Robot assisted selective disassembly for buildings

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Abstract –

This study explores the integration of Building Information Modeling (BIM)-based selective disassembly planning with robotic automation to facilitate the efficient and autonomous retrieval of building components, addressing critical challenges in the construction industry's transition toward a Circular Economy (CE). The BIM-based disassembly planning system developed in previous studies forms the core of this framework, generating optimized sequences for disassembly while considering environmental impacts, cost efficiency, and structural dependencies. This information is processed and utilized by robotic operating systems to execute precise disassembly tasks, as demonstrated through virtual simulations and pilot tests. The results indicate the technical feasibility of robotic selective disassembly for simple building archetypes, highlighting the potential for scaling this approach to more complex scenarios. The proposed method offers substantial decarbonization benefits by enabling material recovery and reuse, reducing reliance on virgin resources, and minimizing waste generation. These advancements directly contribute to reducing greenhouse gas emissions associated with material extraction, processing, and disposal. Additionally, this approach aligns with CE principles by extending the lifecycle of building components and promoting sustainable construction practices. Future work will focus on validating the framework in real-world applications, addressing challenges such as variability in building systems, structural interdependencies, and environmental constraints. The integration of advanced robotics, including AI-driven perception and adaptive control, will further enhance scalability and robustness. Moreover, potential applications in extreme environments, such as extra-terrestrial construction, underscore the versatility of this approach.

Keywords –

Disassembly planning; Robot assisted disassembly; Building Information Modeling; Cradle-to-Cradle; Circular Economy

1 Introduction

Selective disassembly sequence planning (SDSP) is emerging as a transformative technology in the disassembly of buildings, offering several advantages. It facilitates the efficient retrieval of reusable building components and materials [7,9], supports adaptive reuse [15], renovations [16], and maintenance [16], and contributes to the development of superior life-cycle strategies like Design for Disassembly (DfD) [1,5,10,12] and the concept of buildings as future material banks [1,14]. Simultaneously, the field of robotic automation for assembly and disassembly in construction is gaining momentum [8]. The deployment of robotics in this context is proving to increase the efficiency and quality of work, demonstrate both technical and economic feasibility, and address labor shortages in response to the substantial current and future demand for buildings worldwide [4].

The need for implementing SDSP in a systemic manner is critical in today's context for a transition towards a Circular Economy (CE) in the built environment. The construction industry is currently responsible for the depletion of 40% of global natural resources and generates approximately 40% of waste ending up in landfills [1]. These issues are largely due to the fact that the existing built environment was not designed with disassembly, reuse, adaptation, or transformation in mind [12,16]. Additionally, practical SDSP methods and tools have been lacking [14]. However, recent advances have seen the implementation of SDSP [15] and robotic automation [18] using Building Information Modeling (BIM). This convergence has created a clear pathway for leveraging the combined benefits of both technologies to achieve optimized, systemic disassembly of building structures, thereby supporting the decarbonization of the built environment.

The primary aim of this study is to develop a framework for the integration of BIM-based SDSP into robotic automation processes. The framework focuses on the information processing using a previously developed BIM-based SDSP system for enriching the intelligence of robots for the autonomous disassembly of targeted structure components. The information processing will be elucidated for the technical implementation using different types of robotic solutions (e.g. robotic arms and wheeled robots) and virtual simulations (e.g. robotic arm simulator). A functional demonstration has been created to showcase the preparation, processing, and integration of information necessary for the BIM-based SDSP system and the operating system of a robotic solution.

2 Background

2.1 Selective disassembly for buildings

Selective disassembly sequence planning (SDSP) is the process of recognizing the required consecutive steps for dismantling targeted building components, defining deconstruction activities, and ordering them logically. While SDSP for manufacturing products has been developed over the past five decades, SDSP for buildings has gained more attention only in the last decade due to the growing need for a CE in the built environment [15]. In 2018, the BIM-based Sequential Disassembly Planning for Buildings (SDPB) method was developed for the selective disassembly of building components. The SDPB method analyses the disassembly capacity of building assemblies by generating optimized sequences for retrieving targeted components, considering environmental impact, building cost, and rule-based analysis [14]. Mahmoudi and Hosseini Nourzad [9] developed the Hybrid Disassembly Sequence Planning (HDSP) method and tested it with the same building archetypes presented in the SDPB model. Denis et al. [5] developed the Disassembly Network Analysis (DNA) method for selective disassembly planning by applying network analysis. In a subsequent study, Vandervaeren et al. [16] developed the Material Flow Analysis for Demountable buildings (MFAD) method to evaluate the effect of the disassembly capacity on the building material flow. In 2024, Allam and Nik-Bakht [2] proposed a deconstruction planning method using Knowledge Graph (KG) technology to facilitate the evaluation of disassembly sequences for targeted components. In their work, Abu-Ghaida, et al. [1] developed a disassembly network-based approach for accounting for product recovery potential in building life cycle assessments. The primary distinction between the KG technology [2] and the closed-loop lifecycle information flow [18] lies in their respective structures and flexibility. The KG framework is centered on data integration for lifecycle modeling within a structured and organized arrangement, whereas the closed-loop lifecycle information flow illustrates the circulation of data within a dynamic, circular system. Collectively, these data structuring models are complementary, as KGs can facilitate the utilization of closed-loop lifecycle information flows for continuous enhancement and incorporation into BIM. In 2021, Beurskens [3] presented an assessment method to evaluate the reuse potential of buildings and building products. The author proposed the use of Design Structure Matrices (DSM) for establishing the relationships among building components, with the purpose of identifying the disassembly sequence of the components using Steward’s algorithm.

2.2 Robotics for disassembly of building structures

The field of construction robotics has predominantly focused on assembly processes, with numerous successful implementations such as the DFAB House project at ETH Zurich demonstrating robotic fabrication of concrete walls, the SAM100 (Semi-Automated Mason) robot for bricklaying, and the Japanese construction giant Obayashi Corporation's automated systems for steel beam assembly. In contrast, relatively limited research has been directed towards robotic disassembly, particularly in the context of selective disassembly operations [13]. Unlike total disassembly, which involves the complete deconstruction of a structure, selective disassembly represents a more sophisticated approach requiring precise targeting of specific components while preserving the integrity of surrounding elements [14,15]. This strategic methodology, when combined with robotic automation, holds significant potential for enabling adaptive reuse, reconfigurability, and transformability of buildings. Recent advances in robotic technology, particularly when integrated with BIM-based SDSP systems, are beginning to address the complexities inherent in selective disassembly operations, offering promising solutions for more sustainable and circular approaches to building modification and material recovery. However, significant challenges remain in developing robust systems capable of handling the variability and complexity of building disassembly tasks, particularly in terms of component recognition, manipulation strategies, and real-time adaptation to changing site conditions.

Little of the existing literature regarding the integration of robotics with on-site construction activities has focused on disassembly or similar topics. Meta-analyses of robotics in construction (RiC) focused on revealing trends in the technology’s implementation, but did not identify disassembly as a significant topic of recent research [6,17]. In addition, human-robot collaboration (HRC) literature sees a much heavier importance placed on construction than deconstruction [11]. Opportunities for the integration of robotics in total disassembly and selective disassembly are relevant. The use of BIM in building design creates a network of spatial data regarding building materials and assemblies that can be utilized by robotic operating systems for robot assisted selective disassembly. The primary contribution of this paper is the structuring of the SDPB output as an information package compliant with the Industry Foundation Classes (IFC) schema for robotic operating systems, alongside a pilot demonstration of this pipeline simulation.

3 A framework for robot assisted selective disassembly for buildings

The framework is centred on information processing using a BIM-based SDSP system to enhance the intelligence of robots for the autonomous disassembly of targeted components, leveraging a system developed in earlier studies (see Figure 1). This system provides crucial information for autonomous selective disassembly, including optimized sequences for disassembling building parts (components and connections), geometrical and topological information for building parts, three-dimensional coordinates for each part (*x*, *y*, *z*), hosted components, hosted connections, connection type, physical interface characterization, structural composition relationship, graph data structure, extraction directions for each building part (+*x*, -*x*, +*y*, -*y*, +*z*, -*z*), and physical constraining parts in each extraction direction. All this information is used and managed by the robot operating system for developing the disassembly tasks.

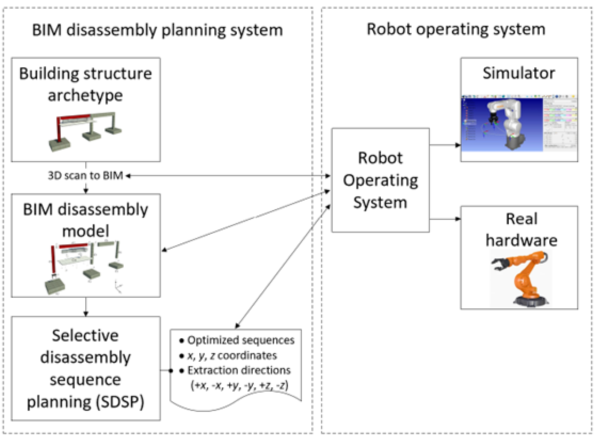

Figure 1. Framework for the integration of BIM-based SDSP for robotic automation

3.1 BIM-based disassembly planning

The BIM-based SDSP system selected for this research is the Sequential Disassembly Planning for Buildings (SDPB) method developed in previous studies. The SDPB method is based on an approach developed for product manufacturing, namely the Disassembly Sequence Structure Graph (DSSG) method. The SDPB method is used to generate optimized disassembly sequences for retrieving targeted components from BIM-based models by considering environmental impact, building cost, and rule-based analysis. The information generated by the system is as follows:

- Optimized sequences for disassembling building components.
- Geometrical and topological information for building parts is the information related to the geometrical characteristics of the disassembly parts. This information is fundamental to the creation of an analytical disassembly model that is consistent with the real conditions of the objects in the space as well as for determining the physical constraints among objects.
- Three-dimensional coordinates for each part (*x*, *y*, *z*) define the origin of a 3D Cartesian coordinate system associated with all the parts of the disassembly model. This characteristic is mainly associated with selective disassembly methods that evaluate extraction directions in a free 3D space, such as matrix-based methods and petri net methods.
- Hosted components and hosted connections register the parts that structurally depend on a host component. This characteristic is exclusive to buildings' disassembly models, in which the static equilibrium plays a critical factor to be able of estimating realistic disassembly patterns.
- Connection type indicates the condition of a fastener for being removed in one direction (e.g. +*x*) or multiple directions (e.g. +*x*, and -*x*).
- Physical interface characterization defines the geometrical and mechanical specifications associated with different types of connections (e.g., bolts, screws, rivets, washers, welding). The physical interface characterization plays a critical role in the accurate study of the disassembly properties of a connection type and the technical feasibility for disassembly.
- Structural composition relationships are an important characteristic for disassembly models of buildings. This characteristic indicates the structural connectivity among parts inside a disassembly model. For manufacturing products, any fastener can be removed from the disassembly model if the fastener is physically accessible. In comparison, in a building composition, some fasteners could be physically accessible but without them, the structural stability of the assembly would be compromised.
- The graph data structure is necessary for establishing the mathematical configuration of the disassembly model. A graph data structure is the

abstract representation of a disassembly model through nodes (vertices) and liaisons (edges).

- Extraction directions are the possible paths for removing any disassembly part. As a generality for SDSP methods, the extraction directions are four in a 2D environment (+*x*, -*x*, +*y*, -*y*) and six in a 3D environment (+*x*, -*x*, +*y*, -*y*, +*z*, -*z*). However, the extraction directions can be increased by adding as many extraction directions as necessary and by adding compounded extraction paths.
- Physical constraining parts are the physical restrictions of a disassembly part in any extraction direction (contact constraints, motion constraints, and projection constraints).

In this study, we tested the BIM-based SDSP system in a building archetype. The BIM-based disassembly model was developed, and the information package was structured according to the IFC. IFC is the most important international standard for open BIM data exchange. IFC is a standardized and continuously expanded data model that facilitates the exchange of BIM data in the AEC domain. Figure 2 shows the building archetype under study, as well as the information package generated by the system.

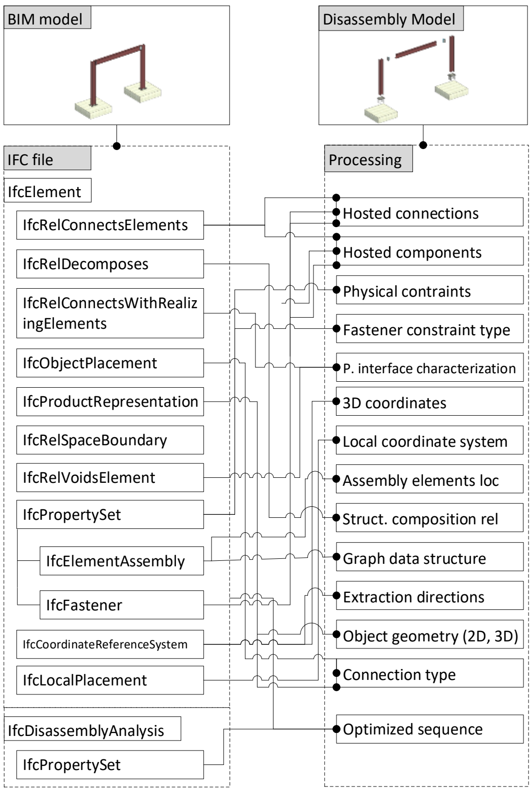

Figure 2. Disassembly sequence IFC information package

3.2 Robotic control architecture for selective disassembly

At the current stage of this research, the BIM-based SDSP framework has been implemented to automatically generate a structured disassembly information package for targeted building components. The robotic simulation and control architecture, however, is proposed as the next stage of development and is therefore presented here as an implementation pathway. The purpose of this phase is to transform the SDSP-generated information into robot-readable commands and environment representations. In this framework, the SDSP output serves as the high-level task planner, while the robotic platform is responsible for motion planning, collision detection, execution logic, and state updates during the disassembly process.

A central motivation for the proposed method is that while IFC preserves rich building information, such as component identities, geometry, spatial relationships, and semantic properties, it is not designed for robot control. Specifically, direct IFC export lacks robot-oriented parameters required for task execution, leaving the challenge of autonomous disassembly unresolved. The proposed SDSP framework addresses this limitation by enriching and reorganizing the BIM-derived data into a structured disassembly information package. In this regard, the SDSP layer acts as an intermediate semantic translation step between the building information model and the robotic execution environment.

The robotic system proposed for this phase consists of a fixed-base articulated manipulator operating within a physics-based simulation. A medium-reach, six-degree-of-freedom (6-DoF) robotic arm is considered appropriate for the initial implementation, as the pilot study involves localized disassembly actions on a simple frame and requires controlled positioning, directional extraction, and manipulation of structural and connection elements. The software stack integrates Gazebo as the simulation environment, ROS 2 as the middleware layer, and MoveIt 2 as the motion planning and manipulation framework. Within this architecture, Gazebo maintains the world model and physics-based actuation, ROS 2 manages inter-node communication for task planning and control, and MoveIt 2 handles collision-aware trajectory planning, kinematic feasibility, and scene updates.

To support this integration, the SDSP information package is translated into a robot-oriented task model. For each component or connection to be removed, the package should provide, at minimum, a unique identifier, sequence index, pose data, end-effector orientation, approach and extraction vectors, dependency list, clearance requirements, and obstacle data. It should also maintain status variables indicating whether an element is intact, detached, grasped, or removed. For connections, attributes such as type, disengagement mode, and any required motion constraints are included. Although some of these fields may be partially inferred from the BIM model, the key contribution of the SDSP framework is that it assembles them into a task-centered representation that is aligned with robotic disassembly planning.

The proposed control architecture follows a hierarchical structure. At the top level, the SDSP module provides the ordered sequence of disassembly actions and inter-component dependencies. At the middle level, a task-planning node in ROS 2 interprets each action and decomposes it into motion primitives such as approach, align, engage, detach, extract, retreat, and place. At the lower level, MoveIt 2 generates feasible trajectories subject to workspace constraints, while the controller executes joint-space or Cartesian commands in Gazebo. After each successful disassembly action, the planning scene and simulation state are updated to reflect the removal of the corresponding component, allowing the next step in the sequence to be planned against the modified environment.

While a full perception layer is outside the scope of the current study, the framework is designed to ultimately incorporate vision and force sensing for closed-loop execution. Vision will confirm component identity and pose consistency relative to the digital model, while force-torque sensing will monitor contact conditions during extraction. In early simulation-based development, these functions will be approximated through perfect-state feedback; later stages can replace these assumptions with simulated depth cameras, joint feedback, and force-sensitive control. Therefore, the proposed system will function as an integrated architecture that bridges BIM-derived disassembly logic with robot-level planning and execution.

3.3 Proposed validation approach for robot assisted selective disassembly

For functional demonstration, a pilot study was developed for robot-assisted selective disassembly of a simple frame (see Figure 3). The BIM model was structured according to the specified needs for a robot operating system. The information package was created automatically for the selective disassembly of the component c_1 (structural column). The optimized disassembly path is: f_1-f_2-c_1. The information package was exported to the robot operating system for the disassembly task. To maintain scope, the current study focused on the BIM-to-simulation information flow, treating robotic execution as a conceptual demonstration rather than a fully implemented control pipeline.

Consequently, the next development stage involves validating the BIM-to-robot workflow in a simulated environment. In this phase, the disassembly environment will be represented in Gazebo, the robot manipulator will be integrated through ROS 2 and MoveIt 2, and the SDSP information package will be used as the task-level input for robotic execution. Under this workflow, the robotic arm executes the prescribed disassembly sequence step-by-step, updating the simulation and planning scene after each completed action. For the frame example, the robot will first perform the task associated with f_1, then update the environment to reflect its removal, then proceed to f_2, and finally execute the extraction of c_1 once the prerequisite steps have been completed. This will allow the proposed framework to test whether the SDSP-generated information can be correctly interpreted and executed within a robotic simulation.

The initial simulation-based validation targets three technical objectives. The first is data interoperability, namely whether the SDSP package can be translated into simulation and motion-planning inputs. The second is kinematic feasibility, namely whether the robot can generate valid, collision-free motions for each step in the prescribed sequence. The third is state consistency, namely whether the simulation environment can be updated correctly after each removal to reflect the evolving disassembly state. Assessment metrics will include sequence completion status, motion-planning success rate, collision occurrences, and any violations of the prescribed extraction or dependency constraints. Additional qualitative observations will be recorded regarding failure modes, such as unreachable approach poses, geometric interference, or inconsistencies between the SDSP representation and the simulation environment.

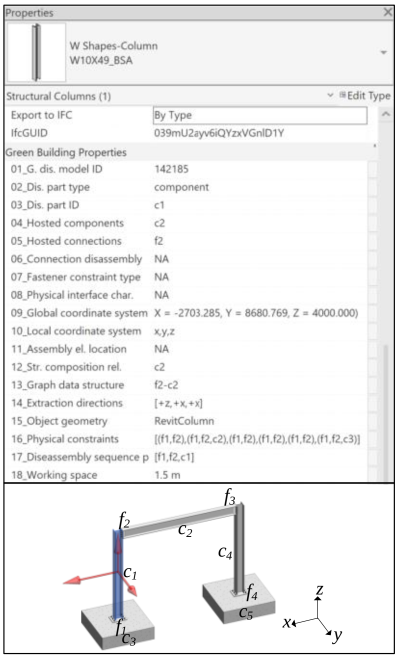

Figure 3. BIM-based Sequential Disassembly Planning for Buildings (SDPB)

The pilot study highlights the framework's ability to integrate BIM-based SDSP data with robotic control systems, enabling the autonomous execution of selective disassembly. These findings underscore the importance of robust data structuring and compatibility with IFC standards to ensure seamless data exchange between BIM models and robotic systems. Future validation efforts will extend the proposed framework to more complex building structures with diverse materials, connection types, and architectural configurations. Additionally, subsequent physical implementations with real-world robotic solutions will address challenges such as unstructured environments, sensor integration, and scalability. These advancements will refine the SDSP framework and support the application in practical construction and deconstruction scenarios.

4 Conclusions and Future work

The study's findings indicate that the BIM-based SDSP system is highly effective in enriching a robot's ability to process information, sense, plan, and execute the retrieval of specific components from a building structure. In this study, we propose the information package that can be automatically produced by a BIM-based SDPB system for performing the disassembly works in an autonomous way by a robotic solution. The results demonstrate the technical feasibility of implementing SDSP with robotic solutions for simpler building structures. This approach offers significant benefits for decarbonization in the construction industry by enabling the efficient recovery and reuse of building materials, thus reducing the demand for virgin resources and minimizing waste. By integrating robotics with BIM-based selective disassembly, the method supports sustainable construction practices and aligns with Circular Economy principles, directly contributing to the reduction of greenhouse gas emissions associated with material extraction, processing, and disposal.

Looking forward, the next steps involve applying this approach to more complex building archetypes with diverse subsystems in real-world scenarios. This entails addressing challenges such as increased variability in component types, structural interdependencies, and environmental constraints. The integration of advanced robotic capabilities, including AI-based perception and adaptive control systems, will be crucial in overcoming these challenges and enhancing the system's scalability and robustness. Additionally, this methodology has potential applications in futuristic scenarios, such as the disassembly of building structures designed for extra-terrestrial construction (e.g., space infrastructure and settlements). Such applications would benefit from the autonomous and precise nature of the proposed approach, specifically through the expansion of the system's future operational capacity to function in extreme conditions.

Future research will also focus on improving the integration between BIM-based SDSP systems and robotic solutions, particularly in terms of real-time data exchange and dynamic task optimization. Exploring human-robot collaboration for selective disassembly tasks could further enhance safety and efficiency. Lastly, validating the proposed framework through experimental testing with physical robotic systems and expanding its application to larger-scale projects will be critical to demonstrating its practical viability and impact on advancing Circular Economy principles in the built environment.

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