BIM-Driven Robotic Disassembly for Resource Recovery in End-of-Life Buildings

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Abstract –

Deconstruction for resource recovery offers a sustainable alternative to traditional demolition practices. However, deconstruction remains labor-intensive and time-consuming compared to demolition of buildings. This study proposes a novel framework that integrates Building Information Modeling (BIM) with robotic systems to automate the recovery of building components. The BIM file is converted into a robot simulation environment, enabling precise disassembly planning by providing location and size information of recoverable resources. A case study on a BIM model of an exposed interior residential wall assembly unit demonstrates the methodology's effectiveness in automating resource recovery of end-of-life building components. The results validate the potential of the proposed framework to reduce manual labor and contribute to the circular economy of the building construction sector.

Keywords –

Building Construction; Building Information Modeling; Circular Economy; Deconstruction; Resource Recovery; Robotic Disassembly; Sustainable Construction;

1 Introduction

The building construction sector plays a critical role in contributing to climate change. According to the United Nations Environment Programme (UNEP), the sector is responsible for approximately 37% of global energy-related carbon emissions [1]. Mitigating emissions within the construction supply chain requires transitioning from a linear economy to a circular economy. A circular economy in building construction emphasizes increasing reuse, recycle, reclaim of resources, thereby minimizing waste and resource production throughout the supply chain (Fig. 1).

Resource recovery from buildings at the end-of-life stage has garnered attention as a strategy to reduce the environmental impact of the building sector. As of 2022, the production of construction materials alone contributed 10% of global energy and process carbon emissions [2]. Additionally, the United States Environmental Protection Agency (EPA) reported that demolition activities in 2018 generated over 500 million tons of landfill debris in the U.S. [3]. By recovering resources through reuse, recycling, and reclamation, the volume of waste directed to landfills and the need for virgin materials can be markedly reduced.

Despite its environmental benefits, the deconstruction of buildings for resource recovery tends to be labor-intensive and time-consuming, requiring up to ten times longer processes compared to traditional demolition methods [4]. Improving the efficiency of resource recovery through automation offers a promising pathway to enhance the feasibility of a deconstruction process.

This study proposes a framework for planning automated resource recovery from end-of-life building assemblies using robotic systems. The approach leverages Building Information Modeling (BIM) enriched with resource information for each component. BIM files are converted into a simulation environment while retaining the resource information. This information is then used to plan robotic disassembly operations which can also be applied to physical world environments.

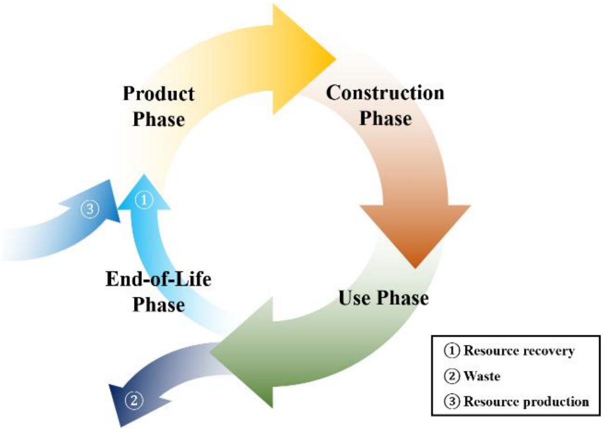


Fig. 1. Circular economy of building construction

2 Literature Review

Efforts to deconstruct buildings and effectively retrieve reusable resources have been widely studied. These approaches can generally be categorized into two main approaches: deconstruction planning up front during the design phase and planning once a building has reached its end-of-life phase.

Deconstruction planning during the design phase is commonly referred to as Design for Deconstruction (DfD). DfD involves incorporating strategies during the early design stages to simplify future resource recovery. These strategies include measures such as using bolted connections instead of adhesives [5], avoiding the use of toxic materials [6], and designing for offsite construction [7], among others. The primary goal of DfD is to streamline deconstruction efforts while minimizing the labor, cost, and environmental impact of the process.

Notable advancements in this field include the integration of BIM to simulate environmental and cost impacts throughout a building's lifecycle, enabling the optimization of designs to minimize these effects. For example, studies have developed BIM-integrated frameworks that enhance construction material management in the early design phase [8, 9]. These frameworks facilitate informed material selection and improve interoperability, ultimately supporting more efficient deconstruction and resource reuse planning at a building's end-of-life.

However, most modern buildings are not designed with deconstruction in mind [6]. Consequently, deconstruction planning often defers until the building reaches its end-of-life stage. In such cases, BIM serves as a critical tool for assessing a building's condition, resource properties, and reuse potential. Mollaei et al. [10] demonstrated the use of BIM's quantity take-off tools to extract material quantities and connection configurations. This data was then integrated into a multi-objective optimization model to evaluate various deconstruction strategies for different materials. Similarly, Sanchez et al. [11] proposed a semi-automated approach for selective deconstruction programming using BIM. Their approach optimized the deconstruction and reuse strategies by incorporating cost and environmental impact analysis.

While existing methods use BIM for deconstruction planning in the design phase or at the end-of-life stage, they often rely on manual processes that are labor-intensive and time-consuming. To improve the efficiency and scalability of deconstruction, researchers have explored the integration of automation and robotic systems. For instance, Lee and Brell-Cokcan [12] proposed a Human-in-the-Loop framework in which an operator defines high-level objectives, allowing robotic systems to execute deconstruction tasks with greater precision and efficiency.

However, deconstruction planning tailored for robotic systems remains largely unexplored. This study addresses this gap by introducing a novel approach that bridges BIM-based deconstruction planning with robotic execution. This method enables practitioners to directly extract information from a BIM model to plan and execute robotic resource recovery commands, enhancing efficiency in the deconstruction process.

3 Methodology

The proposed methodology involves converting a conventional BIM file (e.g., an Autodesk Revit file) into a Universal Scene Description (USD) format, which is compatible with robotic simulation environments (e.g., specifically Isaac SIM [13]). A USD file retains the resource information and hierarchy of the components, enabling the identification of recoverable resources in the simulation. This information is then used as input for robotic disassembly planning. Fig. 2 shows the proposed framework for robotic disassembly. Details of each step are explained in the following sections.

3.1 Converting BIM to USD

The BIM file containing information about the target structure is converted into a USD file. USD is a 3D scene representation file format designed to support complex 3D workflows including robotic simulations. This conversion is facilitated by the Nvidia Omniverse Revit Connector [14], which ensures that all subcategory information from the BIM file is preserved during the transition to the simulation environment. The resulting USD file retains critical resource specifications and hierarchical structural data necessary for accurate robotic simulations.

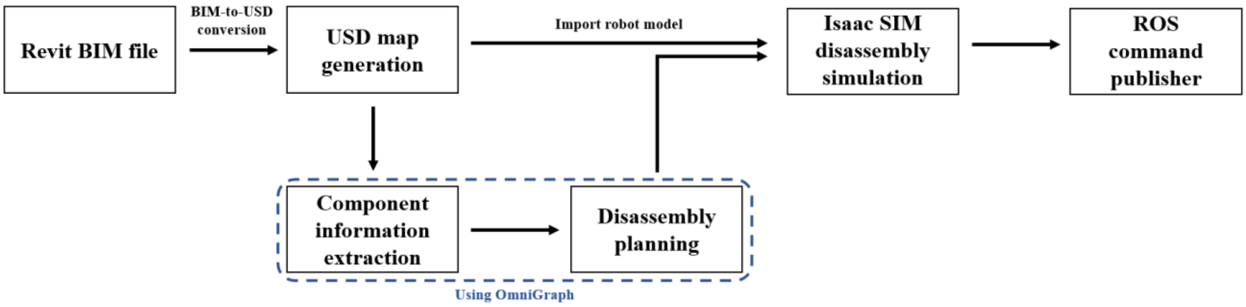


Fig. 2. Proposed framework for robotic disassembly using BIM information

3.2 Using Component Information for Disassembly Planning

The converted USD file is structured with elements defined as *prims* (short for primitives). A prim serves as a container for various attributes within any component in the USD scene, such as cameras, lights, objects, or robots. These prims are organized in a hierarchical structure, including the location and size information of specific components in their subcategories. Each object prim contains transformation coordinates and extent values. The transformation coordinate corresponds to the center of the component and the extent values define the min/max coordinates of the bounding box enclosing the component (Fig. 3).

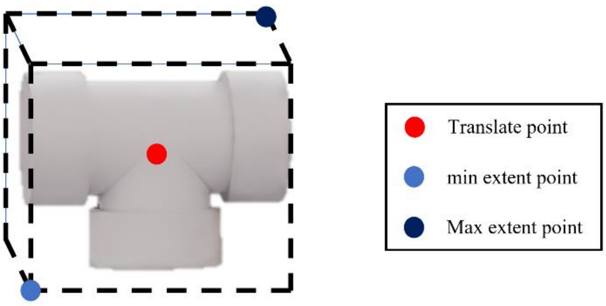


Fig. 3. Visualized example of component information in a prim

To plan and execute robotic disassembly, OmniGraph is used within the Isaac SIM environment. OmniGraph is a visual scripting language that enables dynamic control of robots [15]. It operates by connecting nodes, which perform specific tasks and contain input, output, and state attributes. These nodes are linked through connections, forming a network that controls robotic behaviors and interactions in the simulation. Action Graphs, a type of OmniGraph, define the execution of specific tasks, allowing for precise and flexible robot control.

Additionally, OmniGraph commands can be translated into ROS2 commands for physical world implementation. Isaac ROS2 nodes within the action graph enable the publishing of ROS2 messages, allowing the simulated actions to be executed by physical robots in real-world experiments.

4 Experiments

To demonstrate how the BIM-to-USD conversion process can support robotic disassembly planning, a small-scale experiment was conducted using an exposed interior residential wall assembly unit (Fig. 4(a)). The BIM file for the wall assembly unit was developed with an approximate Level of Detail (LoD) 300, providing detailed information about each component's size, shape, and location. The BIM file was then converted into a USD format and imported into Isaac SIM [13], a robotic simulation platform (Fig. 4(b)). A Franka FR3 [16] robot manipulator was incorporated into the simulation, mounted on a static platform to enhance its reachability during the disassembly process.

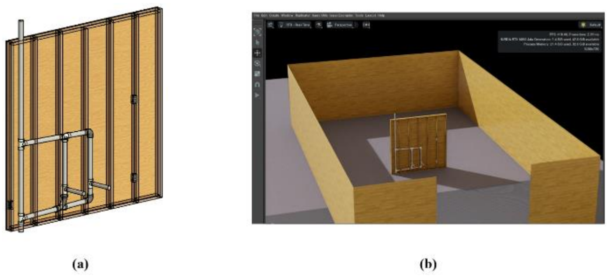
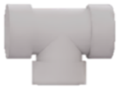


Fig. 4. Wall assembly unit: (a) LoD 300 BIM file and (b) USD file imported into Isaac SIM

Table 1. Recoverable resource attributes in wall assembly

Name	Mesh	Extent [min, max]	Translate	Material
Pipes 302099		[(-1.905,-1.905,-14.943), (1.905,1.905,14.943)]	(1213.926,252.986,38.882)	Plastic
Pipe Fittings 302081		[(-6.826,-6.826,-3.532), (6.826,3.532,3.532)]	(1236.335,252.930,105.643)	PVC
Electrical Fixtures 305293		[(-2.699,-5.080,-4.763), (2.699,5.080,$5.414e^{-}$)]	(1233.557,141.838,33.020)	Steel

For this experiment, the primary objective was to utilize the resource information from the BIM model to demonstrate automated identification and recovery of reusable components. Table 1 shows an example of specific resources within the given wall assembly unit. As depicted in Fig. 3, the translate point indicates the center point of an object.

The disassembly task was executed using a combination of five OmniGraph action graph nodes (Fig. 5). The 'Pick and Place controller' node received inputs of the robot manipulator's joint movements, a target resource translate point, and a predefined placing point from the other four nodes. This combined algorithm enabled the robot manipulator to accurately pick up the center point of an identified resource and place it in a specified location.

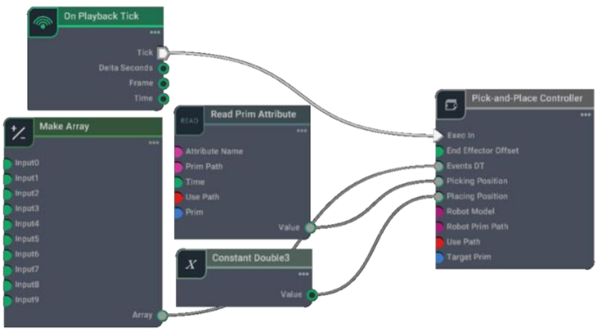


Fig. 5. OmniGraph node combination for resource pick and place task

The node combination automatically leverages the detailed positional data to perform precise disassembly operations (Fig. 6). The results show the potential of the proposed methodology in advancing resource recovery of end-of-life building components with a robotic system.

5 Conclusions

This study presents a new framework for automated resource recovery using a robotic system, addressing key challenges associated with deconstruction in the building construction sector. The methodology integrates BIM with robotic simulation tools by converting BIM files into USD format. The enriched data from the BIM model enables the detailed identification and retrieval of recoverable resources through robotic disassembly planning. A small-scale experiment demonstrates the potential of the approach, outlining the capability to utilize precise size and location information of components to retrieve target resources in the wall assembly unit. The results underscore how BIM-to-USD data conversion can directly support the potential of robotic systems as advanced disassembly tools. The proposed framework enhances the efficiency and feasibility of resource recovery and contribute to a more sustainable construction industry.

5.1 Discussion

While the RosBridge nodes of OmniGraph facilitate the conversion of simulated action graphs into ROS2 commands, significant challenges persist in replicating the simulation to physical world applications. A critical issue lies in the precise registration of simulated environments with their physical world counterparts. Addressing this challenge requires advanced machine

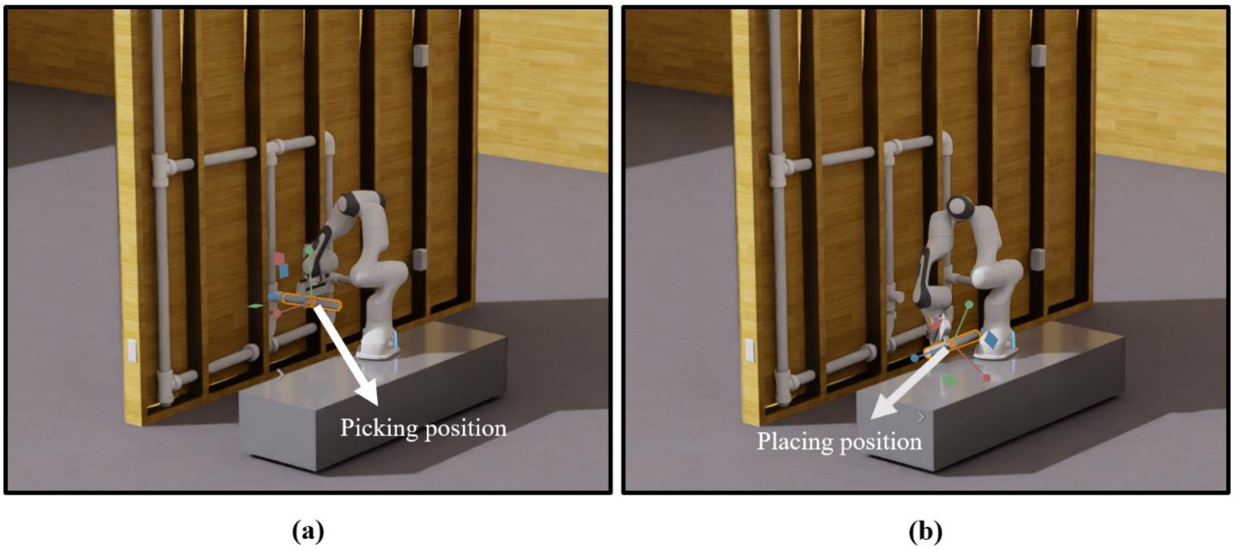


Fig. 6. Results of the robotic disassembly task: (a) picking the target object's translate point, and (b) placing the object at a specified point

vision systems capable of detecting fiducial markers (e.g., AprilTag [17] and QR code) or physical features of the building components to accurately align the simulation and physical world environments.

Future research should focus on determining the specific types and formats of building data that should be incorporated into BIM models to optimize robotic deconstruction processes. Accurate information modeling within BIM is essential for ensuring a seamless conversion to USD format using the Nvidia Omniverse Revit Connector. For example, it is critical to include compatible and detailed information identifying resources that are suitable and intended for robotic disassembly. Enhancing the fidelity of BIM-to-USD conversions should also be prioritized to ensure the accurate and comprehensive transfer of data into robotic simulation environments.

The current case study is limited to a small wall assembly unit in a simulation environment. Scaling this approach to larger, real-world applications will require addressing the complexities of diverse building materials with varying conditions. Unlike controlled simulation environments where material properties are predefined, physical structures comprise materials having different structural integrity, attachment types, and degradation levels. Developing adaptive robotic manipulation techniques capable of dynamically recognizing and adjusting disassembly strategies based on these variables is essential for maintaining efficiency. Furthermore, expanding the versatility of robotic systems is critical for addressing practical constraints (e.g., robot torque, reach, payload, and spatial maneuverability) [18]. Advancements that overcome these limitations will significantly enhance the effectiveness of the proposed framework.

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