Structures and Architecture. REstructure REmaterialize REthink REuse - Rinke & Frier Hvejsel (Eds)
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Advancing the building materials reclamation: An evaluation method for the disassembly potential of glass facade systems

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ABSTRACT: The construction sector is responsible for producing and landfilling high volumes of construction and demolition waste. Design for disassembly (DfD) is deemed a promising strategy to establish a circular building process, enabling the easy separation of material and components at the end of life. Despite efforts to promote DfD, only a few applications of this strategy currently exists, and most buildings are not designed to be disassembled at the end of life. These non-DfD compliant building systems represent a possible source of materials and components, according to the concept of building as a materials bank. The ease of deconstruction of these systems should be evaluated to understand their harvesting capacity and circular potentiality. The purpose of this research is to evaluate the DfD level of the widely distributed facade systems in the high-rise building. Specifically, the unitized curtain wall, the stick facades, and the structural glass facades. In this research, a method to evaluate the DfD level of these facade systems has been developed, including various parameters grouped in three sets, such as the technological, economic and environmental ones. The application and validation of this method allowed to identify, among those investigated, the facade technology that is easier to disassemble. Further improvements to the evaluation method would involve fine-tuning the identified parameters to enhance accuracy.

1 INTRODUCTION

The Construction and Demolition (C&D) waste stream represents 30–40% of global waste, highlighting the need for reduction strategies to mitigate the construction sector's environmental impact (van den Berg et al., 2023). Recovering materials from end-of-life and refurbished buildings can reduce demand for new materials, lower emissions, and minimize waste, aligning with the need to preserve embodied energy (BAMB, 2016). Pre-demolition audits play a crucial role in this process providing valuable data to minimize discarded materials and recommendations for reuse and recycling (Fahy et al., 2024; Wahlström et al., 2019). In Europe, the Waste

DOI: 10.1201/9781003658641-164

Framework Directive prioritises reuse and recycling over landfilling and has set thresholds for C&D waste management across member states (European Parliament and Council, 2008). Recently, the European Commission delivered specific guidelines to conduct pre-demolition audits (European Commission, 2024). These caused a broader adoption of pre-demolition audits across Europe. While hazardous waste audits are usually mandatory, only few EU countries impose mandatory audits for non-hazardous materials (Wahlström et al., 2019). Pre-demolition audits involve five steps: desk study, field survey, inventory, management recommendations, and reporting (European Commission, 2024). The field survey is vital for assessing the building's state and reclamation potential. However, no standardized method exists for accurately evaluating the condition and disassembly of building materials, resulting in varied approaches that often rely heavily on auditor expertise. This can lead to oversimplified assessments, misjudging the building's reclamation potential. Current methods also fail to differentiate among building systems, applying uniform parameters to all components, including facades, structures, and partition walls. Facades require tailored assessments due to their significant contribution to embodied carbon (Kragh and Jakica, 2022), and their complex, multi-material nature, often coupled with a short service life (Hartwell et al., 2021). Although carbon-intensive, facade materials like glass, aluminium, and steel are highly recyclable and sometimes reusable. Their assembly- typically with mechanical connections - benefits reclamation even when not designed for disassembly. Additionally, the geographic context should be considered because it has an impact on the market value and on the reuse or recycling potential available through local supply chains. To address these gaps, a method is presented to support auditors in assessing the reclamation potential of facades. It involves an assessment of the facade materials based on ease of disassembly, material qualify, and geography.

2 PRE-DEMOLITION AUDITS AND ASSESSMENT METHODS

The literature on pre-demolition audits lacks tailored methods for assessing the reclamation potential of facades, focusing instead on general approaches applicable to all building systems. These methods typically evaluate broad parameters like disassemblability and material condition. The European Commission's pre-demolition audit template (European Commission 2024) distinguishes hazardous from non-hazardous materials by identifying waste codes and assessing reuse potential through binary outputs, though it does not evaluate disassemblability. Similarly, the Horizon 2020 CIRCuIT project template (CIRCuIT 2022) incorporates qualitative assessments of disassemblability and material condition using a coarse 0–4 scale. The (De)construct for Circular Economy project template ((De)construct for circular economy 2022) adopts a similar method while also classifying hazardous and non-hazardous materials. Lastly, the work of van der Berg et al. (van den Berg, Hulsbeek, and Voordijk 2023) proposed an evaluation method to compare reuse, recycling, and recovery strategies based on technical feasibility, economic costs, and environmental and social gains. Their approach integrates disassemblability criteria, representing a more detailed evaluation of ease of disassembly. Unlike previous templates, this method uses disassemblability as a parameter to assess reuse and recycling strategies, rather than directly determining material reuse potential. Beyond pre-demolition audits, reclamation potential research offers detailed insights into disassemblability and material condition, evaluating factors like connection typology, accessibility (Cottafava and Ritzen 2021), manageability, and disassembly tools (O'Grady et al. 2021). Hartwell and Overend (Hartwell and Overend 2024) advanced this field with a model incorporating disassemblability, service life, and material degradation, tested on a glazed double-skin façade. This model integrates with Life Cycle Assessment (LCA) simulations. While reclamation potential methods provide greater detail, often leveraging tools like BIM, pre-demolition audits remain limited, primarily identifying hazardous materials without promoting circular economy practices. Integrating these detailed methods into pre-demolition audits—particularly for complex systems like facades—could improve stakeholder engagement and support material harvesting. Further research is needed to unify these approaches and develop comprehensive pre-demolition audit models.

3 REUSE OF FAÇADE MATERIALS: CURRENT SCENARIO

The reuse is not fully exploited at the moment, while recycling seems to be the preferable solutions whenever a material collection from the façade is possible. Experiences with the reuse of façade elements are limited to a few pilot projects and are far from being scaled up.

The reuse of construction materials is strictly dependent on the residual quality of the materials and therefore recycling is often preferred over reuse. In addition, the manufacturing company does not seem interested in small quantities of materials waste and they tend to prefer recycling over the reuse, because with it they can ensure large production output and keep up the quality of the final product. This does not apply for every material, but it is applicable to those materials with high quality requirements, such as glass and aluminium. Glass and aluminium are also the most impactful material in the façade material stream for the high-rise building typology (Table 1).

Table 1. Environmental impacts of the most common facade materials (Hartman & Williams, 2024).

Material	Application in the facades	Embodied Carbon (kgCO2e/ m^3)	Key Factors for carbon footprint	End-of-life scenario
Glass	Windows, beam	3600	Type of glazing, service life	Glass is recyclable, but the post-consumer glass remelted in the furnace is <1%. Reuse is not practiced.
Aluminium	Claddings, curtain wall, windows and door frames, solar shading	6256-19040	Production process, recycling content	Aluminium is highly recyclable without quality loss; the goal is 100% recycled content in new production.
Steel	Cladding and structural element	2614-19232	Production process, recycling content	Steel recycling is well-established, but reuse, an emerging circular practice, is limited by regulatory gaps.
Timber	Claddings, window frames	100-220 (per mass of timber)	Service life and multiple use.	Timber can be recycled into wood panels, but it is often used for energy recovery, releasing stored CO2.
Copper	Claddings	5000-10000	Production process, recycling content	Copper is highly recyclable, with façade cladding often made from high-percentage recycled copper.

Given the raising interest in façade materials, it is essential to develop a method for assessing their reclamation potential. Therefore, facilitating the collection of these materials and sharing end-of-life information with relevant stakeholders is crucial. Glass and aluminium are few examples of this. Post-consumer glass is becoming increasingly valuable due to the decarbonization targets set by the glass industry for 2020 (Glass for Europe, 2022). Similarly, aluminium, with its high recyclability and potential for circularity, plays a crucial role in reducing the environmental impact of façade systems. Considering this, the current study developed the assessment method only for glass and aluminium.

4 METHOD

4.1 *Framework of the assessment method*

In this study, a method to evaluate the reclamation potential from building façade during pre-demolition audits has been developed, and applied to three facade typologies (Figure 1). The

method serves two purposes: first, to provide a tailored approach for assessing the reclamation potential of the façade materials through info on their disassemblability, technical properties and market potential. Second, it seeks to improve communication among deconstruction stakeholders and engage them in the waste supply chain, including manufacturers and recyclers. The method builds on the aforementioned pre-demolition audit techniques from literature and European guidelines.

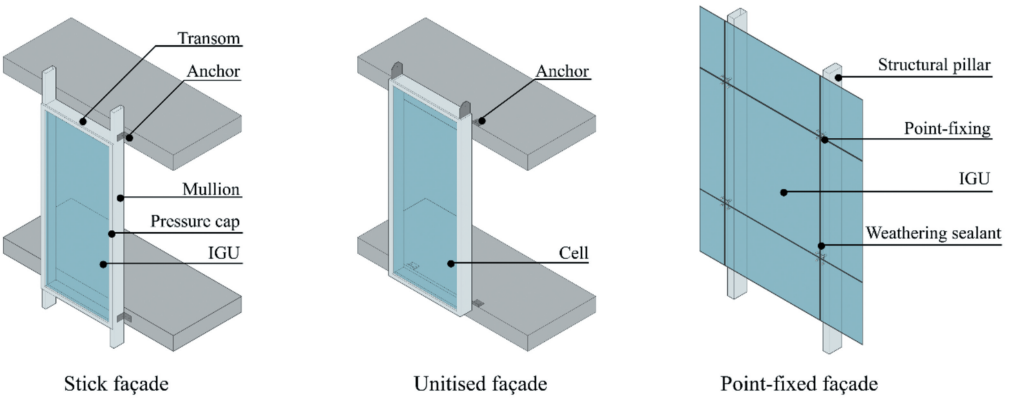


Figure 1. Illustration of the three types of facade system considered in the study.

The developed tool aims to support auditors in conducting both desk study and field surveys. In the desk study auditors, gather information from building documents, assess the deconstruction site to check the presence of big storage areas, and analyse the geographical context for material reuse or recycling logistics. The field survey refines the preliminary bill of materials by validating or modifying it after on site observations, excluding materials unsuitable for reuse or recycling (such as broken window or contaminated material). It also provides detailed material classifications. The tool is an assessment method for the façade system, evaluating sets of parameters, grouped into three indices (I_i): the ease of disassembly, the technical characteristics of the components and the geographical context concerning logistic and market. Each parameter can be assessed at a different level of the façade system: the assembly or the component. The assembly is defined as a set of components attached, while the component is a product manufactured as a distinct unit to serve a specific function (ISO 2020). Examples of assemblies are the façade structure, and the transparent façade elements, while IGUs, mullions, and transoms are components. Each parameter compute a specific feature of the assembly or component and their assessment can be done directly or indirectly. A direct assessment of the parameter involves a direct observation or measurement of the element on site with the use of specific tools, when needed. The indirect assessment of a parameter requires the auditor who conducts the assessment to perform a specific study to collect the information. The three sets of parameters are then associated with three indices, which are calculated by combining the values of each parameter.

4.2 *The ease of disassembly index (Idfd)*

The ease of disassembly index is based on the assessment of five different parameters (Table 2):

- The number of connection types identifies the number of different connections in a building assembly.
- The connection typology details the previous parameter by specifying the typology of each connection. This parameter is evaluated according to the number of connection types.
- The independence is evaluated at the building assembly level and measures the level of independence of each assembly.

- The disassembly step is assessed at the building components level. It measures the number of processes that should completed before having access to the component.
- The handling parameter evaluates if a component needs specific equipment or machines to be disassembled.

The weight assigned in the ease of disassembly index is based on the information found in the standard ISO 20887 (ISO 20887, 2020).

Table 2. Set of parameters defining the ease of disassembly index.

Parameter	Unit of analysis	Unit of measurements	Assessment values (x_i)	Weighting factor (w_i)
Number of connection types	Building assembly	one connection type	3	0.5
		two different connection types	2	
		more than three different connection types	1	
Connection typology	Building assembly	Contact connection (interlocking, pressure, etc.)	3	1
		Connection with added elements (bolted, screwed, etc.)	2	
		Chemical	1	
Independence	Building assembly	The building assembly is fully independent. Parallel assembly and dry connections	3	0.75
		The building assembly showcases a hierarchy of assembly with dry connections	2	
		The building assembly is fully integrated with other assemblies, demolition is needed	1	
Disassembly steps	Building component	less than 2	3	1
		2 to 4	2	
		more than 4	1	
Handling	Building component	One person	3	0.5
		Two people	2	
		Forklift or crane	1	

4.3 *The material qualify index (Iqualify)*

The possible recovery route at the end-of-life of a material is strictly influenced by the technical feasibility of reuse or recycling option, e.g. reusing a laminated glass panel is not feasible as of now due to degradation of its mechanical performance. The material qualify index is based on the assessment of four parameters for the glass and one parameter for the aluminium (Table 3).

The weight assigned to each parameter is based on preliminary interviews with stakeholders and information found in the literature (Rota et al., 2023). The interviews were conducted in an semi-structured way, with the aim of collecting technical insights about the reuse and recycling potential of glass and aluminium.

4.4 *The geography index (IGeo)*

The reclamation potential of façade materials is linked to the geographical context and the logistics of the process (Table 4), as these often limit any recovery route. The market for the secondary materials is also considered, as it is affected by factors such as transportation distances, accessibility to recycling facilities, and regional infrastructure for material reuse.

4.5 *Assessment tool outputs: Parameter and index calculations*

The result of the assessment is associated with a scale of values (x_i), varying between 1 and 3. A score of three represents the best condition for reuse and ease of disassembly, while a score

Table 3. Set of parameters defining the material qualify index.

Material	Parameter	Unit of analysis	Unit of measurements	Assessment Values (x_i)	Weighting factor (w_i)	
Glass	pane composition	IGU	monolithic	3	0.75	1
			laminated	2		
			other (PC cells, fire resistant)	1		
	pane optical properties	IGU	non coated	3		
			coated	2		
			other	1		
	pane strength properties	IGU	annealed	3	0.5	
			thermally tempered	2		
			chemically tempered	1		
	special pane finishing	IGU	without other element	3	0.75	
			with stickers	2		
			enamelled	1		
Aluminium	Frame composition	building component	element section with only aluminium	3	0.5	
			thermally broken aluminium profile	2		
			multimaterial aluminium profile	1		

Table 4. Set of parameters defining the geography index.

Category	Parameter	Unit of analysis	Unit of measurements	Assessment values (x_i)	Weighting factor (w_i)
Logistic	method of collection	Building material	separate from other waste, without breakages	3	1
			separate from other waste, with breakage	2	
			mixed with other waste	1	
Market	Recycling route	Building material	reuse site is present in the country of the building site	3	0.5
			reuse site is present in the continent country of the building site/ no possibility to recycle	2	
			reuse site is not present in the country of the building site	1	
	Transport for recycling	Building material	transport to recycling site <100 km	3	0.5
			transport to recycling site <200 km	2	
			transport to recycling site <500 km	1	
	Reuse route	Building material	reuse site is present in the country of the building site	3	1
			reuse site is present in the continent country of the building site	2	
			reuse site is not present in the country of the building/no possibility to reuse	1	
	Transport for reuse	Building material	transport to reuse site <100 km	3	1
			transport to reuse site <200 km	2	
			transport to reuse site <500 km	1	

of one represents the worse condition, suggesting a situation more favourable to recycling. Each parameter comes with a weighting factor (w_i) to reflect its relevance in the overall assessment. Also, in this case, more relevance was given to the parameters having a higher influence on the decision-making process of materials reuse. To calculate the indices (I_i), each assessment values are multiplied by the respective weighting factor.

$$x_f = w_i * x_i \tag{1}$$

where x_f is the final value of the parameter; w_i is the weight assigned to each parameter; and x_i is the value of the assessment.

The products of each parameter are then summarised according to the following equation:

$$I_i = \sum x_f \tag{2}$$

The index sum (I_i) is then normalised between 0 and 100.

5 CASE STUDY: APPLICATION AND RESULTS

To validate and apply the developed tool, an application of it to the most common façade systems for high-rise buildings is proposed in this research. Specifically, the study examines three façade technologies: the unitized curtain wall system, the stick façade system, and point-fixing glass façades (Figure 1). These systems were selected as a case study due to their high disassembly potential even though normally they are not designed to be disassembled. The method evaluates the parameters and calculates the Idfd, Iqualify and IGeo index for each case study. By analysing the theoretically modeled façade systems, it was possible to identify the façade technology with the highest ease of disassembly and to associate the reclamation potential for its components. Building façades are made of modular units, often repeatable. Therefore, the method was applied to one module per case study. To compare the results of the assessment, the features of the glazing components are equivalent in the three façades. An insulated glazing unit made of one laminated glass and a monolithic coated glass is considered. The composition of the glazing component, together with the elements of the façade system are shown in the section in Figure 2.

For the ease of comparison of the assessment results, the assumptions made for the geographical context are the same for each material (glass and aluminium).

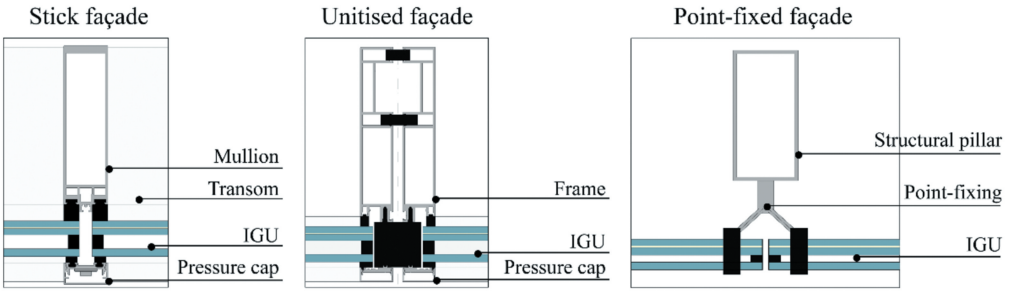


Figure 2. Top view of the three types of facade systems considered in the study.

6 RESULTS AND DISCUSSION

The use of the method during the audit process provides two main outcomes: the first is a detailed knowledge of reclaimed materials and the second is a set of indices classified by topic useful for communication purposes. The detailed knowledge includes information about

the ease of disassembly, the technical feasibility of reclamation and the local supply chain available at the end-of-life. For brevity, only the results of the aggregated indices are reported in Table 5.

Table 5. Results index for the three facade type.

	Idfd	IqualifyGlass	IqualifyAlu	IGeoGlass	IGeoAlu
Stick façade	57	85	67	56	44
Unitised façade	48	85	0	56	38
Point-fixing façade	40	85	100	29	38

Within the Idfd the difference in results allows to identify a hierarchy of the facade systems, suggesting that the stick façade is the easiest to disassemble, followed by the unitised and the structural façade. This was expected as the main parameters influencing the Idfd are the connection type and the number of disassembly steps. The stick façade relies mainly on dry connections, while the unitised and the structural glass façade present a higher number of chemical connections. Although the parameters assessed in the "material qualify" and "geography" sets are of high value for the reclamation potential of the secondary materials, once they are aggregated in the indices (i.e. $I_{qualify}$ and I_{Geo}) it is unclear how these values can be used to compare the different systems under analysis.

Furthermore, the case study application should set out as a benchmark for developing standardised parameters that can allow the application of this method to other façade types, such as cladding walls.

The main differences with the other pre-demolition audit models presented in section 2 are the following:

- A tailored reclamation potential method for facade materials,
- A higher level of detail in describing the disassemblability of the façade systems,
- The method fosters the engagement of stakeholders to gain the knowledge needed to assess the parameters.

7 CONCLUSION

This research offers key insights into the Design for Disassembly (DfD) in high-rise façade systems, focusing on the circular potential of glass and aluminium. The developed evaluation method, encompassing parameters related to the disassembly process, the material quality and the geographical context, successfully identifies the ease of disassembly and material reclamation potential of different façade technologies. However, the aggregation of these parameters into indices has raised challenges regarding their practical application for comparing systems. Specifically, the relationships between these aggregated values and their utility for meaningful comparison between systems remain unclear. To refine and enhance the evaluation method, further research is needed to fine-tune the parameters, as well as the weighting and evaluation systems used. Future studies should aim to increase the accuracy and level of detail of the parameters, which can be achieved through additional interviews with key stakeholders, including façade designers, deconstruction contractors, and material manufacturers.

By improving the evaluation process and expanding the scope of its application, this research can further support the building industry's transition towards a circular economy, facilitating the reuse and recycling of materials and reducing waste in the construction and demolition processes.

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