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A framework for BIM-based disassembly models to support reuse of building components

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Abstract

Reuse of building components and materials is essential in order to reduce global building waste and resource depletion. Reuse can also improve residual utility for building components and materials. Selective disassembly enables such reuse. Implementation of selective disassembly planning for buildings requires accurate and correct analytical disassembly models for building archetypes, which can be provided using Building Information Modeling (BIM). However, appropriate level-of-detail (LoD) for the required BIM-based parametric disassembly models and a methodology for automatically extracting the corresponding parameters from a BIM are unknown. These knowledge gaps are addressed by developing such a methodology for the appropriate LoD. This study aims to describe and validate a methodology for determining parameters for BIM-based disassembly models to support the reuse of building components towards a circular economy in the construction industry. Taking building structures as an example, disassembly model principles for typical building parts are proposed. Then, a framework of disassembly parametric models is determined and applied for BIM. Based on this framework, a method for automatically determining the necessary parameters is developed, and the critical attributes are suggested. Finally, the disassembly parameters of BIM elements are defined and demonstrated for four case studies in order to validate the consistency and effectiveness of this method. The results indicate useful disassembly models are properly produced within a reasonable amount of time.

Keywords: materials reuse, components reuse, disassembly model, disassembly planning, building information modeling, circular economy

1. Introduction

Building component reuse has been identified as a very effective alternative to maximize products' utility and value through several life-cycles (da Rocha and Sattler, 2009). From a life cycle perspective, the construction industry is responsible for the depletion of vast global natural resources and the gross production of landfill waste (Badi and Murtagh, 2019). This inefficiency of the construction life cycle has been addressed for building projects through the use of technologies such as Building Information Modeling (BIM) (Gan et al., 2018; Jalaei, 2015), material passports (Honic et al., 2019), and Life Cycle Assessment (LCA) (Akanbi et al., 2018). However, the end-of-life product recovery from the vast existing building stock is impeded by the lack of integration of deconstruction methods, reclamation protocols, and information technologies for dismantling (Hart et al., 2019; Mahpour, 2018; Sanchez, 2019). Selective disassembly planning has been identified as a promising alternative to effectively address end-of-life product recovery for buildings (Rausch et al., 2019; Sanchez et al., 2019b). Selective disassembly planning, which is the sequence of steps for the dismantling of targeted building components, is a critical part of the building component reuse process (Sanchez and Haas, 2018).

Research on disassembly sequence planning has been developed in the last three decades in the manufacturing industry to optimize the extraction of defective components in products and maximize the recovering of salvageable components at a product's end-of-life (Rausch et al., 2019; Smith, S. et al., 2016). In contrast, this research field is still underdeveloped for the building industry. According to Supachai (Vongbunyong and Chen, 2015), disassembly sequence planning in manufacturing is still performed inefficiently utilizing incomplete information among the assembly and sub-assemblies. Likewise, in construction, updated data for building components is often not available, since as-built models can be nonexistent, not current, or do not include the necessary semantic data. Consequently, disassembly planning depends on manual procedures for determining interrelations between components (Rausch et al., 2019). In a previous study, the authors developed a novel framework for selective disassembly of buildings based on the disassembly graph (DG) model (Sanchez and Haas, 2018). This approach is the first of its kind to implement selective disassembly planning for information models for recovering targeted components. Although this investigation generates great areas of opportunities for the construction sector (Munaro et al., 2020), a major challenge in this work was that key topological interrelations of building parts had to be arbitrated manually, which is ineffective, inefficient, and elicits the propensity for error (Rausch et al., 2019).

BIM technology has become an important system for supporting construction and deconstruction planning processes (ASCE, 2015; Basta et al., 2020; Mattern and König, 2018; Won and Cheng, 2017). Such technology can operate precise information with a powerful and highly organized graphical interface. Even though BIM has been demonstrated to be an effective tool for managing construction projects (Karim et al., 2018; Marmo et al., 2020), current information models do not support important project activities for selective disassembly planning of building structures. This is due to two reasons:

(1) **The lack of appropriate level-of-detail (LoD) for parametric disassembly models that define the correct physical interfaces between building parts, where a building part can be either a component or a connection** (Sanchez and Haas, 2018). In comparison with building parts in as-designed information models, such parts exhibit a significant difference in configuration for disassembly models. For the fundamental framework of BIM, an entire building is discretized into standardized parts and subsequently represented with multiple levels of detail (multi-LoD) in a parametric model (Abualdenien and Borrmann, 2019; Liu et al., 2019). These levels are selected according to the importance of requirements in different phases of a building's life cycle. For example, a medium LoD focused on constructive attributes is required in the construction phase, because the complicated and partial details of building parts are more for the architectural appearance and are therefore usually negligible at this stage. In contrast, a high LoD with emphasis on the physical interface information is required at the disassembly planning phase. Hence, a multi-LoD modeling system is required to support the different phases in a building's life cycle. To the knowledge of the authors, research on multi-LoD parametric models for disassembly models is elusive.

(2) **The lack of a highly efficient method for automatically determining the corresponding disassembly parameters from a high-quality information model** (Sanchez; Rausch et al., 2020; Sanchez and Haas, 2018; Sanchez et al., 2019b). Parameter acquisition is the foundation for establishing an accurate disassembly model (Rausch et al., 2019; Wang et

al., 2020). Some of these parameters are related to attributional and geometric information from BIM objects, which is a relatively trivial task. However, other parameters need the development of sophisticated techniques for determining higher-order of semantics (e.g. topological relationships, building element's interdependence) (Rausch et al., 2019). This has been considered a challenge and remains elusive in many spheres of the construction industry (Lu et al., 2017). In this regard, visual programming languages (VPL) for BIM can be used as an efficient way to develop custom software solutions for the construction industry (Rausch et al., 2019).

Based on the aforementioned arguments, this study aims to boost the application of BIM in selective disassembly planning by improving the efficiency and effectiveness of data capture and storage for building-asset semantic information. In this study, BIM is used as an approach for describing the process of creating and managing digital information about a built asset related to disassembly processes. Taking typical building structures as case studies, the common features of disassembly models for buildings are identified. Then, the multi-LoD characteristics are suggested, according to the specifications for each level, and the BIM parameters are recommended for typical building parts. In the end, the BIM data required for disassembly models are synthesized and a relevant taxonomy developed. This study only considers building components without physical deterioration or degradation which are comparable to newly produced ones. Also, this paper is focused on the analysis of structural subsystem archetypes with disassemblable connections. However, the same approach can be applied in further investigations to extend the research scope towards other building subsystems and more complex assembly systems, as is suggested in (Sanchez; Rausch et al., 2020).

Based on the above, a framework for automatically determining the parameters of information models for selective disassembly of building parts is proposed. The framework is validated with a functional demonstration, through the development of a computational VPL interface plug-in for BIM to implement the proposed taxonomy. This study proves how judgment can be obtained from BIM elements through rule-based VPL algorithms that use three-dimensional Cartesian properties. This method offers a technique to systematically analyze spatial parameters of BIM elements in an automated way, which is validated through a functional demonstration using BIM-based disassembly prototypes. The research outcomes will provide an important reference for the application and implementation of selective disassembly theories for buildings.

2. BIM-based disassembly planning

2.1. Selective disassembly planning for buildings

The first-in-its-class BIM-based Sequential Disassembly Planning for Buildings (SDPB) method for selective disassembly of buildings was developed in 2018 (Munaro et al., 2020). The SDPB method is based on the Disassembly Sequence Structure Graphs (DSSG) theory (Smith, Shana and Hung, 2015; Smith, Shana S. and Chen, 2011), by considering environmental impact, building cost, and rule-based analysis for adaptive reuse of buildings (Sanchez and Haas, 2018). The SDPB method is used to generate optimized disassembly plans for retrieving single targeted components from information models. The method minimizes environmental impacts and deconstruction costs during the selective disassembly planning process (Sanchez and Haas, 2018). In a subsequent study, the SDPB method was extended for multiple-target selective disassembly planning, as well as the development of a novel approach of selective deconstruction programming for buildings (Sanchez et al., 2019b). This approach can create the programming of deconstruction works for retrieving multiple components of a building assembly in a semi-automated way. In another study, the SDPB method was improved to include more deconstruction methods per building component (Sanchez; Rausch et al., 2020). In this study, a weighted multi-objective optimization analysis is used to produce the set of Pareto optimal solutions that minimizes environmental impacts and building costs for the different alternatives of deconstruction plans.

Based on the results, approach, and building assemblage archetype presented in the SDPB study, Denis et al. (2018) proposed an alternative optimization method for selective disassembly planning for buildings by using Network Analysis. Their method is called Disassembly Network Analysis (DNA). The DNA approach involves specific disassembly parameters such as accessibility, transportability, resistance factor, weight, reversibility of connection, and disassembly/demolition time, to define the optimization analysis model. Similarly, a selective hybrid disassembly sequence planning method for adaptive reuse of buildings was developed as an alternative to the SDPB approach (Mahmoudi Motahar and Hosseini Nourzad, 2021). In their study, Mahmoudi and Hosseini Nourzad (2021) presented a new hybrid method for the single-target selective disassembly sequence planning that supports both sequential and parallel approaches. Their proposed method optimizes the disassembly sequence time, cost, and environmental impacts by using the Non-dominated Sorting Genetic Algorithm (NSGA-II).

The research field of selective disassembly planning for buildings is still considered underdeveloped in comparison to the significant advancements in other domains such as disassembly planning of manufacturing products (Munaro et al., 2020; Sanchez and Haas, 2018). Several disassembly planning studies of manufacturing products have been developed in a comprehensive way starting from integrating information on the components and their physical relationships, modeling the mathematical product structure, and developing disassembly analyses from virtual models in sophisticated software platforms (Bouyarmane et al., 2020; Lambert, 2003; Soh et al., 2016; Zhou et al., 2019). For example, in their work Favi et al. (2019) developed a method and a software tool called LeanDfD for quantitative evaluation of disassemblability and recyclability of mechatronic products. Their approach used a semi-automated tool for the optimization of disassembly sequences taking into account disassembly precedencies, liaisons among components, and specific properties of the product modeled in a parametric virtual environment (3D CAD model). In (2019), Zhou et al. developed an extensive review of recent developments and future trends for disassembly planning for manufacturing products. They examined the characteristics of different methods and summarized them according to the perspectives of disassembly mode, disassembly modeling (data preprocessing, disassembly archetype, and analytical disassembly model), and planning method (disassembly objective and optimization method). Recent studies in the field of circular economy for the built environment have pointed out the urgent need for accelerating the research development on disassembly planning methods for buildings in order to take advantage of the residual utility and value of today's immense building stock (Gallego-Schmid et al., 2020; Gan et al., 2020; Munaro et al., 2020).

Even though the presented approaches for selective disassembly of buildings represent feasible alternatives, the methods are limited by the considerable amount of data to manually input into the disassembly models. Critical disassembly information, such as disassembly precedence, disassembly physical constraints, and extraction direction must be easily and rapidly accessible. This problem has been studied for disassembly planning of manufactured products in the last decade (Zhou et al., 2019). Some studies have demonstrated the possibility of automatically determining the disassembly information through the volumetric and geometrical analysis of CAD-based disassembly models for manufactured products (Alrufaifi et al., 2019; Wang et al., 2020; Zhou et al., 2019). Other studies have demonstrated the possibility of creating CAD-based virtual disassembly environments for developing disassembly planning analysis in a compact, fast, and reliable way (Cappelli et al., 2007; Yi et al., 2008). However, there is a lack of studies applied to the automated determination of disassembly information for building disassembly models. In a previous study, the authors developed a method to automatically generate disassembly information for CAD building models via a rule-based algorithm that uses 3D properties and interference recognition among non-semantic CAD elements (Rausch et al., 2019). This method was implemented and validated under the framework of the SDPB approach in order to solely determine the motion constraints of the building components of a disassembly model. One of the differences in comparison to the approach in this study is the inclusion of connections (fasteners) among components as critical points for determining valid motion constraints.

Another main difference is the overall implementation within a BIM environment. CAD models are only graphical objects for describing the geometry of a building (Ding, L. et al., 2014). On the contrary, BIM integrates "smart objects", or BIM objects, enriched with semantic information through model parameters related to the building including all geometric and functional information (Ding, L. et al., 2014). In this study, we claim that in the context of disassembly models, a BIM object must include functional and performance parameters, such as physical interdependency, biunivocal identification as part of the disassembly model, and physical constraints for disassembly works. Also, other sets of instance parameters must be included for specialized disassembly planning and assessment as discussed at the beginning of this section, such as characterization of the connectivity between components, life cycle environmental impacts due to deconstruction, and the associated cost for different methods of deconstruction works. In this respect, BIM is used as a powerful computerized management tool where all of the useful parameters and parameter constraints are modeled, described, traced, and updated across the modeling and design stages either interactively or automatically.

In this study, we focus our method approach on some basic components of the building structure such as steel beams, steel columns, and reinforced concrete elements. Several studies have highlighted the importance and the potential of these building elements for effective deconstruction and reuse. Other studies have demonstrated the life-cycle environmental and economic benefits for the reuse of steel structural members (Eckelman et al., 2018; Minunno et al., 2020; Sanchez et al., 2019a; Yeung et al., 2017). Other studies have focused on the technical assessment of deconstructability of steel structures with the objective of enhancing reuse (Basta et al., 2020; Pongiglione et al., 2021). Also, the field of design for the deconstruction of precast concrete elements highlights the considerable potential for minimizing the life-cycle impact of buildings (Ding, T. et al., 2018; Lizhong et al., 2020).

2.2. Multi-LoD principles for disassembly models

The overall information model and disassembly diagram of a disassembly model is presented in Fig. 1. The information model has the LoD necessary for disassembly models according to the analysis of the previous studies described in Section 2.1. The information model has nine parts (five components and four fasteners). It is important to highlight that according to selective disassembly theory (Sanchez and Haas, 2018), a set of fasteners that connects two components in one direction can be analytically simplified as one fastener. However, for the disassembly planning stage, each fastener of the disassembly model is analyzed. BIM elicits a variety of LoD depending on the purpose for digital representation (Abualdenien and Borrmann, 2019). In comparison with an information model without the specifications of a disassembly model, the building parts of a disassembly model reveal important differences in two features: (1) the representation of the physical interface between components and fasteners, and (2) the definition of building element's membership. The precise representation of the physical interfaces is necessary in order to determine the physical constraints for each building part. For example, in an information model without the requirements for a disassembly model, a bolt that connects two building components is graphically merged into the host component where the bolt is inserted, for simplification purposes. The representation for a disassembly archetype must model the void inside of the host component that the insertion of the fastener is creating (in this case, a bolt). The definition of a building element's membership is necessary to determine realistic disassembly sequences according to the structural and topological relations between building parts. For example, each building component and fastener must have an associated host component or components that are part of the constructive process. A more detailed explanation can be found in (Sanchez and Haas, 2018).

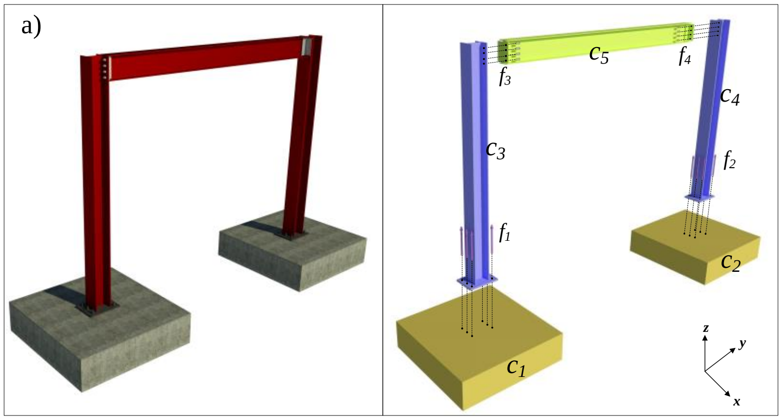


Figure 1. Disassembly model prototype. Assembly components: c_1 and c_2 are concrete isolated foundations 1830x1830x457mm; c_3 and c_4 are steel columns W10x49; c_5 is a steel beam W12x26; f_1 and f_2 are bolt-and-nut pairs (hereafter simply called "bolts") set in pockets (connection between steel column and concrete isolation foundation); f_3 and f_4 are steel bolts (connection between steel beam and steel column).

Hence, the multi-LoD principles should be developed in accordance with existing guidelines (e.g., such as those provided by BIMForum and AIA definitions (BIMForum, 2020)), but also considering additional requirements specifically for disassembly models. Of the existing classes for LoD, two require additional specifications: LoD 350 and LoD 400 (see Table 1). This paper proposes the description of multi-LoD principles considering the commonality and characteristics for disassembly models. This approach aims to add to the model the necessary detailing according to the manifold requirements in different phases of the project. For example, in the design phase for the structural components, it is not necessary to add all the geometrical detailing for disassembly. Simply determining the building elements' membership might be sufficient to ensure the structural coherence of the model. In this respect, the structural coherence of a disassembly model stands for the constructive logic to assembly and disassembly building components to ensure valid sequences (e.g., a beam that is "attached to" and is "supported by" a column, and not the way around). Structural coherence is a critical characteristic to produce a realistic disassembly model for buildings. As discussed in a previous study (Sanchez and Haas, 2018), this characteristic is one of the main differences between a disassembly model for buildings and one for a manufacturing product. For example, in a product assembly, any fastener can be removed as long as it is physically accessible, whereas, in a building assembly, some fasteners could be accessible, but their removal may invoke significant structural instabilities which must be aptly accounted for and analyzed.

In comparison to the design stage, the disassembly planning stage requires a high level of geometrical detail for the physical interfaces among building components in order to determine physical constraints. In this study, we develop an initial framework for multi-LoD principles for disassembly models.

Table 1
Multi-LoD principles for disassembly models

Level of Detail Class	**BIM Forum & AIA Definition** (BIMForum, 2020)	Additional Requirements for Disassembly Models
LoD 100	Model elements are represented only symbolically or schematically (not geometrically).	
LoD 200	Model element geometry is a placeholder using crude volumetric boundaries.	
LoD 300	Quantity, size, shape, location and orientation of elements detailed, and some non-geometric information can be attached.	
LoD 350	Inclusion of parts necessary for coordination are detailed (including supports and connections).	Information required for structural consistency. For disassembly planning, all interface components must be included. All model elements must be assigned metadata for building membership.
LoD 400	Model elements are detailed with sufficient information for fabrication, assembly and installation to directly infer design intent.	High-fidelity representation of all model components such that all interfacing components, fasteners, voids, etc. are detailed. All elements must also be assigned metadata for building membership. In addition, fastener details are sufficient to determine disassembly direction and physical constraints.
LoD 500	Information obtained from field verification of all initial model elements.	

Based on the abovementioned principles, a schematic diagram of the multi-LoD models is illustrated in Fig 2.

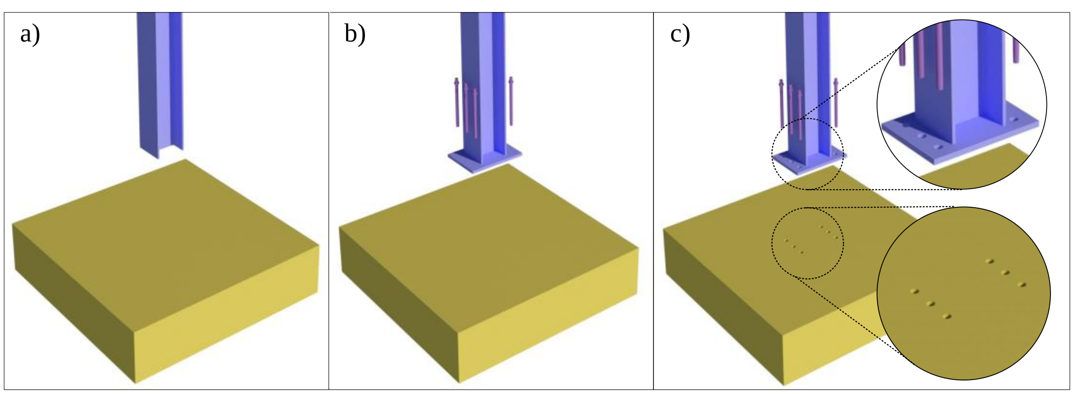


Figure 2. Multi-LoD for disassembly models: a) LoD 200; b) LoD 350; c) LoD 400.

2.3. BIM requirements from the SDPB method approach

The SDPB method is based on the DG theory where disassembly models can be represented by constraint matrices (DG model). Selective disassembly planning based on DGs is a field that has been explored in the last three decades for manufactured products, and several methods have been developed such as DSSG, DSSG-S, Disassembly Constraint Graphs (DCGs), Interference Graphs, Removal Influence Graphs (RIGs), disassembly precedence graphs, AND/OR graphs, liaison graphs, and Garcia's method (Smith, Shana and Hung, 2015; Smith, S. et al., 2012). Each method proposes a particular way to structure the DG model and to find an optimized way for retrieving target elements. As discussed in section 2.1, even though the DG-based approaches for selective disassembly represent feasible alternatives, the methods are limited by the considerable amount of data to input manually. Similarly, the usability of the SDPB method is mainly impeded by the increased amount of data to manually input. All of the spatial, topological, and interdependence constraints of a building assembly under study must be manually organized in the DG model for their computational processing.

Information models can be used as disassembly models for retrieving the DGs information of the SDPB approach. BIM is arguably the most important building design tool which can be used to identify errors at the early stages, schedule construction works precisely, identify conflicts, advocate design alternatives, and facilitate the selection of appropriate solutions for complex projects (Gan et al., 2018; Jalaei and Jrade, 2014). BIM offers designers the ability to assess different design alternatives at the conceptual stage of the project, through virtual simulation of the performance of the final product (Jalaei and Jrade, 2014). An information model integrates the three-dimensional geometry, topology, and physical properties of the model (3D) with other useful information for construction projects. However, current information models do not contain the necessary information to support activities for deconstruction planning such as selective disassembly (Sanchez; Bindal-Gutsche et al., 2020; Sanchez et al., 2019b). To the knowledge of the authors, there are no studies in the field of BIM implementation for selective disassembly planning. Therefore, there is an urgent necessity to focus on determining geometrical and nongeometrical requirements as well to support successful implementation. In this study, the BIM information requirements, or BIM parameters, for disassembly models are identified based on the DGs information from the SDPB approach.

The BIM parameters for disassembly models proposed in this work have been identified as unified features data input for the SDPB approach. According to theories on selective disassembly planning

(Sanchez and Haas, 2018; Smith, Shana and Hung, 2015; Smith, S. et al., 2016), these parameters are fundamental information that must be defined for each element of the disassembly model. Some of this information is indirectly embedded in BIM elements according to the Industry Foundation Classes (IFC) schema. However, the information must be identified, sorted, and defined according to the input data needs of the disassembly planning theory to apply. On the other hand, the inexistent information, that is not part of the structure of the IFC schema, can be generated by analyzing the surroundings and context of each BIM element intended to be part of the same disassembly model. In this study, we propose the taxonomy for the information requirements including both cases: (1) definition of BIM elements' parameters for selective disassembly, and (2) generation of parameters for disassembly models.

3. A BIM-based framework for the determination of parameters for disassembly models

This paper automatically develops key BIM elements' parameters and topological relationships in a disassembly model for the purpose of supporting selective disassembly planning, and explicitly in the previously introduced background (see Fig. 3). In the first stage, the definition of BIM elements' parameters for selective disassembly must be developed by establishing hosting relationships and adding the corresponding parameter values to the data BIM structures. In the second stage, the generation of parameters for disassembly models includes the topological analysis of the disassembly model in order to determine the specific constraint values for each BIM element (physical constraint parameters). In the final stage, for a specific disassembly archetype under study, the DG model can be constructed based on the parameter values determined in the previous stages.

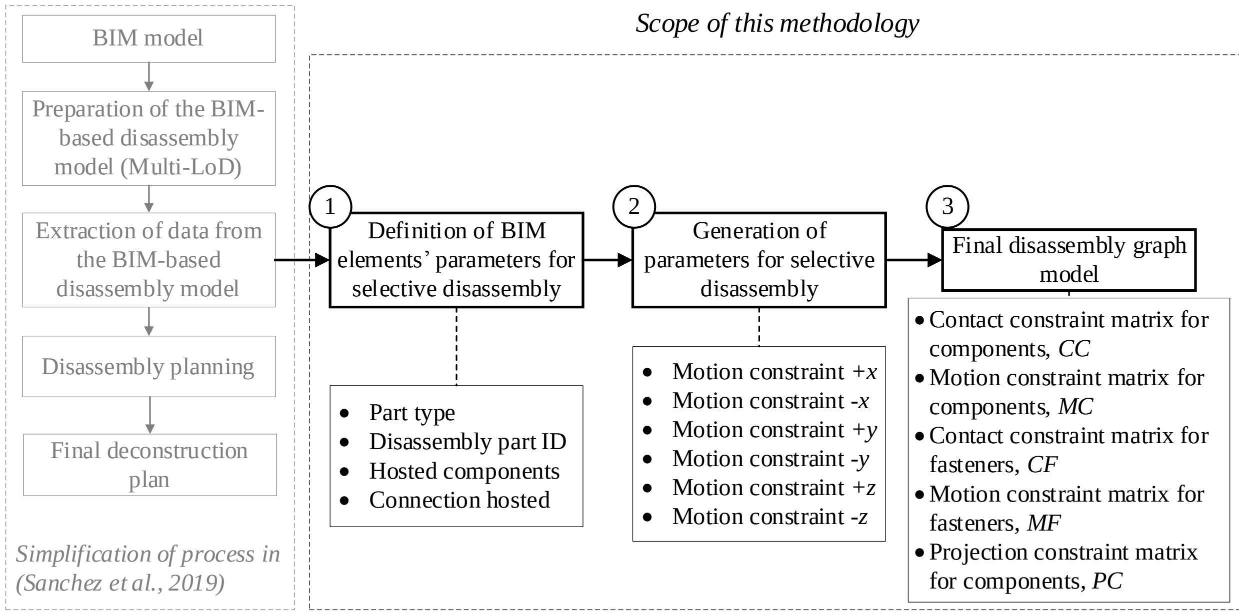


Figure 3. Methodology for determining disassembly data from information models.

3.1. Information taxonomy characteristics for disassembly models

A taxonomy is a scheme of organization for information to identify the explanation of terminology and their associations in the context of a knowledge area (Karim et al., 2018). According to Usman (2017), developing a taxonomy of the objects in a knowledge field improves the exchange of information, aids in recognizing the knowledge gaps, and underpins decision making by standardizing terminology. In this study, the taxonomy for the required information for disassembly models was developed by considering the approach proposed by Karim et al. (2018). They proposed the taxonomy characteristics for data structures for building information models for asset management. This approach includes four iterative steps: (1) establishing the field and the extent of the taxonomy, (2) taking into account other current ontologies, (3) determining the class and corresponding hierarchy, and finally, (4) defining the properties and slots of classes. Their approach is based on a literature review on the topic and a recursive verification process supported by experts and professionals in the field (e.g., interviews, focus groups, etc.). Based on this, they propose different categories of classification with their required information. Then, an information taxonomy is conformed to organize and combine results. For structuring the classification schema, the authors argue that the characteristics of the tree structure approach is the most suitable for building information models. According to Kwasnik (2018), the tree approach leads to taxonomies with a single top class and its subclasses with a hierarchical association in which the entities are related by the partitive relationship. In other words, each class is branched into its segments (part/whole relationship).

In this study, the definition of the structure, classes, and properties of the proposed taxonomy is based on the literature review and on the lessons learned from previous investigations about the development and implementation of the SDPB approach in building case studies (Sanchez; Rausch et al., 2020; Sanchez and Haas, 2018; Sanchez et al., 2019b) (see Section 2.1 and Section 2.3). Through the analysis of the case studies, the critical information needed for disassembly models was determined and structured. Table 2 shows a synthesis of the required information for selective disassembly planning of buildings. The required information was defined at a product level, in other words, we explored the disassembly characteristics for each building component that is meant to be part of the same disassembly model. In Table 2 we also analyzed the most relevant studies of selective disassembly for manufacturing products considering only the characteristics and parameters that are compatible with disassembly models for buildings. Fig. 4 is a graphic illustration of the proposed taxonomy of the essential information for successfully implementing BIM in selective disassembly planning.

Table 2
Required information for selective disassembly planning of buildings

	Classification			**Building element´s membership**					**Spatial characterization**									**Deconstruction specifications**		
Source	Part type	Disassembly part ID	Type name	Unique type ID	Hosted components	Connection hosted	Composition relationship	Physical interface	Motion Constraints in +x	Motion Constraints in -x	Motion Constraints in +y	Motion Constraints in -y	Motion Constraints in +z	Motion Constraints in -z	Working space	Assembly openings	Element’s location	Deconstruction method	Deconstruction cost	Deconstruction LCA
(Sanchez and Haas, 2018)	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
(Sanchez et al., 2019b)	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
(Sanchez; Rausch et al., 2020)	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(Denis et al., 2018)		✓			✓		✓								✓	✓			✓	
(Mahmoudi Motahar and Hosseini Nourzad, 2021)		✓			✓	✓			✓	✓	✓	✓	✓	✓				✓	✓	✓
(Smith, S. et al., 2012)*	✓	✓							✓	✓	✓	✓	✓	✓			✓			
(Smith, Shana and Hung, 2015)*	✓	✓						✓	✓	✓	✓	✓	✓	✓			✓			
(Smith, S. et al., 2016)*	✓	✓							✓	✓	✓	✓	✓	✓			✓		✓	✓
(Desai and Mital, 2003; Tseng et al., 2010)*	✓	✓					✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
(Favi et al., 2019)*	✓	✓		✓				✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
(Mandolini et al., 2017)*	✓	✓		✓				✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	
(Elsayed et al., 2012)*	✓	✓															✓	✓	✓	✓
(Zhou et al., 2019)*review article	✓	✓		✓				✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
(Lambert, 2003)* review article	✓	✓		✓				✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓

*selective disassembly planning for manufacturing products

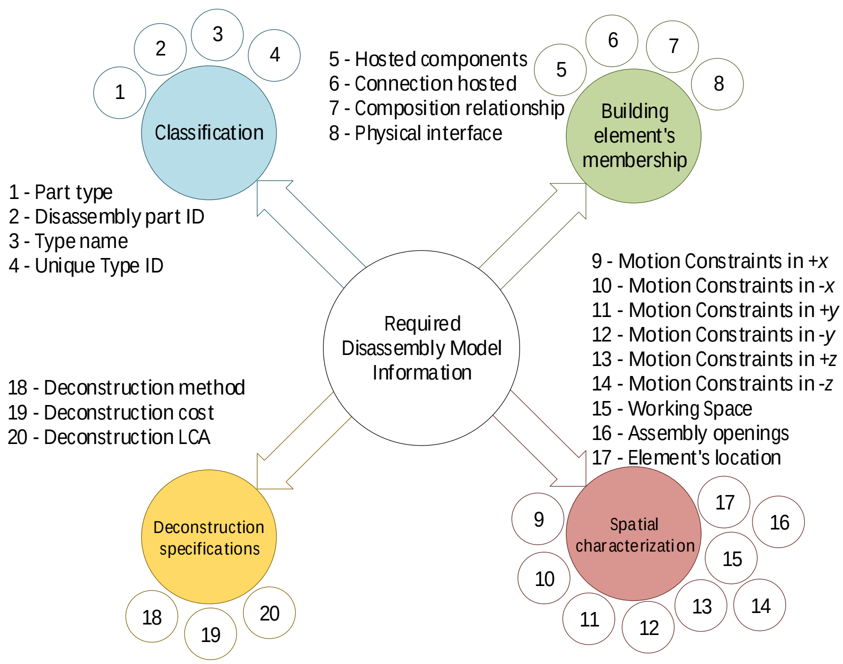


Figure 4. Taxonomy for the required information for disassembly models

The proposed taxonomy has a two-level tree structure with a hierarchical growth process. The highest level is classified into four main branches/classes: classification, building element membership, spatial characterization, and deconstruction specifications. At the second level, 20 subclasses represent the required BIM data/parameters for disassembly models. These data can be gathered from an information model, during the planning and design stage. The nongraphical parameters in the BIM environment can be divided into two kinds of predefined parameters: type parameter and instance parameter. Type parameters are the same for all the existences of BIM elements, while instance parameters are unique to a kind of BIM object. However, the predefined parameters in the IFC schema do not include all the required parameters for the disassembly model taxonomy, therefore, new parameters are recognized (see Fig. 4). Overall, seven common existing parameters and ten new parameters (1 type parameter, 9 instance parameters) were identified. Further properties and slots are identified for these parameters in Table 3.

Table 3
BIM parameters for the required information for disassembly models

Category	Parameter name	Unit	Type/instance	Defined/new
Classification	Part type	Alphanumeric	Instance	New/read
	Disassembly part ID	Alphanumeric	Type	New/read
	Type name	Alphanumeric	Instance	Available
	Unique Type ID	Numeric	Type	Available
Building element's membership	Hosted components	Alphanumeric	Instance	New/read
	Connection hosted	Alphanumeric	Instance	New/read
	Composition relationship	Generic	Instance	Available
	Physical interface	Generic	Instance	Available

Spatial characterization	Motion Constraints in +x	Alphanumeric	Instance	New/generate
	Motion Constraints in -x	Alphanumeric	Instance	New/generate
	Motion Constraints in +y	Alphanumeric	Instance	New/generate
	Motion Constraints in -y	Alphanumeric	Instance	New/generate
	Motion Constraints in +z	Alphanumeric	Instance	New/generate
	Motion Constraints in -z	Alphanumeric	Instance	New/generate
	Working Space	Generic	Instance	Available
	Assembly openings	Generic	Instance	Available
	Element's location	Numeric	Type	Available
Deconstruction specifications	Deconstruction method	Alphanumeric	Type	Existing/write
	Deconstruction cost	Numeric	Instance	Existing/write
	Deconstruction LCA	Numeric	Instance	Existing/write

The classification category includes four parameters. The parameters *Type name* and *Unique Type ID* provide common data classification for the BIM elements. The parameters *Part type* and *Disassembly part ID* are unique identification information for disassembly model elements, and they must be defined during the design stage. The *Part type* is the classification assigned to each disassembly model element that must be either a component or a fastener. The IFC schema has a subclassification in BIM elements (*IfcElement*) for fasteners (*IfcFastener*). Therefore, the fastener elements for the disassembly model can be identified accordingly. For identifying assembly components, the IFC schema classifies all model parts as BIM elements including physically existent objects and void elements such as holes and work planes. Disassembly models must only include physically existent components. Therefore, it is necessary to sort the BIM elements to exclude those which should not be part of the disassembly model. In this respect, a disassembly model can be represented by the *IfcElementAssembly* entity to aggregate the BIM elements that are intended to be part of the same assembly. The *Disassembly part ID* is the unique identification assigned to a BIM element that enables its differentiation from other BIM elements that are meant to be part of the same disassembly model.

The building element's membership category includes four parameters. These parameters are related to the physical interdependence and objectified relationships between elements. The parameters *Hosted components* and *Connection hosted* record the objectified relationship between two components, or a component and a fastener, respectively. This objectified relationship provides the generalization of the connectivity between elements. According to the SDPB approach, this information is necessary for establishing the direct and indirect physical interdependence between all the disassembly model elements that are meant to be part of the same disassembly model. Even though the objectified relationship between elements is included in the IFC schema (*IfcRelConnectsElements*), it is necessary to sort and classify them according to the nomenclature established for DG models. This data can be described during the design stage based on the parameters defined in the classification category. For disassembly models, it is particularly critical to ensure that the objectified relationships are established correctly according to the true physical interfaces between elements. This implies a deep understanding, by the designers, about the logic and relationships between material structures and mechanical properties at the design stage. The accuracy of this information is the basis for finding realistic solutions in subsequent stages for selective disassembly planning (Sanchez and Haas, 2018; Sanchez et al., 2019b).

The spatial characterization category includes nine parameters. These parameters are associated with the three-dimensional location and physical constraints of the elements of the disassembly model. Some of these parameters are already predefined and can be collected during the design stage, such as working space, assembly openings, and element's location. However, the parameters related to the motion constraints do not exist in information models, and they are not part of the IFC schema. The motion constraints information along the six principal extraction directions ($+x$, $-x$, $+y$, $-y$ $+z$, $-z$) depends on a hypothetical kinematic analysis of the elements when the disassembly model is completed. According to Smith et al. (2012), in three-dimensional space, all parts can be disassembled in the six principal directions without losing generality. This is a simplification that can be systematically augmented according to the needs of the implementation by adding more extraction directions or adding a combination of different directions. A motion constraint contains first-level-working-space parts, which are parts that interfere with the extraction projection of a targeted part under study in any given direction (Sanchez and Haas, 2018). The information can be inferred and extracted from the disassembly model by simulating the extraction motion of each element at a time and recording the intersected elements along the extraction path (Sanchez and Haas, 2018; Smith, Shana and Hung, 2015). The six principal extraction directions are essential information to estimate disassembly sequences for targeted components to retrieve from a disassembly model. More complex access and egress checking and planning in 3D are outside the scope of this study, but it is a significant and promising research area, especially for industrial plant refurbishment.

The deconstruction specifications category includes three parameters that must be defined and collected during the design stage. These parameters are necessary data entries for the SDPB approach for developing a multi-objective optimization analysis of the disassembly planning (Sanchez; Rausch et al., 2020; Sanchez and Haas, 2018). The *Deconstruction method* parameter indicates the type of deconstruction method for each component (e.g., selective demolition, destructive disassembly, perfect disassembly). The *Deconstruction cost* parameter indicates the cost for the deconstruction works related to a given deconstruction method. The *Deconstruction Life Cycle Assessment (LCA)* indicates the net environmental impact associated with each of the elements of the disassembly model and an associated deconstruction method. With this information, it is possible to add multiple dimensions to the process of disassembly sequences. In this way, the selection of the best disassembly sequence can incorporate the minimization of deconstruction cost or environmental impacts.

3.2. IFC information for disassembly models

IFC is an open international standard for BIM data that is used for information exchange between BIM software (BuildingSMART International, 2020). The standard involves descriptions that contain essential information for the life cycle stages of building projects (ISO 16739-1:2018, 2020). A variety of studies have applied IFC to combine BIM and other areas. The combination involves the semantic adaptation to specific structures (e.g., Geographical Information Systems [GIS], Facility Management [FM], Building Energy Analysis [BEA]) while IFC brings connectivity between BIM construction-related data and other environments (Xu et al., 2020). To the knowledge of the authors, there is no study that proposed the integration of BIM with disassembly planning theories.

In this study, we analyse disassembly models in order to identify critical data that can facilitate the implementation of BIM into the building's disassembly planning domain. After identifying the critical information, we propose a method for extracting data from the IFC schema for disassembly models (see Fig. 5). As explained in Section 3.1, some of the data must be rearranged, defined, or generated according to the standards of disassembly planning theories. The preprocessing of information for a disassembly model can be developed in several ways. In the context of this paper, the preprocessing has been accomplished by using the VPL environment Dynamo. After the preprocessing of the data, five new IFC extensions are proposed (*IfcPartType, Disassembly Part ID, Hosted Components, Connection Hosted, Motion Constraints*) to be part of the IFC attributes for the IFC element entity (*IfcElement*). The IFC schema extensions are reported according to the EXPRESS description language (described in the international standard ISO 10303-11).

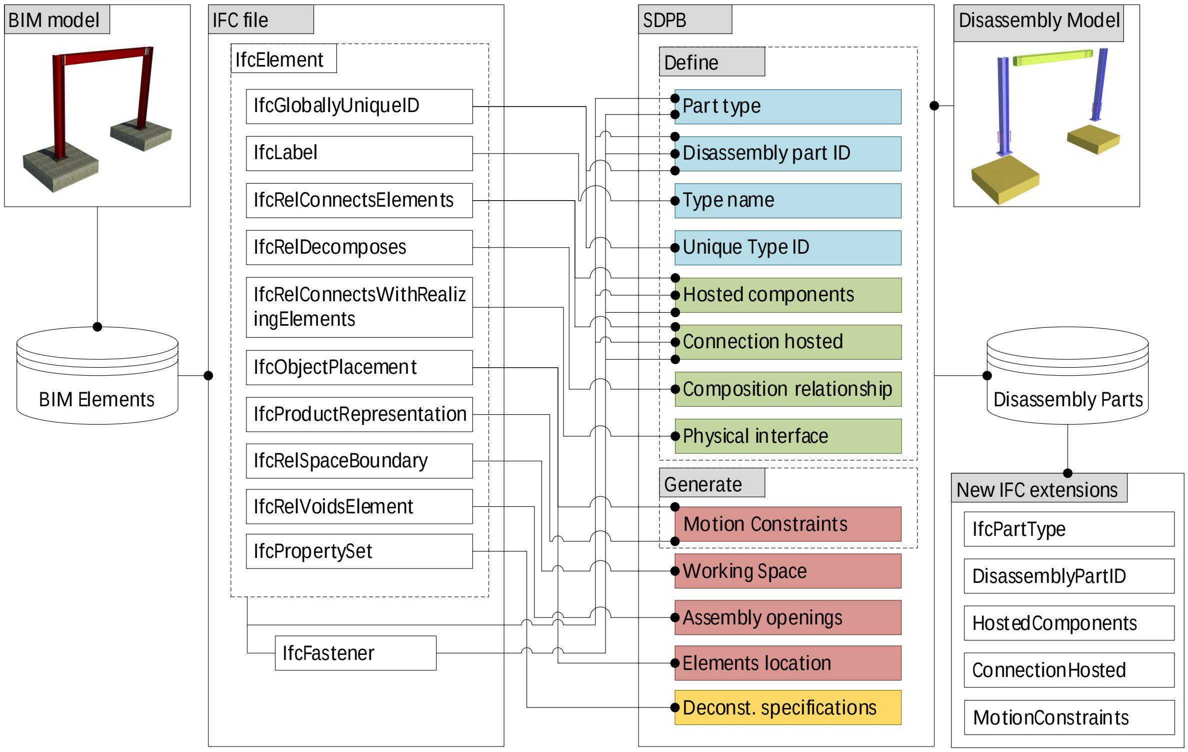


Figure 5. Overall process to extract data from IFC for disassembly models

The *Part Type* (*IfcPartType*) is an entity used to define a specification of an element (part) used within a disassembly model. Disassembly part types (*IfcDisassemblyPartTypeEnum*) apply to two different types of elements that may be used to represent information for disassembly planning: (1) components and (2) fasteners. Since *IfcPartType* is a subtype of *IfcElementType*, the unique description is provided by the inherited attribute *Element Type* given as *IfcLabel*. The relationship between *Part Type* and element occurrences is defined by the objectified relationship *IfcRelDefinesByType*. The *IfcPartType* is proposed as a stub for future auxiliary extensions of the specification. Other existing IFC *IfcElementType* subtypes are focused on the type classification of elements based on shared characteristics rather than the functional state as proposed with the new *IfcPartType*. Figure 6 shows the specification of the proposed IFC extensions.

```
ENTITY IfcPartType
  SUBTYPE OF (IfcElementType);
    PredefinedType         : IfcDisassemblyPartTypeEnum;
  WHERE
    CorrectPredefinedType  : (PredefinedType <> IfcDisassemblyPartTypeEnum.USERDEFINED) OR
((PredefinedType = IfcDisassemblyPartTypeEnum.USERDEFINED) AND EXISTS(SELF\IfcElementType.ElementType));
END_ENTITY;
```

```
TYPE IfcDisassemblyPartTypeEnum = ENUMERATION OF (
  COMPONENT,
  FASTENER,
  NOTDEFINED);
END_TYPE;
```

Figure 6. EXPRESS specification of *IfcPartType* and *IfcDisassemblyPartTypeEnum.*

The *Disassembly Part ID* is an attribute used to biunivocally identify every single part of the same disassembly model. This attribute is necessary for the disassembly planning for targeted components. The existing IFC entity *IfcElementAssembly* sets the conditions for the elements' aggregation for complex assemblies and subassemblies. However, none of its attributes specify the identification for the assembly parts. Therefore, the *Disassembly Part ID* is proposed as a new attribute of the entity *IfcElement*. Figure 7 shows the schematic representation of the new attribute inside the original IFC specification of *IfcElement*.

```
ENTITY IfcElement
  ABSTRACT SUBTYPE OF (ONE OF(…));
  SUBTYPE OF (IfcProduct);
    Tag  : OPTIONAL IfcIdentifier;
  INVERSE
    FillsVoids  : SET [0:1] OF IfcRelFillsElement FOR RelatedBuildingElement;
    ConnectedTo  : SET OF IfcRelConnectsElements FOR RelatingElement;
    IsInterferedByElements  : SET [0:?] OF IfcRelInterferesElements FOR RelatedElement;
    InterferesElements  : SET [0:?] OF IfcRelInterferesElements FOR RelatingElement;
    HasCoverings  : SET OF IfcRelCoversBldgElements FOR RelatingBuildingElement;
    HasProjections  : SET OF IfcRelProjectsElement FOR RelatingElement;
    HasStructuralMember  : SET OF IfcRelConnectsStructuralElement FOR RelatingElement;
    ReferencedInStructures  : SET OF IfcRelReferencedInSpatialStructure FOR RelatedElements;
    HasPorts      :    SET OF IfcRelConnectsPortToElement FOR RelatedElement;
    HasOpenings    :    SET OF IfcRelVoidsElement FOR RelatingBuildingElement;
    IsConnectionRealization  : SET OF IfcRelConnectsWithRealizingElements FOR RealizingElements;
    ProvidesBoundaries  :    SET OF IfcRelSpaceBoundary FOR RelatedBuildingElement;
    ConnectedFrom        :    SET OF IfcRelConnectsElements FOR RelatedElement;
    ContainedInStructure  : SET [0:1] OF IfcRelContainedInSpatialStructure FOR RelatedElements;
   *DisassemblyPartID  : OPTIONAL IfcIdentifier;
   *HostedComponents  : SET OF IfcRelConnectsStructuralDependence FOR RelatedElement;
   *ConnectionHosted  : SET OF IfcRelConnectsStructuralDependence FOR RelatedElement;
   *MotionConstraints  : SET OF IfcRelInterferesElements FOR RelatedBuildingElement;
END_ENTITY;
```

Figure 7. EXPRESS specification of *Disassembly Part ID, Hosted Components, Connection Hosted* and *Motion Constraints.*

Hosted Components and *Connection Hosted* are new attributes of the existing entity *IfcElement* (see Figure 6). These attributes refer to the elements' structural connection relationships. The relationship then refers to the other elements (components and fasteners respectively) that are connected to the host element. The difference from the existing IFC attribute *ConnectedFrom* is that the new attributes distinguish the elements' structural hierarchy. This means that the host component provides the physical support and static stability of the hosted elements. The existing attributes *ConnectedFrom* and *ConnectedTo* do not specify any structural codependence among elements. Rather, they describe the relationship between elements for modeling purposes, where the relationship between element occurrences is defined by the objectified relationship *IfcRelConnectsElements*. Therefore, the creation of a new entity *IfcRelConnectsStructuralDependence* is proposed as a subtype of *IfcRelConnects*. This new entity is complementary to the existing entities *IfcRelConnectsStructuralActivity* and *IfcRelConnectsStructuralMember*. The new objectified relationship provides the generalization of the physical subordination between two elements, which have dependency information as explained above. The concept of two elements being logically connected is described either for elements that are part of the structural system or other subsystems. Figure 8 shows the specification of the new proposed IFC entity extension.

```
ENTITY IfcRelConnectsStructuralDependence
  SUBTYPE OF (IfcRelConnects);
    RelatingeElement  : IfcElement;
    RelatedElement  : IfcElement;
    RelatedDependencyType   : IfcDependencyTypeEnum;
END_ENTITY;
```

```
TYPE IfcDependencyTypeEnum = ENUMERATION OF (
  INDEPENDENT,
  DEPENDENT,
  NOTDEFINED);
END_TYPE;
```

Figure 8. EXPRESS specification of *IfcRelConnectsStructuralDependence* and *IfcDependencyTypeEnum*.

To structure the disassembly motion constraints information, the use of a new IFC attribute *Motion Constraints* and a new entity *IfcExternalSpatialMotionConstraint* extension are proposed (see Figure 7 and 9). *IfcExternalSpatialMotionConstraint* is an abstract entity subtype of *IfcSpatialElement* that defines external volumetric regions to the building elements. These external volumetric regions represent the necessary space for the disassembly, dismantling, and extraction works of building elements (See section 2.3). The boundaries of the external spatial element are virtual boundaries referenced by the *IfcRefSpaceBoundary* extension. For determining the motion constraints, the relationship for indicating that a given external spatial element has an interference with one or many other elements is realized through *IfcRelInterferesElement*. Figure 9 shows the specification of the new proposed IFC entity extension.

```
ENTITY IfcExternalSpatialMotionConstraint
  SUBTYPE OF (IfcSpatialElement);
    PredefinedType  : OPTIONAL IfcExternalSpatialMotionConstraintTypeEnum;
  INVERSE
    BoundedBy  : SET [0:?] OF IfcRelSpaceBoundary FOR RelatingSpace;
END_ENTITY;
```

```
TYPE IfcExternalSpatialMotionConstraintTypeEnum = ENUMERATION OF (
  EXTERNAL_DISASSEMBLY,
  USERDEFINED,
  NOTDEFINED);
END_TYPE;
```

Figure 9. EXPRESS specification of *IfcExternalSpatialMotionConstraint*.

4. Case study

Two VPL prototypes are used to illustrate the functionality of the BIM method approach for selective disassembly of buildings presented in this study. The VPL prototypes were implemented in four disassembly models from other studies and the results are reported for its analysis and discussion.

4.1. VPL prototype 1- Automated definition of BIM elements' parameters for selective disassembly

Fig. 10 shows the main nodes of the proposed VPL process flow for the systematic determination of the parameters for selective disassembly. Fig. 11 shows the shared parameters for selective disassembly of the BIM elements and the completed BIM constraint parameters for disassembly of the element c_3.

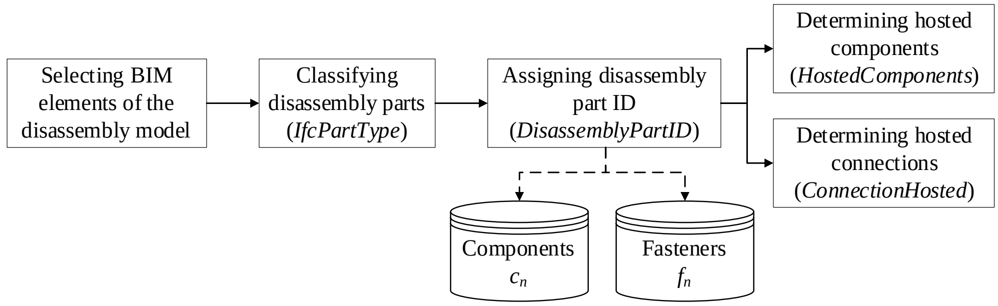


Figure 10. Process flow for selective-disassembly-parameters – VPL Prototype 1.

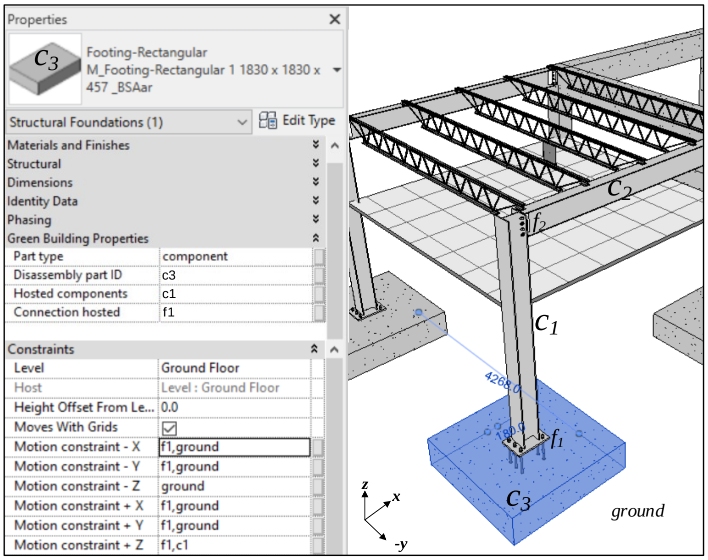


Figure 11. BIM shared parameter values for selective disassembly of c_3.

4.2. VPL prototype 2 – Automated generation of parameters for disassembly models

Fig. 12 shows the main nodes of the proposed VPL process flow for the systematic determination of parameters for disassembly.

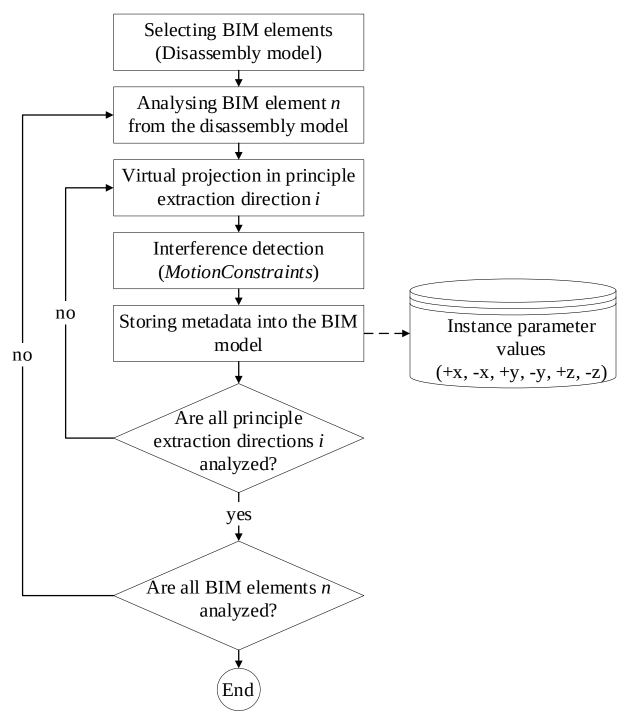
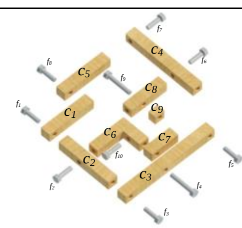
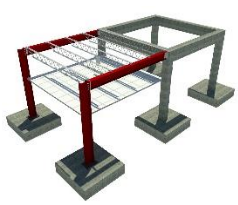
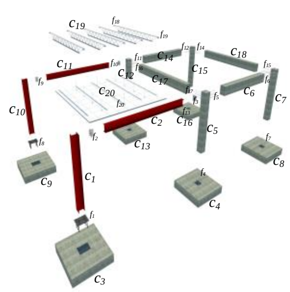
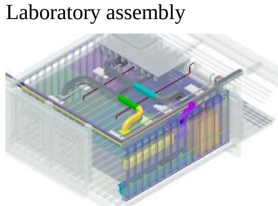
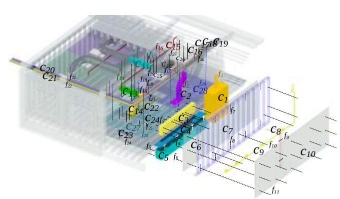
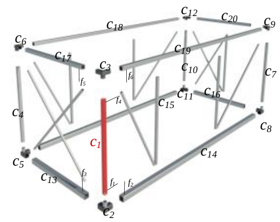


Figure 12. Process flow for selective-disassembly-parameters – VPL prototype 2.

Table 4 shows the results of the implementation of the VPL prototype in four assembly models. The main details about the operation of the algorithmic VPL prototype are explained using the case study of "building assembly" displayed in Table 4. In the first step, the user selects the BIM elements that are part of the disassembly model. Then, the VPL prototype starts analyzing BIM element *n* and the host model. According to the BIM interference check workflow, BIM element *n* is the model element that will be examined to look for interferences. The host model is the group of BIM elements that will be part of the physical constraints for the interference assessment. This node automatically runs the assessment element-by-element in a loop until finishing with the whole disassembly model. In the next step, the VPL prototype defines the considerations for the virtual projection in each principal extraction direction *i* (+*x*, -*x*, +*y*, -*y*, +*z*, and -*z*) according to the coordinates system in the BIM environment. To determine motion constraints, the VPL prototype simulates the virtual projection of a BIM element *n* in each of the principal extraction directions *i* and inside of a user-defined working space (Sanchez and Haas, 2018). This setup can be adjusted to suit the application of interest. Then, the VPL prototype records all the constraining elements from the host model that intersects with the virtual projection of the BIM element *n* under study.

Table 4
Case studies - Automatic determination of BIM parameters for disassembly models

Source	Case study	Disassembly model	Parts	c_n	f_n	Motion constraints
(Smith, S. et al., 2012)	Example assembly 		19	9	10	228
(Sanchez and Haas, 2018)	Building assembly (structure) 		40	20	20	480
(Sanchez; Rausch et al., 2020)	Laboratory assembly 		57	28	29	684

(Rausch et al., 2020)	Modular building assembly			44	20	24	528

*The results generated by the VPL prototypes are consistent with the solution proposed in the source of the case studies where the selective disassembly information was extracted manually from the analytical model.

In the interference detection step, a customized VPL node was developed for clash detection between BIM elements. Fig. 13 shows a graphical representation of the clash detection along the part's projection in the principal extraction directions *+x*, *-y*, and *+z* for a subset of parts analysed in the disassembly model. In Fig. 13, the model element to analyze is the isolated foundation (footing) c_3 and the host model is integrated by the BIM elements *ground*, f_1, and c_1. The principal extraction directions under study are marked in red as well as the elements that collide with the projection of the model element to analyze c_3. In the final step, the motion constraints are loaded into the BIM model as instance parameter values. The VPL prototype is aligned to the workflow for BIM elements interference check.

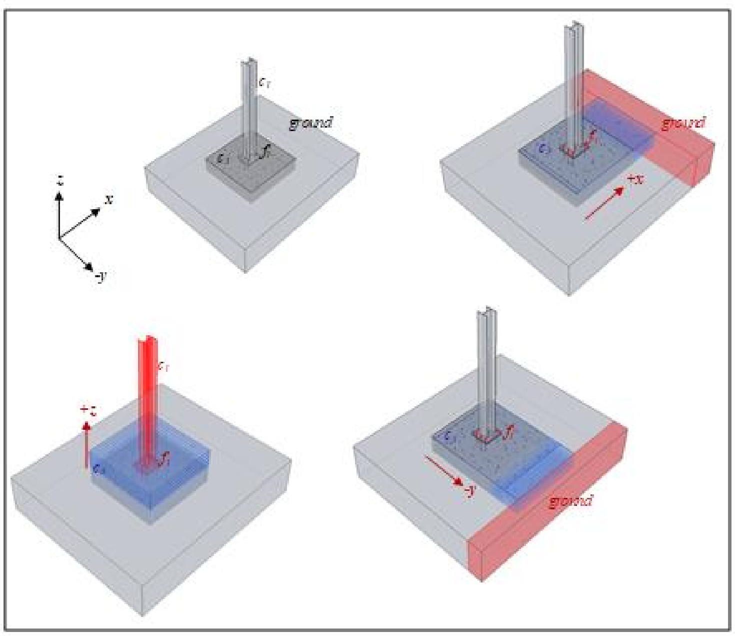


Figure 13. Clash detection for the footing (c_3) along the principal extraction directions *+x*, *-y*, and *+z*.

In a final demonstration step, once the information model displayed in Table 4 (Building assembly) was enriched with the disassembly information, the DG model was generated automatically by recording the physical constraints in cell arrays (*CC*, *MC*, *PC*, *HC*, and *LC* matrices). The constraint matrices have 20 rows and 6 columns (not shown to reduce paper length). The results are consistent with the solution proposed in (Sanchez and Haas, 2018) where the DG model was generated manually from the analytical model. The DG model was used as preprocessed input data for the SDPB approach to generate the disassembly sequences of targeted components. For example, for the targeted component c_2 (steel beam) the approach found a solution $S_1 = (c_2\ f_2\ f_3\ c_{19}\ f_{18}\ f_{19}\ c_{20}\ f_{20})$ and for the targeted component c_1 (steel column) the approach found a solution $S_2 = (c_1\ f_1\ c_2\ f_2\ f_3\ c_{19}\ f_{18}\ f_{19}\ c_{20}\ f_{20})$.

5. Discussion

For the first algorithm, the dynamo prototype was demonstrated to be a functional tool for the automated definition of BIM elements' disassembly parameters. The dynamo prototype establishes the necessary hosting relationships between BIM elements according to the building's elements membership and interdependence. Then, the hosting relationships are added as elements' parameter values into the BIM data structure. According to theories on selective disassembly planning (Sanchez and Haas, 2018; Smith, Shana and Hung, 2015; Smith, S. et al., 2016), these parameters are information that must be identified for the disassembly model, and this is the first step for applying tools and methods for automated planning and optimization of selective disassembly of structures. Even though the BIM structure is not meant to represent a building model as a disassembly model, this study demonstrates that is it possible to bridge this gap by using complementary technology to BIM. On the other hand, the powerful graphical characteristic of BIM complements the workflow for creating an accurate disassembly model where the correct interdependency between elements is critical for creating realistic disassembly planning solutions.

For the second algorithm, the Dynamo prototype was demonstrated to be a functional tool for the automated generation of physical constraints data (BIM element parameters) for disassembly models. The generation of the information is based on the topological assessment of each BIM element, which is meant to be part of the same disassembly model, in order to determine the physical constraint parameter values. This example demonstrates the feasibility of developing algorithms to enrich information models with additional parameters, which is necessary for specific BIM-based assessments such as disassembly planning for buildings. The most relevant feature of the Dynamo prototype is the ability to perform repetitive complex tasks automatically and accurately. The VPL environment is capable of coordinating different modeling functions, such as collision detection, parametric design, and feature modelling in a compact subroutine for the purpose of determining the motion constraints of BIM elements. The results of the two Dynamo examples were compared with the complete DG model described in published case studies, in order to validate their accuracy. It is important to mention that for disassembly models for buildings, the number of components can be overwhelming, therefore these automated tools are an alternative to efficiently complete the missing data in information models.

Even though the presented examples have been demonstrated for building subsystems, further investigations are needed to validate the functionality for other subsystems and complete buildings. Also, the robustness of the computational structures to automatically derive the parameters for disassembly models must be strengthened to be able to handle the complexity of complete buildings. Additionally, it is necessary to test the methods presented in this paper in more case studies with experts and practitioners to cover more diverse perspectives and processes of building structures and system types.

One of the advantages of the presented approach is the straightforward customization of the data preprocessing in the Dynamo platform due to its feature-based parametric modeling nature. The methods developed in this study are calibrated according to the SDPB scope and limitations, however, the data preprocessing can be adapted to the needs of the DG method to implement. For example, more types of connections can be included (e.g., welded components, snap-in connectors, interlocking connections), as well as disassembly methods (e.g., destructive dismantling, modular disassembly, parallel disassembly), and complex building structures (e.g., occluded components, occluded subsystems, compounded extraction directions). In this respect, it is necessary to develop more investigations that expand the scope of the DG methods for buildings. Finally, more experimentations must be developed in order to determine the efficiency of the Dynamo prototypes presented and to propose future improvements.

One important limitation for the implementation of the proposed framework is the current inability of BIM software modelers to develop disassembly models (solely based on current industry practices). Therefore, the geometrical characterization of a disassembly model currently relies on detailed manual inspection (and potential upskilling of practitioners for such processes). Current BIM elements such as BIM objects and BIM building blocks (BIM families) have been designed to fit into information models and to interact with other BIM elements without including the necessary characteristics for disassembly. We argue that the urgent need of increasing the reuse rates of building components in the construction industry will compel different stakeholders to develop and implement the appropriate BIM technology for promoting circular strategies for building assets. For example, an important step in this regard is the integration of disassembly characteristics for BIM elements in the most important BIM guidelines such as The Level of Development Specification (BIMForum, 2020), the international standard for digitization of information ISO 19650 (ISO, 2018), and the level of information need framework BS EN 17412 (BSI, 2020). These guidelines specify the quality, quantity, and detail of information that can be in the form of geometric and alphanumeric information. Such expansions to guidelines would establish the baseline for practitioners (engineers, contractors, suppliers) to implement disassembly designs in a homologous and standardized way. For example, BIM developers (i.e., software vendors) would develop the standardized BIM elements with the appropriate parametric features for disassembly modeling, while designers and other end users (e.g., architects and engineers) would focus on disassembly specifications for the project and design for disassembly. In this respect, we include some illustrative guidelines in the Appendix for applying the proposed approach to other types of building components. In these guidelines, we establish the description required for BIM-based disassembly models in comparison to the specifications on the current BIM guidelines mentioned above.

Regarding the LoD for disassembly models, the developed examples were built according to the specifications of a highly detailed information model LoD 400 (see Section 2.2). This was necessary in order to implement the selective disassembly planning theory properly. In the past decades, multi-LoD for information models (Abualdenien and Borrmann, 2019; Liu et al., 2019) as well as object-space collision detection (Alrufaifi et al., 2019; Chen et al., 2004) has been well studied, concluding that the efficiency of the computational resources required for development decreases dramatically with highly complex geometry models. Further investigations about the impact of multi-LoD for disassembly models are necessary to determine the specific characteristics for particular disassembly planning tasks. For example, a high LoD with the meticulous modeling of physical interphases between components and fasteners is necessary for the implementation of selective disassembly planning. However, the computational requirements for the analysis of a complete building, conformed by an elevated number of parts, might become a significant challenge, either for the information modeling process or for the collision detection (for determining the physical constraints).

Another point to develop as future research is ensuring the quality of information modeling for disassembly models. The method proposed in this study focuses on determining the LoD for disassembly models. As discussed in the paper, the accuracy of the information modeling of the disassembly model is critical for the correct implementation of disassembly planning. According to Uusitalo et al. (2019), it is the responsibility of the project team to agree on how to leverage, adjust, and implement LoD standards based on the project's individual information needs. Therefore, there is a need to develop guidelines for ensuring the quality of information modeling for disassembly models. This study serves as a framework for the development of the guidelines, however, there are important aspects that must be determined in detail such as the allowable tolerances for modeling the physical interfaces between BIM objects, the structural coherence of the disassembly model, and the use of BIM building blocks (BIM families) to automatically modeling the physical interfaces between building components.

Some of the benefits of implementing design for disassembly strategies on building projects are summarized as follows. With these methods, it is possible to create resilient building designs that are efficient for future disassembly or adaptation. Estimating and planning for disassembly can be increasingly automated based on the advances made in this study. The benefits of this automation will save expert labor hours and potentially improve accuracy and predictability of disassembly projects. Also, deconstruction works can be communicated more clearly to stakeholders carrying out these activities. For instance, it could be possible to develop training tools for deconstruction works by using virtual simulation technologies (e.g., Virtual Reality, Augmented Reality). In addition, there are new business models arising in the field of circular economy for the real estate market, where buildings are designed as future raw material banks. Therefore, buildings will have an intrinsic value for the building components they house and the feasibility to retrieve them at the end of their useful life.

6. Conclusions

It has been asserted that current BIM approaches are insufficient for supporting disassembly planning for buildings. BIM is insufficient when building archetypes are conceptualized as disassembly models. Current information models do not support important project activities of disassembly planning projects, such as selective disassembly and product recovery management. In the presented framework, some needs and requirements for information models that support these activities have been identified through (1) the definition of appropriate LoD principles for disassembly models, and (2) an information taxonomy for disassembly models. The requirements are focused on how to effectively represent parts, materials and systems, as well as interfaces between them. Also, additional properties need to be defined such as disassembly parameters and building elements' membership. After defining the information taxonomy for disassembly models this study proposes the integration of the new information into the open BIM standards structure by suggesting five new IFC extensions.

With the development of BIM as a universal tool, it is possible to generate additional technology in order to complete the missing information for disassembly planning of building projects and to support decision making. In this study, we developed a generalizable solution to a case study with two practical examples that solve specific gaps of information models for disassembly planning of buildings. These examples are focused on the field of selective disassembly of buildings. The archetypical problem epitomized by the examples has been solved and validated through functional demonstration. According to previous studies (Sanchez and Haas, 2018; Sanchez et al., 2019b), without a highly organized graphical interface, it is inefficient and ineffective to populate the initial data for a disassembly model for a building. This is because a building can be composed of hundreds or thousands of building parts. The BIM tools developed in this work demonstrate that it is possible to complete the information necessary for a disassembly model in a mostly automated and efficient way. This is an important step to overcome some of the technical barriers for selective disassembly and disassembly planning of buildings.

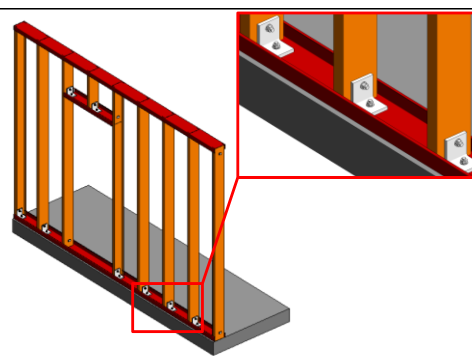
The completion of the study required a framework that has a dedicated building modeling section for selective disassembly planning, proposes the appropriate taxonomy for the required information for disassembly models, and develops a methodology for determining the missing information using an automated plug-in object-oriented interface. The BIM software Revit was deemed suitable for the purpose of this study. An information model involves entities geometry interrelated with predetermined properties/parameters and according to the IFC schema. However, these existing predefined parameters are not sufficient to cover the required information for buildings' disassembly models, and therefore, further parameters must be added. BIM provides the functionality for adding user-defined parameters through VPL environments. This feature was implemented to determine the missing parameters to each BIM element that is meant to be part of the same disassembly model. The results of the experiments show the feasibility of creating disassembly models with the appropriate information requirements. Further investigations must follow the presented study, such as developing the taxonomy for buildings' disassembly planning information requirements for alternative approaches including selective parallel disassembly planning (Smith, Shana and Hung, 2015), destructive disassembly planning (Ziqiang et al., 2015), and interlocking problems in disassembly planning among others (Wang et al., 2020). Different methods for the automatic extraction of disassembly parameters from information models should also be explored for any of the other existent approaches in the field of DG theories.

Appendix

A1. Tables

Tables A1, A2, and A3 show the guidelines for the level of development for disassembly models. The description was developed according to the specifications in the guidelines Level of Development Specification (BIMForum, 2020).

Table A1
Level of development specification for exterior wall construction (cold-form metal framing), Uniformat: B2010.20.20, Omniclass: 21-02 20 10 20 20

Level of Detail	Definition	Information model
LoD 400 (BIMForum)	Cold-formed metal framing is developed with sufficient elements that support the fabrication of the CFMF system. Connection content is development in the wall elements. This includes but is not limited to fasteners, clips, and other related hardware. Cladding and sheathing are not shown for clarity in this image.	

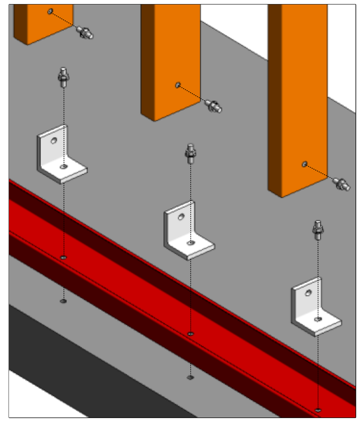
LoD 400 (Requirements for disassembly models)	All the elements are modeled consistently according to a constructible assemblage avoiding volumetric interferences. The physical interfaces between connection elements are developed logically (e.g., coping members, holes for fasteners, extraction direction(s) for fasteners). Each element that is meant to be part of the disassembly models must include the following non-geometrical information: classification, building element's membership, spatial characterization, and deconstruction specifications.	

Table A2
Level of development specification for floor structural frame (wood floor trusses), Uniformat: B1010.10.80, Omniclass: 21-02 10 10 10 80

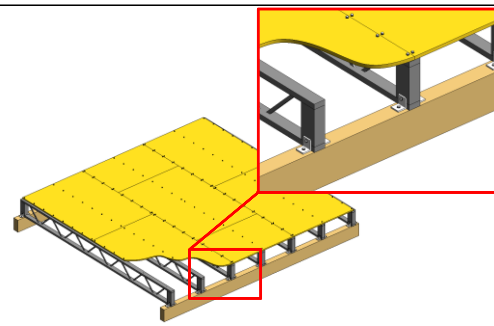
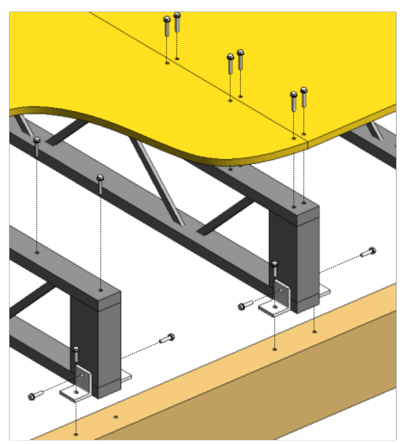
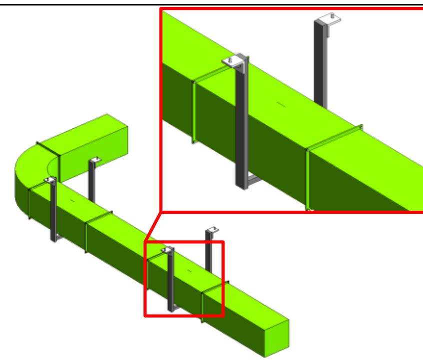
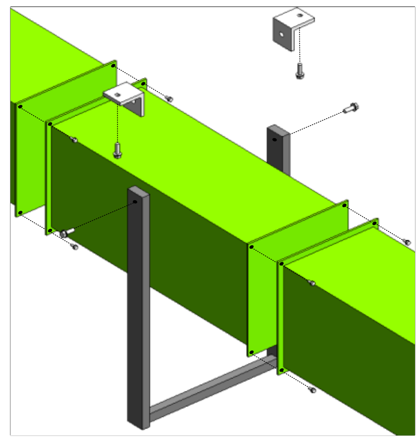
Level of Detail	Definition	Information model
LoD 400 (BIMForum)	Element modeling to include: actual final truss profile with accurate panel points, bridging and lateral braces, fire protection coating, any miscellaneous framing pertaining the truss, erection details for installation, chord and web member section profiles are accurately defined, truss layout in coordination with deck fasteners would be confirmed, hold down locations for large bolts, fasteners, sealant, truss plates and connection material, nails and fasteners, truss plates, deck patterns and joints.	
LoD 400 (Requirements for disassembly models)	All the elements are modeled consistently according to a constructible assemblage avoiding volumetric interferences. The physical interfaces between connection elements are developed logically (e.g., coping members, holes for fasteners, extraction direction(s) for fasteners). Each element that is meant to be part of the disassembly models must include the following non-geometrical information: classification, building element's membership, spatial characterization, and deconstruction specifications.	

Table A3
Level of development specification for exhaust air, Uniformat: D3060.30, Omniclass: 21-04 30 60 30

Level of Detail	Definition	Information model

LoD 400 (BIMForum)	Modeled as actual size, shape, spacing, location, and slope (if required)/connections of duct, dampers, fittings, and insulation for risers, mains, and branches; actual size, shape, spacing, and clearances required for all hangers, supports, vibration and seismic control that are utilized in the layout of all risers, mains, and branches. Actual floor and wall penetration elements modeled. Actual access/code clearance requirements modeled. Supplementary components added to the model required for fabrication and field installation.	
LoD 400 (Requirements for disassembly models)	All the elements are modeled consistently according to a constructible assemblage avoiding volumetric interferences. The physical interfaces between connection elements are developed logically (e.g., coping members, holes for fasteners, extraction direction(s) for fasteners). Each element that is meant to be part of the disassembly models must include the following non-geometrical information: classification, building element's membership, spatial characterization, and deconstruction specifications.	

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