autcon.2019.102921 ISSN 0926-5805.

[5] C. Rausch, B. Sanchez, C. Haas, Spatial Parameterization of Non-Semantic CAD Elements for Supporting Automated Disassembly Planning, Spatial Parameterization of Non-Semantic CAD Elements for Supporting Automated Disassembly Planning, 2019 Modular and Offsite Construction (MOC), Banff, AB, Canada, 2019, pp. 108-115, https://doi.org/10.29173/mocs83 .

[6] B. Sanchez, C. Haas, A novel selective disassembly sequence planning method for adaptive reuse of buildings, Journal of Cleaner Production. 183 (2018) 998-1010, https://doi.org/10.1016/j.jclepro.2018.02.201 ISSN 0959-6526.

[7] Z. Zhou, J. Liu, D.T. Pham, W. Xu, F.J. Ramirez, C. Ji, Q. Liu, Disassembly sequence planning: Recent developments and future trends, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. (2019), 10.1177/0954405418789975.

[8] B. Sanchez, C. Rausch, C. Haas, R. Saari, A selective disassembly multi-objective optimization approach for adaptive reuse of building components, Resources, Conservation and Recycling. 154 (2020), https://doi.org/10.1016/j.resconrec.2019.104605 ISSN 0921-3449.

[9] B. Sanchez, C. Rausch, C. Haas, T. Hartmann, A framework for BIM-based disassembly models to support reuse of building components, Resources, Conservation and Recycling. 175 (2021) 105825, https://doi.org/10.1016/j.resconrec.2021.105825 ISSN 0921-3449.

[10] F. Denis, C. Vandervaeren, N.D. Temmerman, Using network analysis and BIM to quantify the impact of Design for Disassembly, Buildings. 8 (2018) 113, https://doi.org/10.3390/buildings8080113 ISSN 2075-5309.

[11] M. Mahmoudi Motahar, S.H. Hosseini Nourzad, A hybrid method for optimizing selective disassembly sequence planning in adaptive reuse of buildings, Engineering, Construction and Architectural Management. 29 (2021) 307, 10.1108/ECAM-12-2020-1023 ISSN 0969-9988.

[12] C. Vandervaeren, W. Galle, A. Stephan, N. De Temmerman, More than the sum of its parts: Considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings, Resources, Conservation and Recycling. 177 (2022),

10.1016/j.resconrec.2021.106001.

[13] A. Menasce, N. Kobylinska, Exploratory development of graph-based models for disassembly, 2021, .

[14] A. Khalili, D.K.H. Chua, IFC-based graph data model for topological queries on building elements, Journal of Computing in Civil Engineering. 29 (2015), 10.1061/(ASCE)CP.1943-5487.0000331.

[15] S. Isaac, T. Bock, Y. Stoliar, A methodology for the optimal modularization of building design, Automation in Construction. 65 (2016) 116-124, https://doi.org/10.1016/j.autcon.2015.12.017 ISSN 0926-5805.

[16] S. Schaubroeck, R. Dewil, K. Allacker, Circularity of building stocks: Modelling building joints and their disassembly in a 3D city model, Circularity of building stocks: Modelling building joints and their disassembly in a 3D city model, Procedia CIRP, vol. 105, 2022, pp. 712-720, 10.1016/j.procir.2022.02.119 Available at https://www.scopus.com/inward/record.uri?eid=2-s2.0-85127526824&doi=10.1016%2fj.procir.2022.02.119&partnerID=40&md5=3a839546b9cc29633b611091e7723072, .

[17] E. Durmisevic, Transformable building structures: design for dissassembly as a way to introduce sustainable engineering to building design & construction, (2006).

[18] E. Durmisevic, A. Guerriero, C. Boje, B. Domange, G. Bosch, Development of a conceptual digital deconstruction platform with integrated Reversible BIM to aid decision making and facilitate a circular economy, Development of a conceptual digital deconstruction platform with integrated Reversible BIM to aid decision making and facilitate a circular economy, Proc. of the Joint Conference CIB W78-LDAC, vol. 2021, 2021, pp. 11-15, .

[19] P.R. Beurskens, The development of an evaluation method to support circular building design, (2021).

[20] D. Schwede, Application of RecyclingGraphs for the Optimisation of the Recyclability in Building Information Modelling, Application of RecyclingGraphs for the Optimisation of the Recyclability in Building Information Modelling, IOP Conference Series: Earth and Environmental Science, vol. 323, IOP Publishing, 2019, pp. 012044, .

[21] D. Schwede, E. Störl, System for the analysis and design for disassembly and recycling in the construction industry, Central Europe towards Sustainable Building Prague 2016 (CESB16). (2016).

[22] A.J.D. Lambert, Disassembly sequencing: A survey, 41 (2003) 3721-3759, 10.1080/0020754031000120078 ISSN 0020-7543.

[23] L.A. Akanbi, L.O. Oyedele, K. Omoteso, M. Bilal, O.O. Akinade, A.O. Ajayi, J.M. Davila Delgado, H.A. Owolabi, Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy, Journal of Cleaner Production. 223 (2019) 386-396, 10.1016/j.jclepro.2019.03.172.

[24] A. Basta, M.H. Serror, M. Marzouk, A BIM-based framework for quantitative assessment of steel structure deconstructability, Automation in Construction. 111 (2020) 103064.

[25] L. Mattaraia, M.M. Fabricio, R. Codinhoto, Structure for the classification of disassembly applied to BIM models. Architectural Engineering and Design Management. (2021), 10.1080/17452007.2021.1956420.

[26] D. Cottafava, M. Ritzen, J. van Oorschot, Report: D6. 1 Report on benchmarking on circularity and its potentials on the demo sites, (2020).

[27] S.S. Smith, W. Chen, Rule-based recursive selective disassembly sequence planning for green design, Advanced Engineering Informatics. 25 (2011) 77-87, http://dx.doi.org/10.1016/j.aei.2010.03.002 ISSN 1474-0346.

[28] S. Smith, G. Smith, W.-. Chen, Disassembly sequence structure graphs: An optimal approach for multiple-target selective disassembly sequence planning, Advanced Engineering Informatics. 26 (2012) 306-316, https://doi.org/10.1016/j.aei.2011.11.003 ISSN 1474-0346.

[29] Z.-. Li, S. Wang, W.-. Yin, Determining optimal granularity level of modular product with hierarchical clustering and modularity assessment, Journal of the Brazilian Society of Mechanical Sciences and Engineering. 41 (2019), 10.1007/s40430-019-1848-y.

[30] H. Mattern, M. König, BIM-based modeling and management of design options at early planning phases, Advanced Engineering Informatics. 38 (2018) 316-329, https://doi.org/10.1016/j.aei.2018.08.007 ISSN 1474-0346.

[31] F. Karim, F.H. Abanda, V. Christos, W. Graham, Taxonomy for BIM and Asset Management Semantic Interoperability, Journal of Management in Engineering. 34 (2018) 04018012, 10.1061/(ASCE)ME.1943-5479.0000610.