PAPER • **OPEN ACCESS**

Reclamation potential in the built environment: A digitised assessment of two contemporary façade systems

To cite this article: R Hartwell and M Overend 2025 *IOP Conf. Ser.: Earth Environ. Sci.* **1554** 012046

IOP Conf. Series: Earth and Environmental Science **1554** (2025) 012046 doi:10.1088/1755-1315/1554/1/012046

Reclamation potential in the built environment: A digitised assessment of two contemporary façade systems

R Hartwell[1*] and M Overend[1]

[1] Architectural Engineering and Technology, TU Delft, Delft, Netherlands

*E-mail: R.C.Hartwell@tudelft.nl

Abstract. Initial material selection and connections between components significantly impact the feasibility of reuse in the built environment. Yet, the link between material selection and construction methods with the ability to reutilise recovered elements is rarely quantitatively assessed. In this study, a novel digitised assessment method to evaluate the environmental reclamation potential of building elements is applied to two contemporary façade systems. The systems are evaluated over a 75-year reference study period in terms of life-cycle embodied carbon and reclamation potential, with consideration for service life deterioration of components. The reclamation potential is evaluated in three recovery scenarios: system reuse; component reuse; and recycling and/or energy recovery. The reclamation potential through system reuse is shown to rapidly decrease in the first few years of the façade system lifetime due to the influence of service life dependencies and the incorporation of irreversible connection types. The findings of the applied assessment provide key insights into design decisions that lead to reduced life-cycle embodied carbon and enhanced reclamation potential over time. The applicability of the assessment to other construction products and future capabilities of the reclamation potential assessment method are discussed.

1. Introduction

1.1. Multi-life-cycle material efficiency

Material reuse stands as one of the most promising circular economy solutions for reducing greenhouse gas (GHG) emissions in the EU construction sector (1). Further, the implementation of design principles related to the circular economy has the potential to provide benefits to the economy, through cost savings arising from more efficient use of raw materials; and society, through a positive net effect on employment in material recovery sectors where reuse practices are typically more labour intensive than linear extraction and manufacturing processes (2,3). Multi-life-cycle material efficiency opportunities in the built environment remain largely untapped to date (4). The wide-scale uptake of practices in building element reuse relies on a systemic change in existing design practice involving: the ability to deconstruct components from existing buildings; reduction in the perceived risk in specifying reuse components; increased access to reuse markets; cost-effective remanufacturing and reuse certification processes; enhanced digital traceability and marketing; selective sorting of construction waste; extended producer responsibility schemes; preventative maintenance strategies; and shifts in procurement policies and regulation to stimulate demand for reused products (5–7).

The building envelope has been shown to contribute between 10% and 25% of the total embodied carbon in terms of greenhouse gas (GHG) emissions of the building (8). These environmental costs are particularly relevant in the context of contemporary façade systems where – unlike building foundations or principal load-bearing structural systems – they often consist of components with service lifetimes that can range from 10 to 60 years. The replacement of these components thus calls for additional inputs of embodied carbon throughout the lifetime of the building. Stringent legislation on the energy performance of buildings has stimulated the development of façade design strategies and technological innovations that endeavour to improve the operational energy efficiency of buildings. This, together with other important performance criteria – such as indoor comfort, occupant well-being, changing aesthetic requirements, and, more recently, facilitating energy-generation (9) - has catalysed the development of composite, multi-functional façade systems. These systems exploit a wide-ranging palette of materials and advanced processing- and connection-methods such as: gas-filled multi-pane windows with low-emissivity coatings; thicker insulation; solar thermal collectors; and building integrated solar photovoltaic panels. The uptake of these complex arrangements, designed to reduce the energy required to operate the building, has shown little consideration for the ability recover material streams at their end of life. Complex and/or multi-component systems can limit the potential for reuse or recycling of component parts at end-of-life (10,11). For example, the choice of material will influence the reuse and/or recycling options; the type of connection will influence the ease of disassembly; and the service life will influence the replacement frequency and thus the recurring energy inputs throughout the facade life-cycle. It is thus evident that all stages in the building element life-cycle require equal levels of industry and political attention to reduce the net environmental impact of the building sector.

1.2. Life-cycle assessment and benefits beyond primary life-cycle

Life-cycle assessment (LCA) provides an internationally standardised framework to quantitatively assess the environmental impact of products with reference to material and process flows that occur across key life-cycle stages (12). Life-cycle stages include product manufacture and construction (Module A); product operation and use (Module B); end-of-life handling and disposal (Module C); and product recovery (Module D). Benefits and loads beyond the system boundary (Module D) provide a measure of the potential benefits (denoted as a negative quantity) related to the exported energy, secondary materials, secondary fuels and/or secondary products resulting from reuse, recycling and energy recovery through incineration that take place beyond the system boundary. There is no consensus on how to integrate the potential benefits beyond the primary life-cycle into LCA assessment: existing European standards and metrics for technical recovery and reuse are underdeveloped and do not account for performance deterioration of components (13,14). Methods for evaluating disassembly exist however these are typically based on discrete data or lack integration with assessments of environmental value (15,16). A method to evaluate the reclamation potential of multi-component systems with consideration of connections between elements was developed in (17). The assessment method accounts for performance deterioration by utilizing a probabilistic approach to analyse the likelihood of system and/or component failure, and resulting residual value, over the building lifetime. The approach provides a quantitative assessment of how design decisions affect the ability to reclaim and reuse constituent components across the product lifetime.

1.3. Current study

This study will apply the recently developed reclamation potential (RP) assessment method developed by (17) to two contemporary glass façade systems. The details of the two façade systems will be presented and the key system-specific environmental impacts and probability of survival distributions will be identified. The outputs from the application of the newly developed RP assessment will be presented for each system, in terms of initial and cumulative life-cycle embodied impact; system breakdown into sub-systems and components; and RP as a function of time. The key findings from these indicators and limitations of the newly developed assessment method will be discussed. Finally, future development of the assessment and applicability to other systems and construction products will be proposed.

2. Methods

2.1. Functional unit

The newly developed reclamation potential assessment method was applied to two contemporary façade systems: a single-skin façade with a double-glazed unit (SSF-DGU) and a double-skin closed cavity façade (DSF-CCF). The functional unit is a 2.895 m x 3.900 m contemporary glazed façade system. The details of the two façade typologies can be found in Table 1. A schematic sketch of the glass-to-frame interface for each system is shown in Figure 1.

Table 1. Design details for the two glazed façade systems assessed in this study

System name	Type	Glass-to-External Frame Joint	Thickness (mm) of glass	Spandrel Insulation	Shading device
SSF-DGU	Single-skin unitised aluminium system with double-glazing (80% glazing ratio)	EPDM Gasket	55.2 | 6	Mineral wool	None
DSF-CCF	Double-skin aluminium closed cavity façade (80% glazing ratio)	Silicone Seal (outer skin) EPDM Gasket (inner skin)	55.2 (outer skin) 6 | 55.2 (inner skin)	Mineral wool	Venetian blinds in cavity

[a] Glass layers are described in the form of X | Y where X is the exterior glass pane and Y is the interior glass pane. PVB interlayer thickness is described in multiples of 0.38 mm-thick plie (i.e. 55.2 indicates laminated glass with two sheets of 5 mm-thick glass and 0.76 mm-thick PVB interlayer.

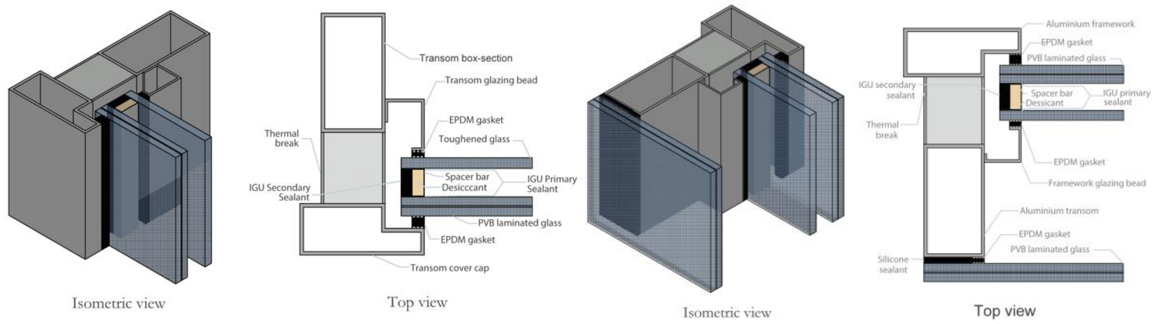

Figure 1. Simplified schematic sketch of the glass-to-frame interface of the SSF-DGU and DSF-CCF. Images are not drawn to scale.

2.2. Recovery scenarios

The three end-of-life scenarios investigated in this study take the form of: system reuse (SYS-REUSE), where the façade system is dismantled from the building and directly reused elsewhere; component reuse (COMP-REUSE), where the façade system is dismantled from the building and the components are disassembled to be re-assembled in a new system; and recycling and energy recovery through incineration (RECYC), where the material groups are separated and reprocessed into a second application. The SYS-REUSE and COMP-REUSE refer to idealised situations, where reuse is made feasible via suitable project-matching and supporting infrastructure.

2.3. Inventory data

Relevant construction drawings and associated bills of materials were inspected to establish a *components inventory* for the SSF-DGU and DSF-CCF systems. The components inventory provides details of the unique component type; component mass (kg); and material type, which links to a reference materials inventory. The *materials* inventory was assembled to document environmental impact data related to material extraction, sourcing, processing, fabrication, transportation, construction, and impacts associated with demolition, deconstruction and reprocessing (for details, see Section A in supplementary material (18)). This data was selected based on guidelines from ISO-14044 (19) from various sources (20,21) including relevant environmental product declarations which comply with ISO-14040 and EN 15804. Inputs for initial and recurring embodied impacts related to components were taken from the materials inventory. Primary raw material data was used where it was verified that embodied carbon data referred to 0% recycled content. The environmental impact associated with reprocessing each material is calculated as the environmental impact associated with the production of the material in its second application with 100% recycled content. This information is used to guide the evaluation of mitigated (avoided) environmental impact through *recycling* materials.

System-specific environmental impact data related to GHG emissions associated with for life-cycle stages A3 to A5 and C1 to C4, were assembled into a *systems inventory* from existing literature and manufacturer-specific data (Section A in supplementary material (18)). Relevant construction drawings were inspected to establish a *connections inventory* detailing the type of connections between components in the SSF-DGU and DSF-CCF systems. The connection type is detailed in terms of ease of separation: “reversible” or “irreversible”. The list of connection types and justification for reversibility can be found in the supplementary material (Section A) (18).

The inventory of components, materials, and connections are called upon to automatically generate a network diagram for the SSF-DGU and DSF-CCF using the Python NetworkX package (22). The nodes in the network diagram represent the components in the system and embed relevant material information. The edges of the network diagram represent the connections between components and their degree of reversibility. The network diagram thus provides all the necessary data to evaluate the reclamation potential over time. At the component replacement or end-of-life stage, the system is deconstructed into sub-systems based on the reversibility of connections present.

2.4. Service life distribution

The reclamation potential assessment method applies a probabilistic approach to account for deterioration in performance and subsequent impact on the value of SYS-REUSE or COMP-REUSE (17). A combined lognormal-Weibull distribution - where wear-out failures are described by the former and early life failures are described by the latter - was considered as appropriate for modelling the service life of the sub-systems and components in the SSF-DGU and DSF-CCF. The probability of survival for the combined lognormal-Weibull distribution used to model the service life of systems and individual components over time *t*, is thus calculated through Equation 1.

Equation 1:

$$P_S(t) = 1 - \left(\int_{\infty}^{t} \left(\frac{1}{\sigma t (2\pi)^{0.5}} \times e^{\left[-\frac{1}{2} \left(\frac{\ln t - \mu}{2\sigma^2} \right)^2 \right]} \right) \partial t \right)_{Lognormal} - \left(e^{\left(-\left(\frac{t}{\eta} \right)^{\beta} \right)} \right)_{Weibull}$$

Where in the lognormal distribution, parameter t refers to a specific time interval and μ, and σ, represent the mean and standard deviation of the *ln(data),* respectively. β and η are the distribution parameters used in the Weibull distribution, where β*,* is the *shape parameter* and η, is the *scale parameter* or *characteristic life*: the life at which the probability of failure is equal to 63.2%. The distribution parameters were adjusted to fit a cumulative lognormal-Weibull distribution that produced a close fit to an existing study on the failure of insulated glazing units over time (23) as detailed in Section B in supplementary material (18).

2.5. Life-cycle cumulative embodied environmental impact (LCEEI)

The life-cycle cumulative embodied carbon of a multi-component system is calculated through Equation 2.

Equation 2:

$$LCEEI = Initial\ Embodied\ Carbon_{SYS} + Recurring\ Embodied\ Carbon_{SYS}$$

Where the initial embodied carbon is evaluated as the embodied carbon associated with life-cycle modules A1 to A5. The recurring embodied impact is evaluated for life-cycle modules B4 and B5 (replaced components) and C1 to C4 (end-of-life operations). Service life dependencies between components are accounted for using the approach proposed by (17): the service life of a system is that of the component with the shortest service life (Section C in supplementary material (18)).

2.6. Reclamation potential

The reclamation potential is a function of the mitigated (i.e. avoided) environmental impact *MI*, that would be achieved from utilising recovered systems, components and/or materials in place of primary raw material resources. Components from the current (CURR) system at age *t*, and components recovered throughout the life-cycle due to component replacement (REPL) up to age *t*, are evaluated as represented by Equation 3.

Equation 3:

$$MI = MI_{CURR} + MI_{REPL}$$

Where MI is evaluated in terms of GHG emissions and MI_{CURR}, refers to the mitigated impact through redeployment of the current system (SYS-REUSE), components (COMP-REUSE) and/or constituent materials (RECYC), and MI_{REPL}, refers to the mitigated impact through redeployment of the components replaced over time.

The mitigated impact for the current system (MI_{CURR}) in the SYS-REUSE and COMP-REUSE scenarios is evaluated with reference to the probability of survival function (Section C in supplementary material (18)). In the RECYC scenario, it is assumed that all replaced components/sub-systems are recovered for recycling (90% to second application and 10% to landfill). The mitigated impact for the current system (MI_{CURR}) in the recycling scenario is evaluated through Equation 4.

Equation 4:

$$MI[CURR]_{RECYC} = \sum_{k=1}^{o}\left(\sum_{l=1}^{p}\left(RF \times 0.9 \times EI_{SA} \times mass_{component}\right)\right)$$

Where l, is equal to the first component of a unique material *M*; *p*, is the total number of components made from material *M*; *k*, is the first unique material type in the system; and *o*, is the total number of unique materials in the system. For all recovery scenarios, the mitigated impact for the components that are replaced (MI_{REPL}) across the life-cycle are evaluated through Equation 4. The reclamation potential RP (%), at a time t (years), is then evaluated through Equation 5.

Equation 5:

$$RP\ (\%) = \left(\frac{MI}{LCEEI}\right) \times 100$$

3. Results

3.1. Initial and recurring embodied carbon

The system network map and system details for the SSF-DGU and DSF-CCF are shown in Figure 2 and Table 2, respectively.

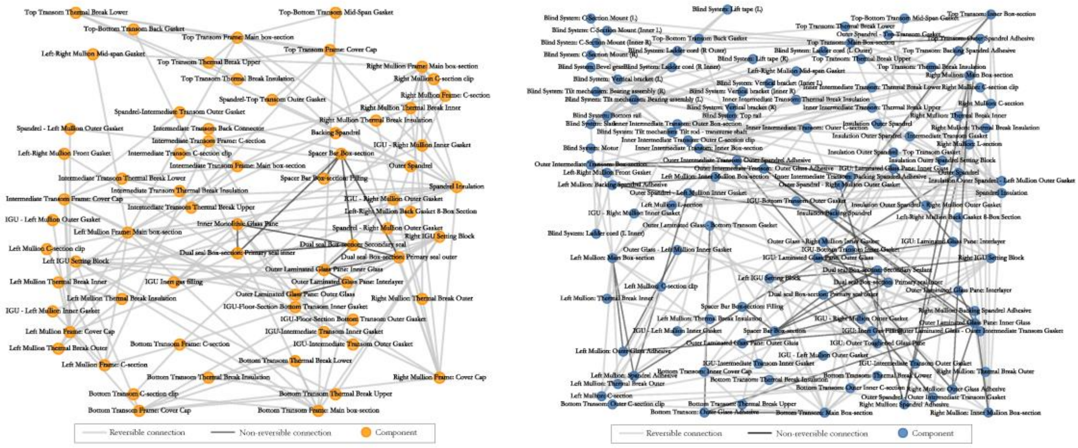

Figure 2. Network diagram of SSF-DGU and DSF-CCF. The nodes correspond to a component in the façade system and the edges denote the connections between components.

Table 2. Properties of SSF-DGU and DSF-CCF

System name	System mass (kg)	System service life (years) [a]	Total number of components	Total number of connections	Total number of sub-systems [b]
SSF-DGU	532	25	66	143	58
DSF-CCF	790	15	115	235	73

[a] System service life is that of the shortest lifetime component.

[b] Total number of sub-systems are those remaining once all reversible connections have been removed.

The initial embodied carbon for life-cycle stages A1-A2 for the SSF-DGU and DSF-CCF is shown in Figure 3. The life-cycle embodied carbon inclusive of life-cycle stages A1-A5, B4-B5, C1-C4 and service life-dependencies across the 75-year time frame is shown in Table 3 and Figure 4.

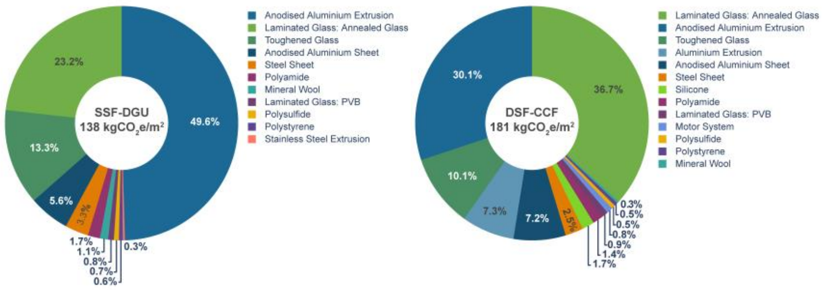

Figure 3. Initial embodied carbon (A1-A2) of SSF-DGU and DSF-CCF in $kgCO_2/m^2$ façade surface area.

Table 3. Cumulative embodied carbon at 0-, 25-, 50- and 75-year time step where Module C contributions are evaluated with reference to the SYS-REUSE scenario.

System name	0-year ($kgCO_2eq/m^2$)	25-year ($kgCO_2eq/m^2$)	50-year ($kgCO_2eq/m^2$)	75-year ($kgCO_2eq/m^2$)
SSF-DGU	178	259	425	517
DSF-CCF	227	417	628	836

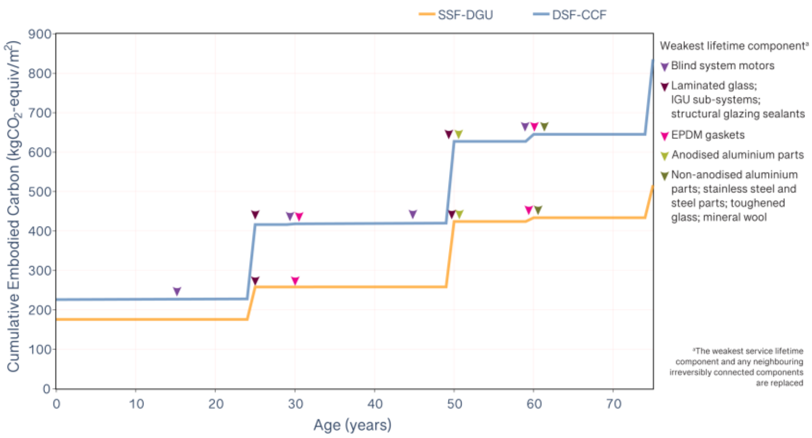

Figure 4. Life-cycle embodied carbon inclusive of life-cycle stages A1-A5, B4-B5, C1-C4, where component replacements are highlighted in legend. Life-cycle module C contributions are evaluated with reference to the SYS-REUSE scenario.

3.2. Reclamation potential

The reclamation potential (RP) at 0-, 25-, 50- and 75-years is detailed in Table 4 and the corresponding RP- graphs for the SSF-DGU and DSF-CCF is shown in Figure 5.

Table 4. Reclamation potential for SSF-DGU and DSF-CCF at 0-, 25-, 50- and 75-year time step.

Recovery Scenario	System name	0-year	25-year	50-year	75-year
SYSTEM REUSE	SSF-DGU	84%	43%	22%	22%
	DSF-CCF	86%	24%	22%	26%
COMPONENT REUSE	SSF-DGU	75%	57%	43%	34%
	DSF-CCF	76%	56%	32%	29%
RECYCLING	SSF-DGU	52%	42%	44%	40%
	DSF-CCF	43%	38%	38%	37%

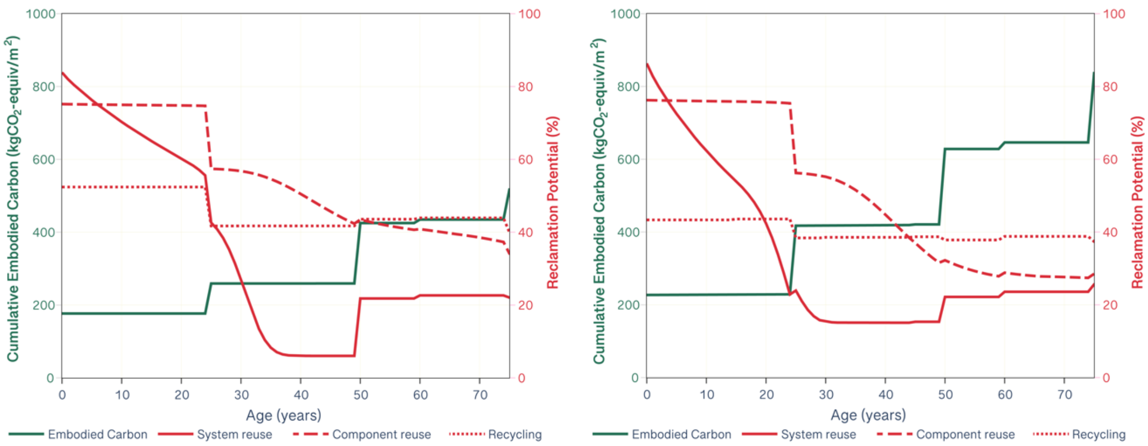

Figure 5. RP-graph for SSF-DGU (L) and DSF-CCF (R).

4. Discussion

4.1. Life-cycle embodied carbon

The initial embodied carbon of the single- and double-skin façade typology equates to 178 $kgCO_2/m^2$ and 227 $kgCO_2/m^2$ respectively (Table 3), which is consistent with the evaluation of initial embodied carbon from existing literature (24,25). The double-skin façade (DSF-CCF) exhibits an initial embodied carbon that is 28% higher than the single-skin façade system (SSF-DGU). Depending on climatic conditions, double-skin facades often outperform single-skin facades in operation (26). Further investigations on the trade-offs between embodied carbon and operational carbon are necessary to determine if the additional initial embodied carbon is offset by improved operational performance.

The less complex SSF-DGU shows reduced recurring embodied carbon inputs over the façade life-cycle (Figure 4) compared to DSF-CCF: at 75-years, the cumulative embodied carbon is 290% and 368% higher than the initial embodied carbon for the SSF-DGU and DSF-CCF respectively. The magnitude of this increase is striking in the context of building design. Whilst primary load-bearing structural elements (e.g. structural floors, beams, columns etc.) may contribute a greater proportion of initial embodied carbon in buildings, their design lifetimes may exceed 100 years. By contrast, it is evident through this work, that the complexity of service lifetimes in contemporary façade systems can lead to a lifetime embodied carbon impact up to 368% greater than the initial embodied carbon impact over a 75-year timeframe.

4.2. Reclamation potential

The reclamation potential (RP) in the RECYC scenario is relatively stable over the 75-year time frame. The RP through RECYC does not exceed 52% because the avoided impact of re-introducing materials through recycling is limited by the energy-intensive reprocessing operations. The mitigated impact through RECYC accounts for material-specific secondary applications based on existing available recycling infrastructure, thus highlighting the impacts of downcycling to be clearly identified, as seen in for the replacement of laminated glass at year 25 in Figure 5.

The SSF-DGU exhibits a higher RP in the COMP-REUSE and RECYC scenarios than the DSF-CCF. The RP For SYS-REUSE drops rapidly after the first few years for both the SSF-DGU and DSF-CCF, after which COMP-REUSE becomes a favourable recovery option in terms of RP (up to year 50 and year 44 for the SSF-DGU and DSF-CCF respectively). This may be explained by the fact that the performance deterioration of the components in the COMP-REUSE scenario does not rely on other components. A key implication of this finding is that in the absence of effective reconditioning methods to restore the original performance of multi-component façade systems, COMP-REUSE may be a more environmentally favourable recovery method to pursue.

Up to year-25, the RP through SYS-REUSE decreases much more rapidly for the DSF-CCF than the SSF-DGU. This is owing to the DSF-CCF containing a greater number of components (Table 2 and Figure 2). The RP therefore decreases much more rapidly because the probability of survival of the system is evaluated as the product of the probability of survivals of components. The higher proportion of irreversible connections in the DSG-CCF, leads to premature component replacement, leading to higher relative increase in LCEEI, but also leading to a relative improvement in RP through SYS-REUSE when compared to the SSF-DGU at later time intervals.

The reclamation potential (RP) assessment provides a quantitative indicator that evaluates the environmental value of systems, components, and materials beyond their first use cycle with consideration for connection types and service life interdependencies. The dependency of the RP on the probability of survival factor means that the results for the RP in the SYS-REUSE and COMP-REUSE scenarios are by no means conclusive. Data from enhanced test methods and monitoring of building element performance to estimate performance deterioration over time should be incorporated into the RP assessment. Future development and upscaling of the assessment would benefit from automating the process of extracting data from digital design drawings and enhanced consideration of disassembly tasks and sequences which impact the viability of reuse methods. In addition, accounting for uncertainty in embodied carbon datasets through consideration of future changes to energy provision and GHG discounting factors would increase the reliability in modelling future deployment scenarios.

5. Conclusions

This study provides a comparative analysis of the reclamation potential of two contemporary multi-component façade systems. Three different recovery scenarios were evaluated: system reuse, component reuse, recycling and energy recovery through incineration.

The application of the newly developed assessment method in this work highlights its capability to assess the embodied impacts of multi-component systems over time. The contribution of recurring embodied carbon is found to be significant, particularly in the instance of the more complex double-skin facade system. This further highlights the importance of considering all life-cycle stages related to embodied impacts, to avoid promoting the development of designs that appear materially efficient today. Further work is required to evaluate the operational performance (aesthetic and/or functional) alongside the reclamation potential.

Through this study, it is evident that prioritising system reuse yields limited reclamation potential for multi-component short lifetime building elements. In the absence of viable reconditioning processes, other recovery routes, such as component reuse and/or recycling, yield greater environmental benefit. These findings also serve as a driver to develop reconditioning processes that increase the probability of survival of components over time. In this way, product utility would be improved so that the reclamation potential is sustained for longer time periods.

The results underscore the implications of incorporating irreversible connection types which lead to significant reductions in RP through system reuse. Future research would benefit from exploring the reclamation potential of durable long-life components connected via reversible methods.

6. Acknowledgements

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) for the University of Cambridge Centre for Doctoral Training in Future Infrastructure and Built Environment (EPSRC grant reference number EP/L016095/1). The authors would like to sincerely thank Janneke Verkerk and Hans Jansen for sharing their experience on behalf of Scheldebouw/Permasteelisa s.p.A. and providing additional financial support for the newly developed method to be applied to typical façade systems. The authors would like to thank Lisa-Marie Mueller and Dr. Michela Turrin for their insightful comments on future developments of the approach applied in this work.

References

1. Gallego-Schmid A, Chen HM, Sharmina M, Mendoza JMF. Links between circular economy and climate change mitigation in the built environment. J Clean Prod. 2020;

2. Aguilar-Hernandez GA, Dias Rodrigues JF, Tukker A. Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies. J Clean Prod. 2021;278.

3. Wijkman A, Skånberg K. The Circular Economy and Benefits for Society: Jobs and Climate Clear Winners in an Economy Based on Renewable Energy and Resource Efficiency. The Club of Rome. 2015.

4. Hertwich EG, Ali S, Ciacci L, Fishman T, Heeren N, Masanet E, et al. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics - A review. Environmental Research Letters. 2019;

5. Giesekam J, Barrett J, Taylor P, Owen A. The greenhouse gas emissions and mitigation options for materials used in UK construction. Energy Build. 2014;

6. Hopkinson P, Chen HM, Zhou K, Wang Y, Lam D. Recovery and reuse of structural products from end-of-life buildings. Proceedings of the Institution of Civil Engineers: Engineering Sustainability. 2018;

7. Densley-Tingley D, Davison B. Design for deconstruction and material reuse. Proceedings of the Institution of Civil Engineers - Energy. 2011;164:195–204.

8. Clark DH. What Colour is your Building?: Measuring and reducing the energy and carbon footprint of buildings. RIBA Publishing. 2013.

9. Cucuzzella C, Rahimi N. The Evolution of the Architectural Façade since 1950 : A Contemporary Categorization. Architecture. 2023;1–32.

10. Durmisevic E. Transformable Building Structures. Technische Universiteit Delft; 2006.

11. Hartwell R, Macmillan S, Overend M. Circular economy of façades: Real-world challenges and opportunities. Resour Conserv Recycl. 2021;175.

12. BSI. EN15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. 2011.

13. Anderson J, Ronning A, Moncaster A. The Reporting of End of Life and Module D Data and Scenarios in EPD for Building level Life Cycle Assessment. IOP Conf Ser Earth Environ Sci. 2019;323(1).

14. Eberhardt LCM, van Stijn A, Rasmussen FN, Birkved M, Birgisdottir H. Development of a life cycle assessment allocation approach for circular economy in the built environment. Sustainability (Switzerland). 2020;12(22):1–16.

15. van Vliet M, van Grinsven J, Teunizen J. Circular Buildings. 2021.

16. Zandin K. MOST Work measurement systems. 2003.

17. Hartwell R, Overend M. Reclamation potential in the built environment: A method and metric for assessing environmental benefits beyond first use. Build Environ. 2024;263.

18. Hartwell R. Supplementary Information: Reclamation potential in the built environment: A digitised assessment of two contemporary façade systems [Internet]. Zenodo. 2025 Jun [cited 2025 Jun 5]. Available from: 10.5281/zenodo.15599489

19. ISO. ISO/IEC 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines. 2006.

20. Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B, et al. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess [Internet]. 2016 [cited 2018 Aug 23];21:1218–30. Available from: https://link.springer.com/content/pdf/10.1007%2Fs11367-016-1087-8.pdf

21. Öekubaudat. Life Cycle Assessment within BNB - Online Tool eLCA and materials database. In: World SB4 [Internet]. Barcelona; 2014 [cited 2018 Aug 22]. Available from: www.oekobaudat.de.

22. Hagberg AA, Schult DA, Swart PJ. Exploring network structure, dynamics, and function using NetworkX. In: 7th Python in Science Conference (SciPy 2008). 2008. p. 11–5.

23. Lingnell AW, Spetz JL. Field Correlation of the Performance of Insulating Glass Units in Buildings—A Twenty-Five Year Study. In: Thermal Performance of the Exterior Envelopes of Whole Buildings X International Conference [Internet]. 2007 [cited 2019 May 6]. p. 66–70. Available from: https://web.ornl.gov/sci/buildings/conf-archive/2007 B10 papers/066_Lingnell.pdf

24. Pomponi F, Piroozfar PAE, Southall R, Ashton P, Farr ERP. Life cycle energy and carbon assessment of double skin facades for office refurbishments. Energy Build. 2015;109:143–56.

25. Asdrubali F, Roncone M, Grazieschi G. Embodied energy and embodied GWP of windows: A critical review. Energies (Basel). 2021;14(13).

26. Straube J. A critical review of the use of double façades for office buildings in cool humid climates. Journal of Building Enclosure Design. 2007;48–52.