Design for Circular Disassembly of High-Performance Facade Systems

Naomi Grigoryan[1] and Alexandros Loutsioli Daskalakis[1]

[1] Schüco International, Virtual Construction Lab, United States
ngrigoryan@schuco-usa.com, aloutsioli@schuco-usa.com

Abstract –

The construction sector faces significant challenges in reducing emissions, with extending the lifespans of architectural products emerging as a key strategy. As stakeholders of the built environment focus on decarbonization, the concentration of efforts diverges towards either sustainable development of future products or sustainable preservation of the existing built environment. Critical intersections between development and preservation are the reuse, repurpose, repair, and refurbishment stages within a circular economy. This research investigates the integration of Design for Disassembly (DfD) principles into the lifecycle of high-performance facade systems, as complex architectural systems frequently utilize materials and methods that hinder circularity, such as fixed connections. Designing and advocating for future uses is challenging without explicit disassembly standards or supporting infrastructure. By analysing existing disassembly methodologies, a tailored approach was developed for high-performance façade design, leveraging Schüco KG's existing digital infrastructure to optimize disassembly workflows. This methodology focuses on the generation of practical disassembly outputs, for use cases across designing, manufacturing, and constructing façade systems. Coordinating with fabricators, a proof-of-concept for a Disassembly Application is developed to integrate with existing digital infrastructure. The case study on the AWS 75.SI+ window system highlights the feasibility and benefits of incorporating disassembly planning from the early design stage. This framework provides a scalable model for reducing construction waste, improving material reuse, and supporting circular economy goals for high-performance façade systems and across complex building systems.

Keywords –

Design for Disassembly; Life Cycle Analysis; Built Environment; Building Façade System; Case Study

1 Introduction

There is a substantial amount of embodied energy in existing buildings. Demolishing obsolete buildings in favor of higher-performing new construction is a popular path, but the energy cost of demolition and disposal must be addressed. Standard Architecture, Engineering, and Construction (AEC) education and practice center buildings with lifecycles of 30-50 years, programmed for demolition rather than renovation [1]. Frequent technological advancements increase the rate of technical obsolescence of façade systems. Instead of considering future technological upgrades as a design criterion, many façade systems are replaced in their entirety in favor of higher-performing systems. High-performance façade systems often contain aluminum and other critical materials in the Critical Raw Materials Act (CRMA) [2]. Smart façade systems with integrated technology contain critical raw materials such as cobalt, coltan, and lithium. The technology sector and transportation sector account for critical material recovery, but the building sector does not have a comprehensive recovery strategy. Demolition involves all materials going to landfill, with no planned recovery. Deconstruction, however, is the systematic recovery of materials with circular intention. Disassembly refers to the capacity for deconstruction in a system, meaning systems intended for deconstruction must be designed with easy part disassembly [3]. Design for Disassembly (DfD) is a research field and design practice developed within the manufacturing and construction industries, geared towards expanding material circularity. DfD considers the various parameters including material composition, component connection, data accessibility, material flow, stakeholder incentives, and local options. Developing infrastructure to facilitate DfD across construction would allow valuable materials to re-enter the Material Bank [4] and outline opportunities for future designs, reducing both resource extraction and construction waste.

Disassembly for architecture has decades of existing research and methods, with many digital solutions and case studies; however, there is a gap in disassembly research pertaining to high-performance facade systems and associated components and processes. While façade systems often use critical and high-value materials such as aluminum and steel, high-performance systems rely on polymers and adhesives, that reach technical obsolescence sooner, to meet structural, thermal, and acoustic criteria. Although high thermal performance significantly lowers operational carbon, current practice uses fixed connections, permanently sealing non-circular materials to systems. Thus, although facade assemblies are historically among the most demountable, reconfigurable, and reusable building systems, the only End-of-Life options for these high-performance systems are recycling, incineration, and landfill.

This research begins with a brief review of published disassembly methodologies, identifying applicable modeling for high-performance facades. A methodology is developed to integrate into existing digital design and manufacturing infrastructure. The product catalog provides a wide range of façade systems with varying degrees of performance and disassembly. Various electronically operated systems assist with ventilation, solar shading, security, operability, and comfort. As with other technology devices, these smart components contain cobalt, lithium, and coltan. The documentation of disassembly data serves three main purposes: it improves the efficiency and effectiveness of deinstallation during fabrication, construction, maintenance, and at End-of-Life; it improves circularity and circularity documentation; and lastly, it assists with product design, improvement, and development related to product circularity. Next, the methodology and case study portions follow Schüco system AWS 75.SI+ to develop a disassembly application. The research aims to bridge existing construction disassembly theories and studies with AEC workflows.

2 Review of Published Methodologies

For this research, multiple published disassembly and work estimation methodologies were reviewed and assessed for applicability. The review included Durmisevic's Knowledge Model [5], BIM-DAS [6], Selective Disassembly Planning for Buildings (SDPB) [7], Disassembly Network Analysis (DNA) [8], Method Time Measurement (MTM) [9], Maynard Operation Sequence Technique (MOST®) [10], Adaptive Reuse Model (ARP) [11], AdaptSTAR [12], and the Parent Action Child (PAC) model [13]. With considerations of users, inputs, outputs, and level of automation, four main methodologies were selected. Durmisevic’s Knowledge Model is one of the older and most referenced disassembly methodologies. Outputs include disassembly sequences, connection-type knowledge, and an independence and exchangeability aggregated score. While it considers small-scale connection information applicable for facade systems, the manual process cannot be easily integrated into existing workflows [5]. The BIM-DAS method is a Building Information Modeling (BIM) based Deconstructability Assessment Score, developed to assess and minimize construction waste from the design stage. Outputs include the Deconstruction Score, the Reuse Score, and finally, the Deconstructability Assessment Score (0% being the lowest, 100% being the highest). The scores are not appropriately weighted, and the focus is on larger scale building connections than facade systems [6]. Consideration of component end-of-life conditions is necessary for disassembly effort assessment. The PAC model divides products into assemblies and subassemblies, further categorized into parents, actions, and children. Considering disassembly failures (DFs), the PAC model outcomes include the Disassembly Effort Index (DEI) and the circularity index (CI). The DEI represents the time required to perform an action and disassemble a component, and the CI represents the circularity of the components after disassembly [13]. Disassembly failures are categorized into three types: Type One occurs during product use and are related to the children in the PAC model, Type Two is associated with actions in the PAC model, and Type Three affects the parents, meaning both the action and one or more children are impacted. MOST® is a predefined motion time system used in industrial settings to establish the standard time required for a worker to perform a task. Tasks are broken down into individual motion elements and assigned Time Measurement Units (TMUs), where 100,000 TMUs equal one hour [10]. This information can be integrated into the PAC model to assess the DEI, providing a comprehensive understanding of the disassembly process and identifying areas for efficiency improvements [13].

3 Methodology

The existing disassembly methodologies described in the methodology review portion were assessed for criteria related to facade system product lifecycles: intended user groups, required inputs, outputs, and transparency. Existing methodologies were also selected based on the availability of case studies. A methodology was defined by analysing the physical components and life cycles of facade products, as well as the existing product documentation and company-wide digital infrastructure. Existing information necessary to disassembly was mapped, and remaining information was identified.

Building Façade Systems (BFS) are composed of elements and components. Façade elements are the functional assemblies: external walls, doors and windows.

Façade systems are combinations of multiple elements. Components are the parts that make up the elements, such as the frame, handle, or reinforcement profile. The functions of components are structural support, thermal and acoustic control, aesthetic and resilient finish, and integration to other components through connection [3]. The disassembly of façade systems is dependent upon the separation and removal of components for replacement and reuse. Components can serve multiple functions, which constitutes a closed façade system. If the functions of components are separate, they are considered functionally independent. A component can be removed from the element if it is functionally independent, and a system comprised of functionally independent components is considered an open façade system [5].

As shown in Figure 1, there is currently no selective disassembly and recovery integrated into the standard facade system product life cycle. All façade building materials are either sent to recycling or landfill. Highlighted in green is the "closed loop" of material circularity, stages A3 - D. Life cycle stages aligned according to ISO 14040 [14].

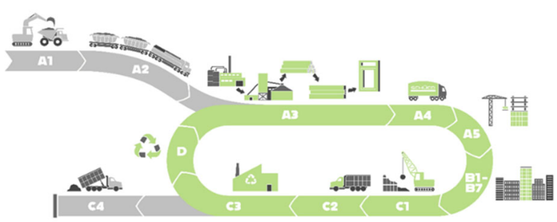

Figure 1. The typical product life cycle of a facade system product.

Figure 2 shows how building materials gain the opportunity to be diverted from the two previous End-of-Life pathways, to be refurbished and reused in new products without shredding. Existing products have many reusable components that do not need the additional energy use of recycling. Additionally, this analysis can be used by product designers to develop future products that have higher disassembly potential.

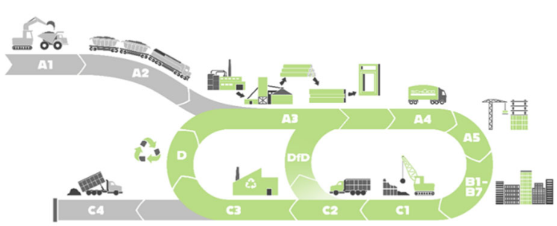

Figure 2. Integrating Design for Disassembly (DfD) into the facade system product life cycle.

Product ordering, fabrication, and assembly are often well-documented across facade systems. However, there is a large gap in documentation of deconstruction and deinstallation of products. From lifecycle stages A1-A5, extensive product information is accessible through internal digital infrastructure, BIM tools, and product documentation such as EPDs and BOMs. This methodology limits the necessary input from fabricators, manufacturers, and designers by utilizing available data. Fabrication processes vary, even across facilities at the same company. Necessary inputs for disassembly calculation are thus split into two lists: existing company data and data to collect from users (see Table 1). User input is necessary to map a disassembly process to a product system once. Then, it can be stored for future applications using the same products.

Table 1. Data Sourcing

Existing Internal Data	User-Input Needed
System Type	Connection Type
Element Type	Disassembly Sequence
Component Type	Disassembly Action
Material	Disassembly Equipment
Weight	Component Recoverability
Assembly Action	

One of the key outputs of the application is the breakdown of materials based on their End-of-Life potential. All components in a BOM are sorted into three categories: reusable, recyclable (but not reusable), and waste. This breakdown is shown in item count as well as item weight. An additional valuable materials End-of-Life breakdown documents materials that must be recovered in the material flow; ideally none which go to landfill/incineration. Unaltered and slightly altered reusable components can be salvaged and reused with minimal alteration. For example, un-crimped cleats cannot be re-crimped but can be screwed on a second configuration. The list of unrecoverable elements guides product designers to identify weak points of design in relation to disassembly. The disassembly sequence output is the written list of directions to dismantle the configuration. First, the objects in the BOM are sorted into element groups, such as an operable vent, fixed light, door, or framing. Within each element group, each item is placed in descending order based on Sequence ID. Lastly, all identical items within each field group are grouped to condense the disassembly sequence. In the case of complex façade systems, this is necessary to avoid tediously lengthy lists that spell out the directions for every individual screw and other small components, where there may be dozens, if not hundreds. The disassembly sequence thus lists the number of components in each element to dismantle for each step, with the time estimate. For components that cannot be disassembled, that is reflected instead of an instruction and time estimate. The total number of steps and the total time estimate are provided along with the sequence. An output for sustainability experts includes the Material Circularity Indicator (MCI), developed by the Ellen McArthur Foundation; quantifies the minimization of linear material flow and maximization of restorative flow for all component materials in a product [15]. A score of 100% implies total repurposing upon completing a lifecycle. Typically, the MCI of a facade product is calculated using an EPD generated for life cycle stages A1-A3; in this methodology, the MCI is calculated considering the realistic end-of-life of the product, including potential disassembly failures. Similarly, The Water Circularity Indicator (WCI) is measured as the ratio, in cubic meters, of circularly sourced water over the total amount of water used. The Energy Circularity Indicator (ECI) is measured as the ratio of renewable energy used over the total energy used [16]. An output geared towards product designers involves a summary of all limitations to disassembly identified in the product. This includes conditions such as rolled thermal breaks, permanently sealed joints, structural sealant, and petroleum-derived materials. This section explains the reasons these decisions are typically made and provides suggestions for improvement. In the Case Study section, this methodology is implemented on a specific façade product, Schüco's AWS 75.SI+.

4 Integration and Operability

Building Information Modeling (BIM) facilitates collaboration across all project stakeholders. Disassembly information affects design, engineering, LCA, and construction means and methods; therefore, it should be accessible to all stakeholders. Single platform hosting all performance metrics allows for easy comparison and assessment, weighing the trade-offs of disassembly capacity with structural, thermal, or acoustic performance and cost. As the disassembly information may change across the supply chain, having a single source of truth for reference is essential.

Users of a disassembly application must be able to add all related data points for their model. Product designers can initially specify the BIM content of an architectural component, documenting this initial disassembly data in a standardized "Information Delivery Specification" (IDS) format. Developed by buildingSMART, IDS is a standard for specifying alphanumeric information following the Industry Foundation Classes (IFC) schema [17]. This format is appropriate for applying the outlined disassembly specifications and can be supplemented with additional specifications, such as recommended assessment criteria in ISO 20887(EN) [18]. This documentation can then be shared with engineers for simulation and calculation, shared with sales and other contributors, and collaboratively finalized in an interoperable format such as IFC. For the disassembly information to be open source and publicly accessible, this IFC compliance is critical [19].

Once the product model is complete, all complex system logic and disassembly documentation are available for the project architects, engineers, and contractors. These models can be used in all IFC-compliant BIM tools, such as Autodesk Revit® and Tekla Structures®. In addition, disassembly outputs can be generated and accessed in addition to existing outputs within the BIM tools. As the project develops, these stakeholders can also update the architectural component. For disassembly, this is necessary when, for example, a component is designed as fully deconstructable, but the structural engineer makes a call to use a permanent connection for a site-specific wind load; this disassembly information would be updated in the BIM model to reflect the change for the deconstruction team's disassembly instructions.

5 Case Study

The case study implementing the methodology outlined in this research uses Schüco's AWS 75.SI+ window system (see Figure 3), which shares many manufacturing and fabrication processes with similar window and facade systems, within Schüco and across the facade industry. The disassembly planning was mapped for an inoperable fixed light as well as for an operable turn-tilt window, both with the standard dimensions of 1480 x 1230 mm. A simplified overview of Schüco's workflow begins with product designers and engineers creating profiles and systems; next, manufacturers extrude, cut, and assemble composite profiles; next, fabricators assemble configurations based on project specifications. Many locations provide maintenance services during the products' use phase, and several locations and product types provide recovery services for materials after use. All Schüco profiles and accessories have unique identification numbers that contain profile data, including material, weight, price, description, and more, and are accessible through various internal portals. The digital infrastructure contains documentation platforms, ordering, planning, modeling, and calculation software, and a material passport system. Although the profile data is comprehensive for many applications, disassembly data is not included. The case study interfaces with configuration tool SchüCal, which is utilized across the value chain. Order, fabrication, and physics data can be exported, including BOMs and EPDs. These two exports are mapped to additional disassembly data, used to derive disassembly metrics in a disassembly application.

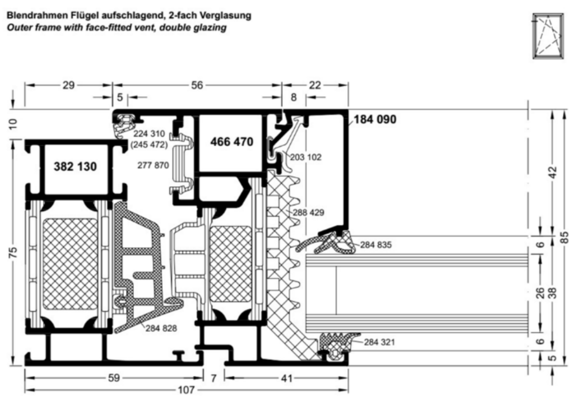

Figure 3. AWS 75.SI+ outer frame with face-fitted vent

The system contains aluminum profiles that are thermally broken with polyamide (PA) or proprietary material Polythermid (PT) isolators, which are permanently rolled into the aluminum profiles with insulation in between each thermal break component. Gaskets are made of EPDM and PE foam is used for insulation. Corners and profile joints are fixed with aluminum cleats and sealed with epoxy in addition to steel screws. Locking bars are a combination of plastic and metal, and most fittings are metal and fully removable.

5.1 Network Analysis

Integrating disassembly to each system type starts with system network analysis. Following the process mapped in Durmisevic's Knowledge Model, all system components are plotted as nodes and all components and connections are labeled. This mapping highlights the hierarchies and dependencies and the order in which they can safely be separated from the total configuration. Network analysis also highlights which components are inaccessible for removal due to sequencing and permanent connections. This process establishes a disassembly sequence for each system type and provides the necessary framework for disassembly metrics via a component database. This mapping requires coordination with fabricators familiar with the products' assembly processes. Fabricators are familiar with the physical limitations of product components and the adjustments necessary during imperfect assembly, knowledge that is not documented in Schüco internal resources, making disassembly mapping, product design, and onboarding incoming fabricators more challenging. For the case study of Schüco's AWS 75.SI+ window system, there was coordination with fabricators. AWS 75.SI+ is a high-performance window system with a depth of 75 mm. Increased thermal insulation for efficiency and performance is included in the center gasket and glazing rebate insulation in addition to standard gaskets and insulation foams [20].

In Figure 4, the left image shows an exploded axonometric view of a corner condition of an AWS 75.SI+ frame, and the top right image shows the frame cross-section. The bottom right diagram shows the network of these components.

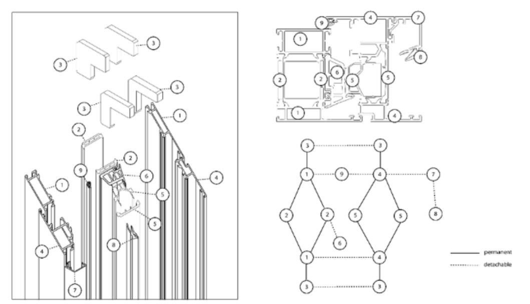

Figure 4. AWS 75.SI+ Network Analysis

Maintaining the connection network, Figure 5 details all names, materials, and article numbers. Connections are distinguished between permanent, detachable, and easily detachable, with connection-type descriptions, and arranged from left to right in order of assembly steps. The aluminum profiles are first rolled with thermal breaks in a permanent connection. After cutting and processing the profiles with end cuts, holes, notches, and slots, the corner cleats are nailed, screwed, or crimped into position, and then sealed with epoxy to secure mitered frame corners. In coordination with fabricators, these two permanent connections were highlighted as assembly challenges, as mistakes during these steps cannot be reversed. Finally, glazing and gaskets are snapped into place, starting with the bottom glazing gasket, after which the aluminum glazing bead is snapped in, followed by the other gaskets. In configurations with operable vents, all fittings are attached after the gaskets and glazing. Schüco's proprietary fitting kits are designed to be easily attached and removed in no specific order.

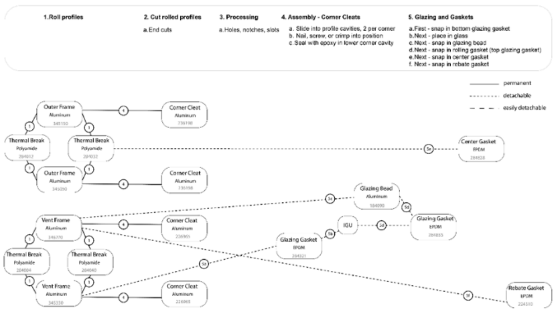

Figure 5. Assembly Sequence Mapping

Using the assembly sequence mapping as a reference and relying more on fabricator knowledge, the disassembly sequence is mapped in Figure 6, showing the components in the order in which they are removed. The remaining components are shaded to indicate that disassembly is no longer possible at these stages.

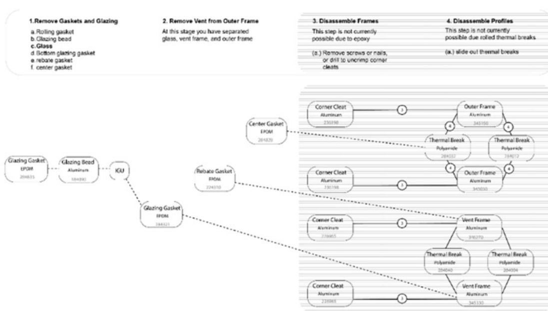

Figure 6. Disassembly Sequence Mapping

5.2 Disassembly Mapping

With system analysis and sequencing complete, disassembly mapping is expanded following portions of the BIMDAS, PAC and MOST® methods. Each separate component from the network analysis is assigned a unique identifier from e^1 to e^n, and each associated connection is assigned a unique identifier from c^1 to c^n. A table is created using these unique identifiers, placing all disconnection actions sequentially, assigning a Sequence ID for every element. Following the principles documented in the BIMDAS method, each component type is assigned several necessary attributions for calculating the Deconstruction Score, the Recovery Score, and DAS. This process establishes a disassembly database for the system. This documentation stage is flexible to adjust for workflow and output goals. Several data points can be mapped from SchüCal, while the rest are mapped from a disassembly database developed for this application to fill the gaps of disassembly documentation. Existing system information taken from SchüCal is the BOM, EPD, system type, and glazing information. Component-specific information from SchüCal is article number, material, secondary finishing, weight, and field number.

Table 2 contains all mapped data of the disassembly database. Column T refers to the component type (ex., frame, gasket, etc.). These tags can be set as defaults for each element type in a system, assuming they are the same for each type. Weight is kilograms, and Material is the material description or associated material code. Fixed (Cf), Bolted (Cb), Nailed (Cn), Prefab (P), Reusable (Ru), Recyclable (Rc), Secondary Finishing (Sf), and Nontoxic (N) are all filled as either true or false. Here, several additions and alterations are made to the table framework detailed in the BIM-DAS method to incorporate inputs for the PAC and MOST methods as well Schüco practices: fitted connections (Cft), demountability (D), the disassembly action (DA) as a description of how to remove the component, the sequence ID (SID) integer placing the component along the disassembly sequence, and disassembly time (DT) as the measure of time it takes for that action based on the MOST methodology, measured in TMUs, converted into minutes at later stages.

Table 2. Mapping Data

T	Cf	Cb	Cn	Cft	P	Ru	Rc	Sf	N	D	DA	SID	DT

Database rows are mapped to each component in the BOM fetched by API from SchüCal. A separate API fetches the system's EPDs to calculate circularity indicators following the MCI [15, 17]. In the case study, this database is used to generate disassembly outputs via an external application, but it can also be used for material passport data in Internet of Facades (IoF), the material passport system. Connection-types for each component can be found in the Fabrication Manuals of Schüco products; this is not a guarantee for other companies' workflows. The case study application is designed as a desktop application. With SchüCal open, a user may select any configured project. The application fetches available configuration data and maps disassembly data to each component in the BOM. Figure 7 shows the application workflow with two input streams, internal software SchüCal (for BOM and EPD) and disassembly database (compiled per component, developed with fabricators), and the four disassembly output categories: disassembly instructions, recovery material lists, disassembly and circularity metrics, and design improvement recommendations.

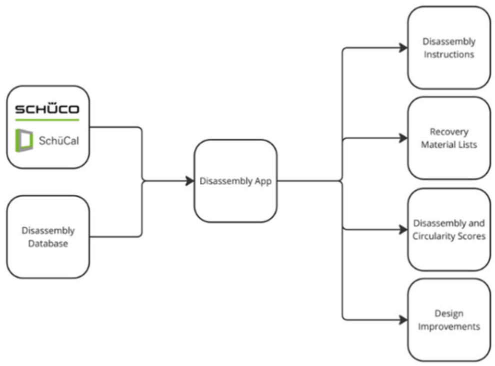

Figure 7. Application Workflow Diagram

The application consists of multiple services, each containing equations and processes relevant for their outputs. The main service maps BOM components to that system's disassembly database and calls calculation engines. One service calculates all ratios necessary for the Deconstruction Score, Recovery Score, and aggregated Deconstructability Assessment Score, and sorts components for material breakdowns and recovery lists. A second service groups and sequences components for the disassembly sequence, calculating time and noting the limitations. The total disassembly time is estimated using the MOST® process. A third service calculates the Material Circularity Indicator, Water Circularity Indicator, and Energy Circularity Indicator. Lastly, a Document Service synthesizes the results from each service into PDF output. Although not included in the case study, this information can also be entered into a material passport to provide stakeholders with up-to-date data.

6 Results

The disassembly sequence for AWS 75.SI+ is an almost direct reversal of the assembly sequence. For configurations with operable vents, disassembly begins with the removal of all fittings. After gaskets and glazing components are removed, the corner cleats and thermal breaks cannot be separated from the aluminum profiles, leaving the outer and vent frame assemblies without any more recoverable components, as thermal breaks and corner cleats cannot be removed without damaging the elements around them. Some assumptions were made to calculate the time required for the complete window disassembly, including that only one skilled worker is required to disassemble the window, and the second assumption is that only one workstation is required. The AWS 75.SI+ fixed light contains 25 components and 6 materials. 5 items are reusable with a total weight of 1.32 kg, 14 items are recyclable at 11.40kg, and 6 items totaling 0.12 kg are designated for waste, none of which contain valuable materials. It has an MCI of 45%, a Deconstruction Score of 79%, a Recovery Score of 57% and an aggregated score of 68%. It has a realistic disassembly time of 42 minutes, with 9 total steps, 3 of which are not possible. Limitations identified are rolled thermal breaks, permanent sealants, and petroleum-derived materials. The AWS 75.SI+ with a Turn-Tilt vent contains 50 components and 7 materials. 11 items are reusable with a total weight of 3.43kg, 32 items are recyclable at 23.48kg, and 7 items totaling 0.21kg are designated for waste, none of which contain valuable materials. It has an MCI of 43%, a Deconstruction Score of 80%, a Recovery Score of 55% and an aggregated score of 67%. It has a realistic disassembly time of 57.85 minutes, with 23 total steps, 6 of which are not possible. There are no additional limitations identified. The most time-intensive process is removing all the hardware from the frames.

7 Conclusion

Design for Disassembly (DfD) for high-performance façade systems is critical to minimizing the extraction of raw materials, lowering recycling energy demands through material reuse, and lowering emissions in the construction sector. Standardization of disassembly modeling and documentation is currently lacking across AEC. As the objectives of circularity regulations and certifications solidify, comprehensive and accessible disassembly documentation future-proofs the framework. In this research, existing disassembly methodologies are compared for relevance to façade system application; components of BIMDAS, Durmisevic's Knowledge Model, PAC, and MOST® are utilized, with network analysis, sequencing, instruction, time estimation, and end-of-life modeling identified as critical to a comprehensive framework. The proposed framework is not exceedingly complex and can integrate with existing digital workflows seamlessly. Interdisciplinary coordination and data collection are front-loaded in the process, consolidating the inputs necessary for multiple disassembly methodologies. Thus, disassembly calculation and presentation processes remain highly modifiable, depending on the use case, generating outputs for various user groups. Fabricator-specific outputs include material recovery lists and disassembly sequencing and time estimation. Designer-specific outputs include disassembly metrics and design limitations and improvement suggestions. Sustainability expert-specific outputs include circularity metrics, recovery lists, and Global Warming Potential. Accessible internal databases are supplemented with input from experienced fabricators. A proof of concept for a disassembly application was developed to interface with Schüco's existing digital platform SchüCal, documenting the disassembly of the AWS 75.SI+ system for a case study.

In future development, this research's integration of disassembly documentation with BIM tools has the potential to be incorporated directly into the modeling workflow, with a library of parametric components available for connections in new products. Similarly, disassembly modelling can lead to a more dynamic design workflow and results. Digital twin systems can be utilized in combination with BIM and enable real-time monitoring, predictive analysis, and automated decision-making. After construction, BIM data to be continuously updated with sensor feedback and IoT data, ensuring designers and engineers can assess structural conditions, material degradation and disassembly feasibility over time. This research can expand towards the creation of a library of generic and manufacturer-specific products, publicly accessible for utilization in BIM tools.

The methodology outlined in this research and demonstrated in the case study can be adapted to a range of complex building systems, applicable to existing building stock, existing system designs, and future design development. It is particularly pertinent to modular, prefabricated, and high-rise construction. This research demonstrates how disassembly modeling can be integrated into the existing digital workflows of AEC and implemented to map selective deconstruction and Design for Disassembly across lifecycles of building systems.

References

[1] S. Ji, et al. "Building life-span prediction for life cycle assessment and life cycle cost using Machine Learning: A big data approach." *Building and Environment, vol. 205*, 2021.

[2] European Critical Raw Materials Act, Publications Office of the European Union, 2023.

[3] O. Deniz, et al. "Building façade system for deconstruction." *Journal of Sustainable Architecture and Civil Engineering, vol. 8*, 2014.

[4] Homepage | Urbanmining. On-line: www.urbanmining.org, Accessed: 12/12/2024.

[5] Durmisevic E. "Transformable building structures; Design for disassembly as a way to introduce sustainable engineering to building design & construction." Delft , 2006.

[6] O. Akinade, et al. "Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS)", *Resources, Conservation and Recycling*, Volume 105, 2015.

[7] B. Sanchez, et al. "A selective disassembly multi-objective optimization approach for adaptive reuse of building components" *Resources, Conservation and Recycling*, Volume 154, 2020.

[8] D. François, et al. "Using network analysis and BIM to quantify the impact of design for disassembly." *Buildings, vol. 8*, 2018.

[9] MTM (Methods-Time Measurement). The Process Language Methods-Time Measurement (MTM). On-line:mtm.org/en/about-mtm/mtm, Accessed: 12/12/2024.The MOST® Technique, Maynard Operation Sequence Technique. scott-grant.co.uk/terms-and-techniques/most-technique, Accessed 12 Dec. 2024.

[10] C. Langston, et al. "The application of ARP modelling to adaptive reuse projects in Hong Kong." *Habitat International,* vol. 40, 2013.

[11] S. Conejos, et al. "AdaptSTAR model: A climate-friendly strategy to promote built environment sustainability." *Habitat International*, vol. 37, 2013.

[12] G. Formentini, et al. "Design for circular disassembly: Evaluating the impacts of product end-of-life status on circularity through the parent-action-child model." *Journal of Cleaner Production*, vol. 405, 2023.

[13] International Organization for Standardization. ISO 14040: Environmental management—Life cycle assessment—Principles and framework, 2006.

[14] S. Jones, et al., *Methodology an Approach to Measure Circularity*. On-line:https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o, Accessed: 12/12/2024.

[15] A. González et al. "Methodology to assess the circularity in building construction and refurbishment activities" *Journal of Resources, Conservation & Recycling Advances*, vol.12 ,2021.

[16] buildingSMART International. IDS: Computer interpretable (XML) standard to define Information Delivery Specifications for BIM. On-line: https://github.com/buildingSMART/IDS, Accessed: 12/12/2024.

[17] International Organization for Standardization. ISO 20887 Sustainability in buildings and civil engineering works — Design for disassembly and adaptability, 2020.

[18] Tomczak, et al., Requiring Circularity Data in Bim With Information Delivery Specification, *Journal of Circular Economy*, 2024.

[19] Environmental Product Declaration. On-line: www.byggfaktadocu.se/miljovarudeklaration-1299181/fil-files/schuco_EPD.pdf, Accessed: 12/12/2024.