Knowledge Graph-based Deconstruction Planning of Building's Products

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Abstract –

The transition from a linear economy (take-make-dispose) to a circular economy in the construction industry (i.e., circularity in construction) necessitates adopting deconstruction instead of demolition. Deconstruction planning methods need to be investigated to facilitate this transition. Successful deconstruction planning requires considering various information to capture the destiny of the extracted building's product. Therefore, there is a dire need to propose a deconstruction planning method that is interoperable, easily integrated with various data sources, and conducive to stakeholder collaboration. To this end, this paper aims to propose a deconstruction planning method using Knowledge Graph (KG) technology. Firstly, the authors extracted the characteristics of the facility to be deconstructed, including hosting and hosted relations of components. Secondly, the characteristics of the facility's products were transformed into a KG. Finally, disassembly rules were defined, and new knowledge was inferred via automated reasoning. The developed method was tested on two case studies, involving two-dimensional and three-dimensional representations. The results aligned with other methods in the literature, requiring fewer inputs.

Keywords –

Deconstruction planning; Disassembly sequence; Knowledge graph; Circularity in construction

1 Introduction

The construction industry has been identified as one of the largest consumers of virgin materials and a major contributor to landfills through Construction, Renovation, and Demolition (CRD) waste [1]. It is estimated that the construction industry is responsible for more than 30% of the world's total waste, and it consumes around 50% of the world's virgin materials [2]. The End-of-Life (EoL) phase of the built facility is the most critical phase regarding the amount of waste generated from the construction industry; more than half of the generated waste is caused by the implemented scenario to handle the facility at the EoL [3]. Two EoL scenarios can be implemented, namely, demolition and deconstruction [4]. Demolition is the act of destroying a built facility regardless of the recoverability of its products (materials/components/subsystems); most of the generated waste is landfilled with little consideration for recycling [5]. The resource-friendly scenario is deconstruction, which is a planned disassembly of products from the built facility. The output of this scenario can serve several purposes such as building relocation and repurposing, product reuse, and recycling [4].

Demolition, with its short-term economic benefits and quicker process, remains the prevalent EoL scenario compared to deconstruction, which offers environmental, social, and long-term economic benefits. In response to this, the deconstruction planning research line has gained prominence. Deconstruction planning is divided into strategic and operational planning [6], [7]. Strategic planning is more high-level (e.g., minimizing the total duration of the deconstruction project), while operational planning is more in-detail and tactical (e.g., minimizing the duration of a single activity). Both planning methods are crucial and complement each other; strategic planning objectives may serve as the set of constraints to be followed in operational planning.

Deconstruction planning requires integrating various pieces of information to make informed decisions on how to execute deconstruction most efficiently, including (i) building type; (ii) building age and condition; (iii) Bill of Quantities (BoQ); (iv) the existence of hazardous materials; (v) health and safety considerations; and (vi) legal requirements [6]. We refer to the information required for deconstruction planning as 'disassembly information'. Achieving the main goal of deconstruction, circularity in construction, necessitates three main pillars: deconstructability, capability, and marketability [8]. Deconstructability involves the ability of a facility's products to be deconstructed, handled, loaded, and transported, encompassing information on type of the facility, products' type, quantity, and condition, as well as working space, and lifespan. The capability pillar focuses on stakeholder and infrastructure readiness, collecting information such as contractor resources, infrastructure capacity, and legal requirements [9]. In terms of the marketability pillar, engaging potential customers and stakeholders early on is essential to quantify the demand for reused products.

Although the labor-intensive nature of deconstruction yields environmental and social benefits [7], [8], it remains one of the primary reasons stakeholders opt for demolition to expedite the removal of the built facility [10]. With the imminent large-scale retirement of aging facilities, there is a dire need to shorten the required duration for implementing deconstruction. To achieve this objective, it is essential to plan each deconstruction activity before its execution [6]. To this end, this paper aims to propose a deconstruction planning method that is interoperable, easily integrated with various data sources, and conducive to stakeholder collaboration to facilitate objective decision-making. The proposed method adopts a bottom-up approach, specifically focusing on operational deconstruction planning.

2 Existing Operational Deconstruction Planning Methods

In practice, operational deconstruction planning is based on professionals' experience, which leads to suboptimal workflow due to the subjective nature of decision-making. To provide an objective method for deconstruction planning Sanchez and Haas (2018) developed a single-target Sequence Disassembly Planning for Buildings (SDPB). The proposed method was inherited from the Disassembly Sequence Structure Graph (DSSG) model theory for manufactured products. The disassembly graph of this method consisted of 11 constraint matrices; 9 of them representing the physical, functional, and interdependence between components and fasteners, while the other two related to the environmental impacts and the cost of the disassembly works. The output of this method is an inverted tree graph of the chosen path of disassembly; root nodes in the inverted tree represent target components, leaf nodes represent parts that constrain the target components, and the links between them represent constraints. This research line that Sanchez and Haas (2018) started was the keystone for other works to explore the field of operational deconstruction planning.

In this sense, Sanchez et al. (2019) extended the SDPB to include multiple targets. The multiple-target SDPB was obtained by merging the all single-target SDPB, by matching the identical components that have the same extraction direction. To cut the computational time, they introduced limits of design, which represents the unmodified components in the models. the components within the limits of design were not included in the disassembly model but however they were considered as physical and motion constraints. The output of the multiple-target SDPB was exported to Microsoft Project (MS) to develop the deconstruction baseline schedule. Yet, the developed SDPB methods rely only on a single deconstruction method. In this, another extension of SDPB was considering different deconstruction methods such as selective demolition, destructive disassembly, and perfect disassembly [13]. In the same vein, Mahmoudi Motahar and Hosseini Nourzad (2021) proposed a hybrid method for disassembly planning for buildings that support sequential and parallel approaches. Instead of using expert rules to cut the computational cost, they utilized the Non-dominated Sorting Genetic Algorithm (NSGA-II).

All the previously mentioned methods are mainly based on physical, interdependency, accessibility, and motion constraints. However, as mentioned in the introduction section, disassembly information includes more attributes than the ones mentioned in the previous studies. In this context, Denis et al. (2018) proposed a Disassembly Network Analysis (DNA) method that plans for disassembly by considering several product's attributes such as accessibility, transportability, condition, weight, reversibility of connection, disassemble time, demolition time, and sequential dependence. Based on the values of these parameters, a flowchart of four steps has been followed to (i) check the possibility of disassembling the target component; (ii) identify potential paths to access the target component; (iii) determine the recoverable elements and lost ones during disassembling; and (iv) make decisions based on recovered elements, lost elements, and disassembly time for each path.

Deconstruction is a significant step towards the adoption of circularity in construction. To ensure reaching this goal, post-deconstruction (i.e., the destiny of the extracted building's products) needs to be considered [16]. This necessitates integrating various information beyond the building level such as technical feasibility, market feasibility, and legal environment in the region. Given these complexities, there is a pressing need to conduct deconstruction planning using methods that are interoperable, easily integrated with various data sources, and conducive to stakeholder collaboration. This is where semantic web technologies can play a crucial role. Recently, in the manufacturing industry, studies are modeling disassembly information using Knowledge Graphs (KGs) to describe manufactured products [17]. Knowledge graphs are capable of modeling, consolidating, and deducing insights from intricate, diverse data originating from various sources, offering scalability, expressiveness, and extensibility [18]. Its strength resides in its semantic processing and interconnected organizational abilities, forming the foundation for intelligent information applications [19].

3 Disassembly Information Modeling

To construct the KGs in this study, three sequential steps were followed by the authors. Firstly, extracting the characteristics of the facility to be deconstructed including hosting and hosted relations of components. Secondly, the characteristics of the facility's products were transformed into knowledge graph. Finally, disassembly rules were defined, and a new knowledge was inferred via automated reasoning.

To test the proposed method for deconstruction planning, a simplified typical building frame assembly was used as a case study in both two and three-dimensional representation, as shown in Figure 1. This case study was introduced by Sanchez and Haas (2018a) and has been utilized in the literature to prove the concept of other deconstruction planning methods [14], [15], [20]. Figure 1 illustrates the components and connections of the assembly in both dimensions. This information was translated into two matrices: a hosted component constraint matrix (HC) and a liaison constraint matrix for components (LC). Due to space limitations, the HC and LC matrices of the two-dimensional case study are shown in Equation 1 and Equation 2, respectively. HC records the individual relationship between host and hosted components, while LC documents the fasteners physically attaching the hosted components to the hosting component under analysis. Both HC and LC were utilized as inputs for the selective disassembly sequence planning method proposed by Sanchez and Haas (2018a).

$$\begin{bmatrix} HC1 \\ HC2 \\ HC3 \\ HC4 \\ HC5 \\ HC6 \\ HC7 \\ HC8 \\ HC9 \\ HC10 \end{bmatrix} = \begin{bmatrix} C4 \\ C5 \\ C6 \\ C7 \\ C7, C8 \\ C8 \\ C9, C10 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} LC1 \\ LC2 \\ LC3 \\ LC4 \\ LC5 \\ LC6 \\ LC7 \\ LC8 \\ LC9 \\ LC10 \end{bmatrix} = \begin{bmatrix} f1 \\ f4 \\ f7 \\ f2 \\ f3, f5 \\ f6 \\ f8, f9 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

The information extracted in the previous stage was represented by Resource Description Framework (RDF) triples to form the Deconstruction Knowledge Graph (DKG). RDF serves as a versatile and universal data model employed for the representation and amalgamation of data through directed labeled graphs [21]. Each triple consists of two nodes (i.e., subject and object) connected with an edge (i.e., predicate) that defines the relationship between them. In this research, Blazegraph Database was utilized to construct the knowledge graph of the case study [22]. RDF triples were encoded using turtle format. Figure 2 shows part of the DKG of the 2D case study that includes all the in-flow and out-flow edges of nodes C7, C9, and C10. Two kinds of nodes were utilized in the DKG: Internationalized Resource Identifier (IRI), represented by circular borders, and literal nodes, represented by no borders. IRI nodes are used to describe entities that will have a unique addresses or references, while literal nodes are used to represent values such as strings, numbers, or dates. The relationships between the nodes were described using 6 predicates as depicted in, Table 1. Two of these predicates, indicated by red arrows in Figure 2, were inferred after applying specific rules. More details about the inferred knowledge will be explained in the next paragraph.

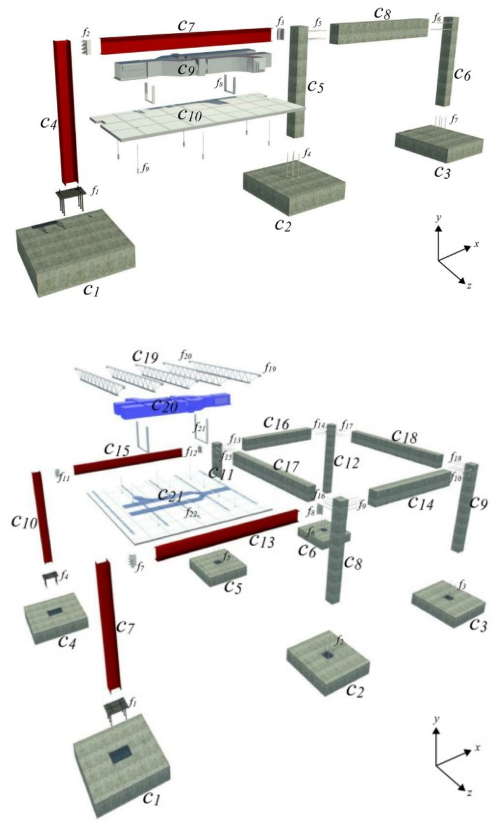

Figure 1. The prototype building in 2D and 3D - adapted from Sanchez and Haas (2018a)

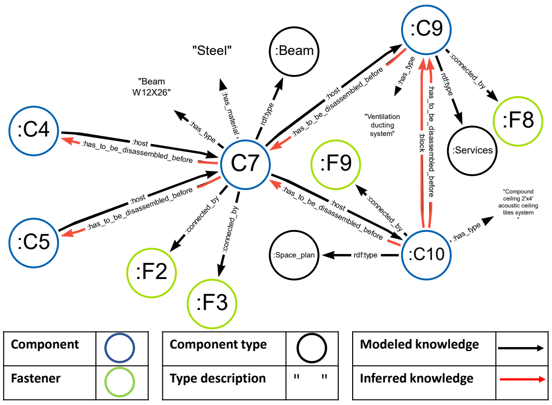

Figure 2. Part of the disassembly knowledge graph for C7, C9, and C10 of the 2D case study (Processed by Arrows.app)

Table 1. Predicates used to define relationships.

Predicate	Description	Reciprocal relation
:host	Records hosting hosted relationship between components	:is_hosted
:block	Records what components block the accessibility to the target component	:is_blocked
:has_to_be_disassembled_before	Records the predecessor(s) that need to be disassembled before disassembling the target component	:disassembled_after
:connected_by	Records how the hosted component is connected to the hosting component	NA
:has_material	Describes the material of the component	NA
:has_type	Describes the component and connection type	NA

Some rules will be used to infer new knowledge that will be used to develop the deconstruction plan. In the manufacturing industry, disassembly task planning (i.e., deconstruction planning) refers to the generation of the sequence of tasks, disassembly direction, and the tool to be used [23]. Table 2 lists the rules which were covering two main aspects, structural stability and accessibility. The structural stability was defined based on the host hosted relationship, while the accessibility was defined based on the theory of building layers, which describes six classes according to their life expectancy, stuff, space plan, services, skin, structure, and site [24]. It should be noted that other rules were encoded to define the inverse relationship between node (when applicable). The rules were applied utilizing SPARQL query language that is capable of retrieving and updating data stored in RDF format.

Table 2. Rules used to infer new knowledge

Rules	Description
?c1 :host ?c2. ?c1 :host ?c3. ?c2 a :Services. ?c3 a :Space_Plan > ?c3 :block ?c2	If a component (C1) is hosting other components (C2 and C3); C2 is either plumping, electrical, mechanical, or hydraulics; and C3 is either internal wall, partitioning, finish, or furniture, then the space plan layer (C3) block the accessibility to the fasteners of the service layer C2.
?c1 :host ?c2 > ?c2 :has_to_be_disassembled_before ?c1	If a component (C1) is hosting another component (C2), then the hosted component (C2) needs to be disassembled before the hosting component (C1) to ensure the stability of the structure.
?c1 :block ?c2> ?c1 :has_to_be_disassembled_before ?c2	If the fastener of component (C1) needs to be accessed and another component (C2) is restricting its accessibility, then the barrier component (C2) needs to be disassembled to reach the fastener of C1.
?c1 :host ?c2 > ?c2 :is_hosted ?c1	If a component (C1) is hosting another component (C2), then the C2 is hosted by C1.
?c1 :block ?c2 > ?c2 :is_blocked ?c1	If a component (C1) is restricting the access to the fastener of another component (C2), then the C2 is blocked by C1.
?c1:has_to_be_disassembled_before?c2 > ?c2 :disassembled_after?c1	If a component (C1) needs to be disassembled before another component (C2), then the

C2 can be disassembled after C1.

4 Model Solution and Deconstruction Plan

To assess the effectiveness of the proposed knowledge graph-based deconstruction planning method, two case studies were employed. As illustrated in Figure 1, the 2D example comprises 10 components and 9 connections, whereas the 3D example involves 21 components and 22 connections. SPARQL query language was used to retrieve the deconstruction plan from each example, as shown in Figure 3. The retrieved deconstruction plan is divided into two main parts. The first part records the phase in which the deconstruction activities take place; activities within the same phase can be performed in parallel. The second part provides a description of the component to be disassembled, including its connections to the hosting component. The proposed method in this study was tested by developing the deconstruction plan to extract the target components (C5) and (C19) in the two- and three-dimensional case studies, respectively. These two components were chosen because their deconstruction plan was proposed using the method developed by Sanchez and Haas (2018a).

Figure 4 shows a visual representation of the results of the 2D and 3D case studies. Four phases were required to extract the target component (C5) in the 2D example. In the first phase, two components can be disassembled in parallel. Then, starting from phase B and all the way to phase D one component can be disassembled per each phase. In the three-dimensional case study, the deconstruction plan of the target component (C19) was sequential, i.e., only one component per each phase. The two knowledge graph-based deconstruction plans are aligned with the plans proposed by Sanchez and Haas (2018a). What sets the knowledge graph-based deconstruction planning method apart from the previous methods is that it needs fewer inputs to develop the plan. The proposed method did not require inputs indicating physical and motion constraints for fasteners and components, and still it provided the same results with 5 matrices less from the existing methods in the literature.

It should be noted that the proposed KG-based deconstruction planning method serves as a proof of concept. In the upcoming stages of this ongoing project in deconstruction planning, various pieces of information will be integrated, including both deconstruction and post-deconstruction phases.

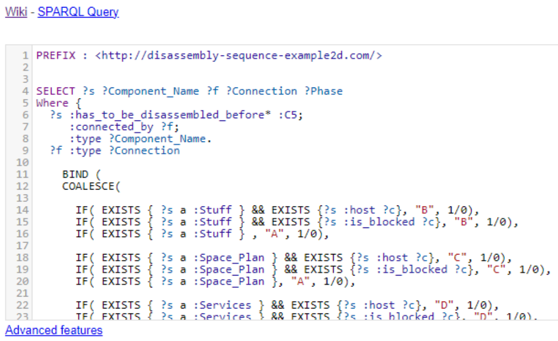

Figure 3. A snapshot of the applied SPARQL query to plan for deconstruction operations of the 2D case study

5 Conclusion

The transition towards circularity in the construction industry is gaining momentum, primarily to achieve the sustainable development goals, especially SDG12 (Responsible Consumption and Production). In this context, deconstruction should be adopted instead of demolition at the end-of-life (EoL) stage. Unlike demolition, deconstruction is a labor-intensive task that requires detailed planning. Therefore, this paper developed a deconstruction planning method based on knowledge graphs. The developed method was tested on two case studies, involving two-dimensional and three-dimensional representations. The results aligned with other methods in the literature, requiring fewer inputs. The developed method was able to infer new knowledge with minimum inputs possible.

The main contribution of this work was the proof of concept that knowledge graphs can be used to develop deconstruction plans in the construction industry. However, the work has the following limitations: (i) deconstruction performance criteria, such as deconstruction cost, environmental performance, and the duration of each activity, should be considered while developing the plan; and (ii) the two case studies mainly focused on structural components.

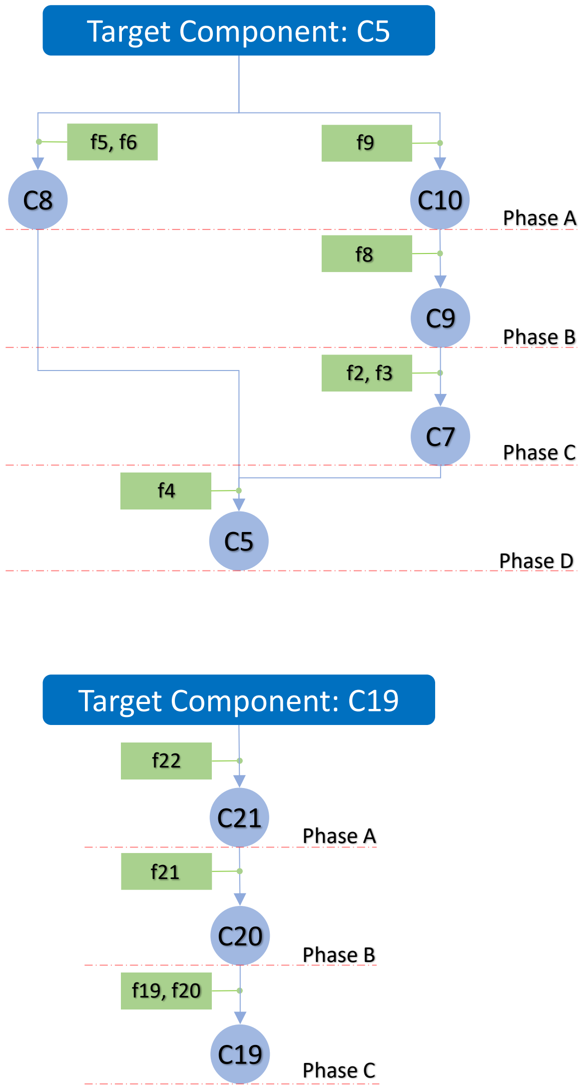

Figure 4. The deconstruction plan for components 5, and 19

6 References

[1] Ajayebi, A., P. Hopkinson, K. Zhou, D. Lam, H. M. Chen and Y. Wang, "Spatiotemporal model to quantify stocks of building structural products for a prospective circular economy," *Resour. Conserv. Recycl.*, vol. 162, no. June, p. 105026, 2020.

[2] Miller, N., "BBC Future," 2021. [Online]. Available: https://www.bbc.com/future/article/20211215-the-buildings-made-from-rubbish. [Accessed: 18-Feb-2023].

[3] Akanbi, L. A. *et al.*, "Salvaging building materials in a circular economy : A BIM-based whole-life performance estimator," *Resour. Conserv. Recycl.*, vol. 129, no. May 2017, pp. 175–186, 2018.

[4] Akinade, O. O. *et al.*, "Waste minimisation through deconstruction : A BIM based Deconstructability Assessment Score (BIM-DAS)," *Resour. Conserv. Recycl.*, vol. 105, pp. 167–176, 2015.

[5] Panizza, R. O., A. S. Allam, A. Kasliwal and M. Nik-Bakht, "Labeling Construction, Renovation, and Demolition Waste through Segment Anything Model (SAM)," in *Construction Research Congress 2024*, 2024.

[6] Hübner, F., R. Volk, A. Kühlen and F. Schultmann, "Review of project planning methods for deconstruction projects of buildings," *Built Environ. Proj. Asset Manag.*, vol. 7, no. 2, pp. 212–226, 2017.

[7] Allam, A. S., and M. Nik-Bakht, "From demolition to deconstruction of the built environment : A synthesis of the literature," *J. Build. Eng.*, vol. 64, no. 15679, pp. 1–18, 2023.

[8] Allam, A. S., R. O. Panizza and M. Nik-Bakht, "A SWOT Analysis for Deconstruction of the Canadian Built Environment," in *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2023*, 2023, pp. 1–13.

[9] Panizza, R., and M. Nik-Bakht, "Building stock as a future supply of second-use material – a review of urban mining methods," *Waste Manag. Bull.*, vol. 2, no. 2, pp. 19–31, 2024.

[10] Allam, A. S., and M. Nik-Bakht, "Barriers to Circularity in Construction: An analysis of experts' perspectives," in *2023 European Conference on Computing in Construction*, 2023.

[11] Sanchez, B., and C. Haas, "A novel selective disassembly sequence planning method for adaptive reuse of buildings," *J. Clean. Prod.*, vol. 183, pp. 998–1010, 2018.

[12] Sanchez, B., C. Rausch and C. Haas, "'Deconstruction programming for adaptive reuse of buildings,'" *Autom. Constr.*, vol. 107, no. August 2018, p. 102921, 2019.

[13] Sanchez, B., C. Rausch, C. Haas and R. Saari, "A selective disassembly multi-objective optimization approach for adaptive reuse of building components," *Resour. Conserv. Recycl.*, vol. 154, p. 104605, 2020.

[14] Mahmoudi Motahar, M., and S. H. Hosseini Nourzad, "A hybrid method for optimizing selective disassembly sequence planning in adaptive reuse of buildings," *Eng. Constr. Archit. Manag.*, 2021.

[15] Denis, F., C. Vandervaeren and N. De Temmerman, “Using network analysis and BIM to quantify the impact of Design for Disassembly,” *Buildings*, vol. 8, no. 8, pp. 1–22, 2018.

[16] Allam, A. S., and M. Nik-Bakht, “Supporting circularity in construction with performance-based deconstruction,” *Sustain. Prod. Consum.*, vol. 45, pp. 1–14, 2024.

[17] Wu, H., Z. Jiang, S. Zhu and H. Zhang, “A Knowledge Graph Based Disassembly Sequence Planning For End-of-Life Power Battery,” *Int. J. Precis. Eng. Manuf. - Green Technol.*, no. 0123456789, 2023.

[18] Kebede, R., A. Moscati, H. Tan and P. Johansson, “Circular economy in the built environment: a framework for implementing digital product passports with knowledge graphs,” in *2023 European Conference on Computing in Construction*, 2023.

[19] Peng, J., and X. Liu, “Automated code compliance checking research based on BIM and knowledge graph,” *Sci. Rep.*, vol. 13, no. 1, pp. 1–12, 2023.

[20] Mahmoudi Motahar, M., S. H. Hosseini Nourzad and F. Rahimi, “Integrating complete disassembly planning with deconstructability assessment to facilitate designing deconstructable buildings,” *Archit. Eng. Des. Manag.*, pp. 1–18, 2023.

[21] Kebede, R., A. Moscati, H. Tan and P. Johansson, “Integration of manufacturers’ product data in BIM platforms using semantic web technologies,” *Autom. Constr.*, vol. 144, no. March, p. 104630, 2022.

[22] “Blazegraph Database.” [Online]. Available: https://blazegraph.com/. [Accessed: 11-Dec-2023].

[23] Yu, J., H. Zhang, Z. Jiang, W. Yan, Y. Wang and Q. Zhou, “Disassembly task planning for end-of-life automotive traction batteries based on ontology and partial destructive rules,” *J. Manuf. Syst.*, vol. 62, no. 947, pp. 347–366, 2022.

[24] Brand, S., *How Buildings Learn: What Happens After They’re Built*. 1995.