Robotic Disassembly and Window Upgrading

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Abstract: Regular renovation of the built environment is essential for regulatory compliance and environmental impact reduction, with window upgrades significantly improving energy efficiency and reducing carbon footprints. Upgrading involves disassembling windows for repair or replacement and extending their life through reuse, repair, and remanufacturing. A Disassembly Map guides this process, showing different routes toward the end-of-life (EoL) for window components, ensuring efficient disassembly, repair, or replacement, thereby minimizing environmental impact. The 'Right to Repair' proposal in the EU promotes sustainable consumption, emphasizing the need for detailed disassembly planning. Robots can enhance disassembly efficiency, reduce costs, and decrease energy use. This study introduces a methodology for robotic window disassembly, focusing on an aluminum frame window to validate the method for upgrading window components. It includes a virtual simulation stage using RoboDk software and a demonstration stage with a UR10e robotic arm, emphasizing the critical role of Disassembly Maps in guiding efficient and sustainable upgrades.

Keywords: Windows Disassembly, Robotic Disassembly, Upgrading, Disassembly Map

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1 Introduction

Regular renovation of the built environment is crucial for complying with regulations and minimizing the environmental impact of buildings. A significant aspect of these renovations is the upgrading of building components, especially windows, which plays a vital role in enhancing energy efficiency and reducing carbon footprints. Upgrading windows involves disassembling their components for repair, replacement, or recycling, thus extending their lifespan and aligning within the New Consumer Agenda and the Circular Economy Action Plan, which aim to overcome barriers to repair and promote sustainability, contributing to the goal of making Europe the first climate-neutral continent by 2050.

Disassembly, therefore, is essential not only for extending the lifecycle of construction components but also for reducing waste through material recovery options such as reuse, remanufacturing, and recycling. A Disassembly Map plays a critical role in this process by outlining the sequences and process to minimize environmental impact. However, most windows are designed and manufactured without considering EoL and disassembly, which significantly increases their environmental burden. Given the complexity of windows and other building components, detailed EoL scenarios must be developed to enhance sustainability.

Effective disassembly planning requires a high level of detail regarding the physical interfaces among building components to identify physical constraints and sequence the necessary steps for dismantling [1]. This process defines and logically orders the deconstruction activities. Factors such as the joint type, material type, required performance, and target automation level are crucial in disassembly planning [2]. Disassembly planning and sequencing further formalize this process by illustrating the geometrical and technical features involved. Typically, precedence relations of components are represented graphically, where disassembly graph planning which can be defined as Disassembly Map, is treated as a tree search problem. This method begins from the assembled state and searches for a sequence of actions until a fully disassembled state is achieved, which can then be automated using robotics [3].

1.1 Research Gap and Contribution

Disassembly often requires intensive manual labor, which can limit material recovery options. However, robots, with their ability to perform precise, repetitive movements consistently, offer a significant advantage in reducing material waste. Robots in product disassembly can lead to semi-automated, intelligent production that enhances disassembly efficiency, reduces operational costs, decreases energy consumption, optimizes cycle time, and increases flexibility. In this context, Disassembly Maps play a crucial role by defining the motion sequences necessary for the robotic disassembly of windows, ensuring a systematic and efficient process. These maps provide essential details such as a minimum set of parts, the order of disassembly, and the directions for part removal.

This study makes two key contributions to the field. First, it develops an innovative methodology for disassembling building components, specifically focusing on upgrading and remanufacturing windows to comply with current regulations and reduce environmental impacts. This methodology includes detailed procedures and techniques designed to ensure both efficiency and sustainability. Second, the study introduces a comprehensive systematic framework for the robotic disassembly of windows, emphasizing the critical role of Disassembly Maps. These maps, a key component of the framework, guide the disassembly process by providing detailed instructions and pathways, enhancing the precision and effectiveness of the upgrading process, and facilitating material recovery options at the end of the window’s life cycle. By doing so, the study promotes sustainability in the built environment, aligning with broader goals of reducing environmental impact and improving resource efficiency.

2 Disassembly Modelling, Planning, and Sequencing

Disassembly is a process of dismantling and separating EoL products into its components and subassemblies prior to reconditioning operations that restore EoL products to or nearly to original equipment manufacturer standards through an ordered set of parts and disassembly directions [4, 5, 6,]. Determining an optimal disassembly sequence is a critical decision within disassembly operations and may change based on the quality of an EoL product [7]. Disassembly planning, a crucial and impactful process, involves systematically determining the sequence of operations for disassembling complex objects into their constituent components [6]. A visual representation of the disassembly process is a powerful tool for design decisions [8] and disassembly map representation. The Disassembly Map is an intuitive design repair tool suitable for product designers, architects, engineers, design consultants, and researchers [8]. The Disassembly Map, a key component of this process, is crucial in guiding design decisions. Such diagrams help designers navigate the disassembly process, identify difficulties, focus on cost-driving tasks, pinpoint defect-prone steps, and find solutions [9]. However, building component disassembly planning needs standardized methods and defined characteristics [1], which still limits the disassembly approach for building components. Previous studies of disassembly maps have not dealt with developing disassembly maps for building components. Most studies in the field have focused on the disassembly map development of the product, particularly for the early design phase of the product, and utilizing the disassembly approach as a tool for design decisions.

Disassembly is performed with the scope of isolating (i) hazardous components that should not enter the de- and remanufacturing flow, (ii) reusable parts with high residual value, and (iii) parts that need to go through a dedicated process chain [2]. The performance and the level of disassembly should be considered before the disassembly process, which is crucial for the disassembly planning process. Three main types of disassembly levels exist: complete, partial, and selective disassembly. Selective disassembly is the optimal order of operations that disassembles a specific component and regarding the remaining components, saving disassembly time and increasing disassembly profit [7, 10]. Selective disassembly is generally used to repair and maintain a product or end-of-life disassembly [11]. Therefore, we utilized selective disassembly to perform with the scope of reusable parts with high residual value through selective disassembly level to upgrade the windows to extend their lifecycle.

3 Robotic Disassembly for Window Upgrading Process

Upgrading construction products through robotic disassembly adds value by extending the life of building products and reducing waste. According to the level of independence and exchangeability of building components, all building structures can be grouped into three categories: category 1 has a low disassembly potential of 30%, and category 2 has a medium disassembly potential of 30-70%. Category 3 is a high disassembly potential where both indicators of transformation (independence and exchangeability) have more than 70% of their best values. This category is made of integrated structural, mechanical, electrical, envelope, and partitioning systems in a way that will stimulate their independence and exchangeability in different phases of the building's life cycle [12]. Also, typically, windows last about 20-25 years and must be updated to meet technological advancements and regulatory requirements [13]. In that sense, although windows are arguably the most complex systems in any building that frame, exterior finishes, glazing, etc., ıs needed to be changed for repair or appearance every 25 years, they are also in category three with the highest independence and exchangeability. That explains why windows are important for this study in developing disassembly maps for robotic disassembly automation.

In the literature, windows reduce energy consumption, carbon emissions, and waste while maintaining building value, which can be achieved by upcycling the window parts or components by replacing single-glazed windows with double or triple-glazed ones, significantly saving energy. Aluminum windows are stable and suitable for large surfaces and heavy-duty buildings [14]. The current study adopts a case study approach in that a 1.3mX1.3m aluminum frame window, which is a common dimension of the aluminum window in Germany and thus representative of a significant portion of the market, is scaled to 0.4mx0.4m to validate the disassembly map methodology for upgrading window components through robotic disassembly. The configurational space of the robotic arm (UR20) and the working field of the 3D printer (Prusa) determined the aluminum window dimension of 0.4mx0.4m.

In the built environment, many windows are designed and manufactured without considering the EoL and material recovery options at the end of the window's life to minimize the disposal and maximize the amount of material and component recovery where disassembly plays a crucial role. A major problem with disassembly map development is the need for detailed geometrical documentation and, if possible, a three-dimensional window model to define the precedence relations, which is hard to get before dismantling the window from the building or studying it at the warehouse. However, construction documents such as drawings and specifications, which are highly detailed, are a necessity before constructing the building. On the other hand, construction documents are also challenging to get for many buildings and window types. Therefore, the first step of this case study is to search for the aluminum windows section drawing to model it and define the geometrical precedence and constraints before defining the disassembly map. The two-dimensional section drawing is converted into a three-dimensional model using 1:1 section detail as a starting point, which is required for stages one and two. Then, a 3D window model is 3D printed and disassembled in the second stage to evaluate the disassembly map methodology. This study has two stages: 1) a simulation in the virtual environment and 2) Demonstration with a robotic arm.

3.1 Stage 1: Virtual Simulation

The disassembly map is formulated as a tree search problem, beginning from the assembled state and identifying a sequence of actions to reach the disassembled state for 0.4mx0.4m aluminum-framed single-glazed window units. (Figure 1). The 3D model of the window, which is also the assembled window model, is utilized for disassembly map development to investigate geometrical preferences, fastener locations, and details following a disassembly-by-assembly approach. This process defines each step of robotic automation by disassembly motion sequences. The outer aluminum profiles were planned to be disassembled individually for the four edges. Subsequently, the gasket would be removed and recycled, and the single-glazed flat glass would be removed and replaced with double or triple-glazed ones.

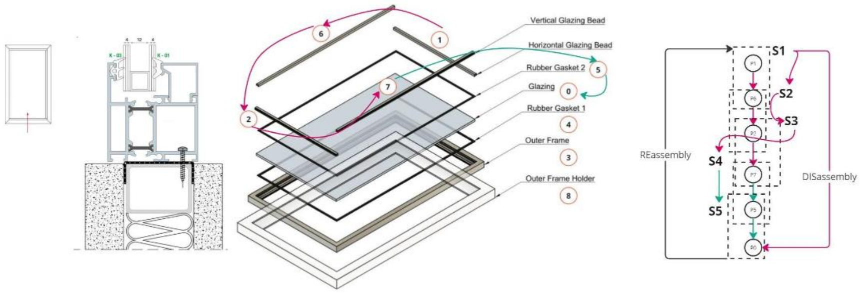

Figure 1: Aluminum-framed window section and axonometric decomposition of the parts, including disassembly planning graph for aluminum-framed window upgrading

The disassembly map allows us to get the disassembly planning and sequences to simulate the sequence in the virtual environment. The simulation was performed using RoboDK software. In the virtual environment, the window model is broken into components and exporting them as .igs files, with their original positions and spatial coordinates preserved. Window component models are preprocessed in the RoboDK environment by converting .stl files to .igs data format and identifying frames for each component import. These files were then imported into RoboDK, a versatile offline programming and simulation software for industrial robots (Figure 2).

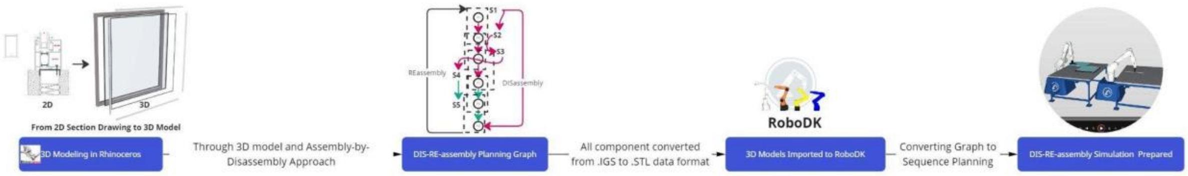

Figure 2: Workflow of Rootic Disassembly for Alumınum-framed Single-Glazed Window

The disassembly planning graph plays a crucial role in defining the sequence plan of the robot in RoboDK software, allowing for the determination of each step, or ‘target,’ in the simulation environment. The sequence plan was generated by creating a path through the disassembly planning graph, enabling a complete disassembly simulation. An ID-to-component map was used to obtain target coordinates in the world coordinate system. The disassembly path moves multiple parts from the assembled state on Table 1 to the target-disassembled state on Table 2, with the initial disassembly of outer frames following the sequence: {P1, P6, P2, P7}. After disassembling the outer frames and gaskets, the glazing beads {P5} are removed in a predetermined sequence. The single-glazed glass is then dismantled on Table 1 and upgraded to double-glazed glass as {P0} (Figure 3).

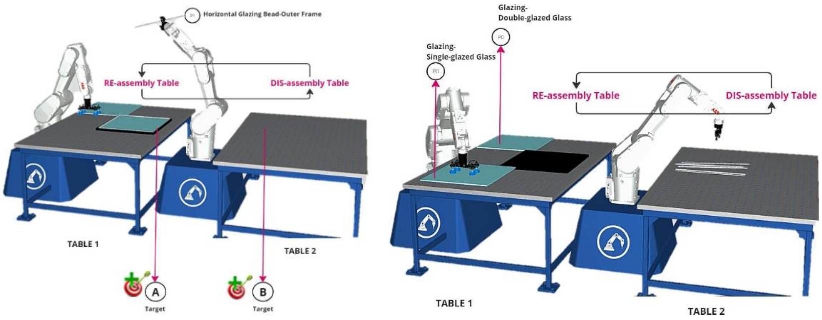

Figure 3: Left: Disassembly path between RE-assembly - DIS-assembly Tables for P1
Right: Upgrading single-glazed glass to double-glazed glass on table 1

3.2 Stage 2: Demonstration with robotic arm

The demonstration with a UR10e robotic arm used a custom-designed and 3D-printed end-effector tool. This end-effector, a parallel gripper manufactured using PLA, features a spur gear mechanism driven by a servo motor for precise parallel movement of the rack-connected finger. Its seamless integration and operation, controlled by an Arduino Nano, reassure its compatibility with the robotic arm. The necessity for this custom build arose to meet specific project requirements and enhance flexibility, allowing future upgrades, such as incorporating a screwdriver with minimal modifications to the base structure. After that, demonstration with the robotic arm by following the disassembly map to motion planning for the robotic arm at URScript. Then, a robotic arm is demonstrated, which is not gone as it is simulated (Figure 4). Currently, it is noted that gripping the outer aluminum profiles by custom-designed end-effector is where required improvement both in design and material choice of it.

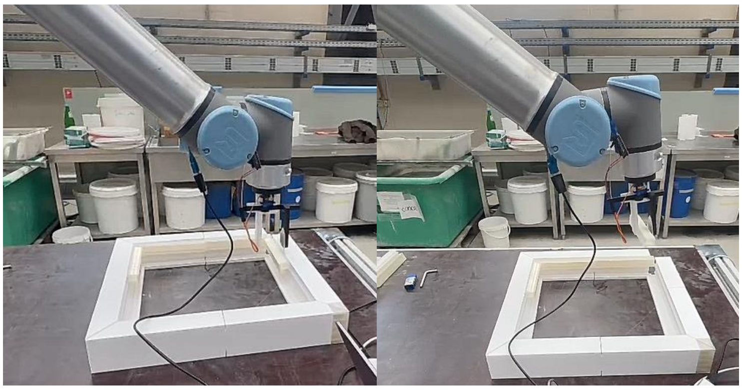

Figure 4: Robotic window disassembly demonstration

4 Conclusion

This study presents a two-stage approach to upgrading building components, specifically focusing on windows, through robotic disassembly. The first stage involved a virtual simulation through a 3D model of an aluminum-framed single-glazed window. A disassembly map, formulated as a tree search problem, was developed to define the sequence of actions for robotic automation. A UR10e robotic arm was employed in the second stage to demonstrate the physical disassembly process through a custom-designed and 3D-printed end-effector tool. The study highlighted the critical role of the Disassembly Map in defining disassembly path planning and motion sequences, ensuring an efficient and systematic process for manual and robotic disassembly through section drawings of the windows at the EoL stage. This research contributes to the field by developing a methodology for upgrading building components to meet regulatory requirements and reduce environmental impacts. Emphasizing the use of disassembly maps not only ensures the precision but also the effectiveness of the upgrading process, promoting sustainability in the built environment.

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