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Reclamation potential in the built environment: A method and metric for assessing environmental benefits beyond first use

Rebecca Hartwell *, Mauro Overend

Department of Architectural Engineering & Technology, Delft University of Technology, Julianalaan 134, 2628 BL, Delft, The Netherlands

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ABSTRACT

Direct reuse and recycling of materials can significantly reduce the net environmental impact of the global construction sector. The feasibility of reuse and recyclability of building systems is affected by the materials used and the interfaces between constituent components. Yet there is a lack of quantitative methods for assessing the environmental benefits of alternative recovery strategies for multi-component and multi-material systems over the building lifetime. In this work, a novel assessment method was developed to enable a systematic and quantitative evaluation of the transient environmental reclamation potential (RP). The reclamation potential is a measure of the ability to disassemble and reuse recovered building systems at their end-of-life and is influenced by the constituent components and the interfaces between components. The proposed method accounts for the technical service lifetimes of components, including performance degradation over time, and can thus inform decisions on the most suitable recovery route for new and existing designs. The graphical outputs from the RP assessment are a network diagram which highlights the system components and connections between components, and an RP-graph which illustrates the embodied environmental impact and reclamation potential over time of alternative reuse/recycling strategies. The methodology is demonstrated on a glazed double-skin façade where the influence of component service lifetimes and replacements over time is quantified in terms of embodied energy and embodied carbon. The outcomes of the assessment can guide decision-making in design for disassembly (DfD) strategies and/or aid in the identification of high-value material recovery strategies at the end-of-life stage.

1. Introduction

1.1. Material efficiency and the circular economy

Building elements require energy and resource inputs from the natural environment throughout their life-cycle: at the construction stage throughout operation and at end-of-life. Reusing components directly, reduces waste to landfill and obviates the energy required for recycling the component. Therefore, the decision that a building or building element has reached its end-of-life and the associated choice of what to do with the unfit element, has important consequences for the overall resource use and environmental impacts of buildings [1,2]. Stahel [3] set out a vision to minimise the strain on natural resource reserves and eliminate waste by extending the lifetimes of existing products (Fig. 1).

The principles of the circular economy (CE) are based on Stahel's theory of product life alternatives [3]. CE strategies minimise resource input and waste, emission and energy leakage by incorporating design strategies that close, slow and narrow existing resource loops [4–7]. At the design and fabrication stage, this entails seeking: light-weight designs; more efficient use of natural resources and low-carbon materials; and improved production yields [8–11]. At the product use and end-of-life stage, it demands: more intensive product use e.g. increased use intensity of buildings through flexible functionality for different users at different times of the day; improvements in durability; effective maintenance; repair, reuse, remanufacturing and refurbishing; and high-value recycling [12,13]. Material reuse emerges as one of the most promising CE strategies for reducing greenhouse gas emissions in the EU construction sector [14].

Evermore stringent energy performance standards will necessitate higher rates of building refurbishment [15–18]. It is essential to develop material recovery methods that retain the embedded environmental value of building elements that are replaced in the process of refurbishment. Designers and builders, do not typically make end of life provisions for systems during the design stage [19–21]. This leads to technical and economic constraints at the end-of-life stage that hinder high-value recovery, which is compounded by the increasing

* Corresponding author.
E-mail addresses: R.C.Hartwell@tudelft.nl (R. Hartwell), M.Overend@tudelft.nl (M. Overend).

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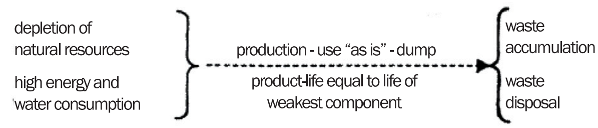
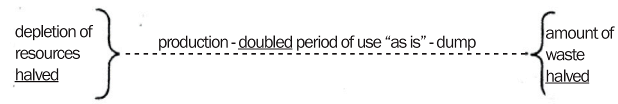
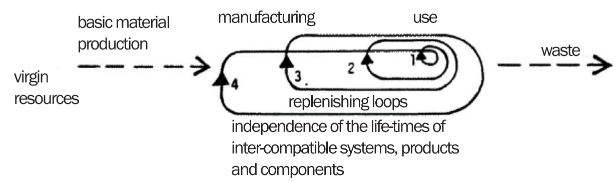


(a) "The fast replacement system" synonymous with short-life, incompatible goods and products characterized by lack of repairability [Stahel, 1982].



(b) "The slow-replacement system (long-life products)" achieved through exploring methods that increase the durability of existing products [Stahel, 1982].



(c) "The self-replenishing system" through product-life extension which seeks to minimise resource-depletion, energy-flow and environmental deterioration without restricting economic growth or social and technical progress [Stahel, 1982].

Fig. 1. Three basic approaches to product life alternatives proposed by Stahel [3].

complexity of contemporary building elements. However, reuse strategies have been successfully deployed in a small number of buildings by focusing on more thorough deconstruction processes and sourcing locally available materials [22–27]. These pioneering examples provide only a limited insight on the applicability to other buildings and the scalability of the approach to the mainstream construction industry on the basis of environmental impact, financial cost, occupant satisfaction and aesthetics.

1.2. Durability and adaptability: Influence of multi-component/multi-material systems

The long lifespan of buildings makes it difficult to predict which materials will have salvage value and what technologies will be available to extract materials at the building end-of-life. The multi-component nature of building elements means that whilst some components may have reached their end-of-life, other components may be perfectly functional. Façade systems for example, are designed to warrant a typical design life of 60 years as defined by BSI [28]. They may not perform to their full functional performance throughout this period. The incorporation of components with shorter service lifetimes such as polymer gaskets and motorised components leads to short replacement cycles which will contribute to recurring additions of resource use, during the building lifetime (Fig. 2). The effective recovery and reuse of constituent components for a second usage cycle thus presents itself as an important alternative to directly reusing the whole system.

1.3. Life-cycle assessment

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 product life-cycles. Various environmental indicators can be evaluated including, amongst others: non-renewable energy (NRE), renewable energy (RE), global warming potential (GWP), eutrophication potential (EP), ozone depletion potential (ODP), and abiotic depletion potential (ADP) [31–34]. BSI [33] provides guidelines for the life-cycle stages to consider when conducting an LCA (Fig. 3). Life-cycle stages are identified as: product manufacture and construction (Stage A); product operation and use (Stage B); end-of-life handling and disposal (Stage C); and product recovery (Stage D). The environmental impacts associated with *material use* (Stages A1–A5, B2–B5, C1–C4) and *operation* (Stages B1, B6–B7) are respectively referred to as the embodied- and operational-impacts.

The environmental impacts associated with the initial embodied stage associated with products (Stages A1–A3 on Fig. 3) and the trade-offs with operational energy (Stage B6 on Fig. 3) has received significant attention in existing academic literature on LCAs in the built environment [35–40]. These studies provide valuable information on the upfront environmental impact of buildings. Benefits and loads beyond the system boundary (Stage D), provides 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 takes place beyond the system boundary. This is one of the most complex stages to model [41] because there is no consensus on how to integrate the potential benefits [42,43], in particular there are concerns surrounding double-counting potential benefits [2,44]. For example, if the first cycle of aluminium framework receives credit for sending the framework for reuse and the second cycle receives the framework burden-free, the overall impact of initial production would not be accounted for. For these reasons, existing standards [33,34] and relevant guidance in the construction industry [45,46] advise for module D data to be communicated separately i.e. not aggregated within life-cycle stages A–C. There are additional concerns surrounding data uncertainty [47] and uncertainty in the actual recovery route deployed. For example, including the benefits of recycling components when in practice it ends up being disposed of in landfill. These uncertainties lead to over-simplifications or complete omission of the end-of-life and product recovery stages [48,49].

1.4. The missing link: End-of-life specific metric

Until recently, sustainable product recovery in the form of evidence-based decision-making received little attention within the built environment. Building elements are typically multi-component systems consisting of a variety of materials and connection types that fulfil specific functions, designed and maintained by a global supply-chain. Generally, deconstruction takes place between elements, components and systems which have different functional and technical lifetimes.

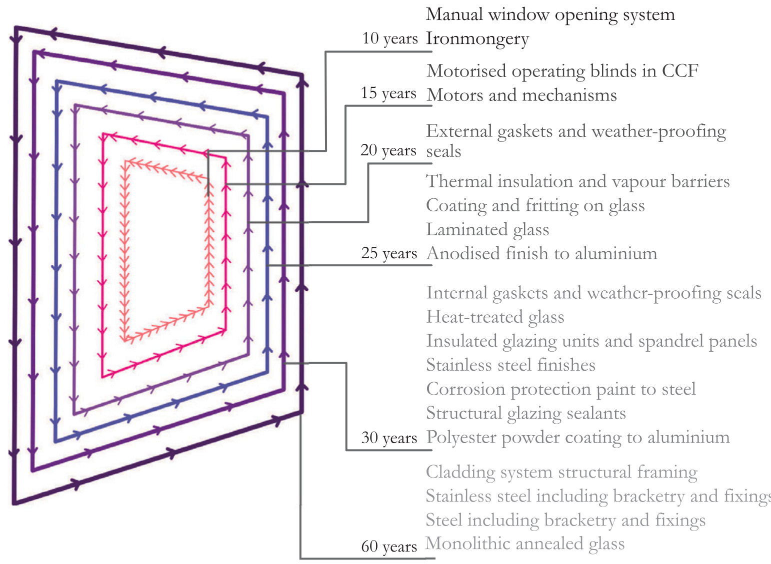


Fig. 2. "Shearing layers" concept by Brand [29] applied to the components in a contemporary façade system [30]. Façade design life data was obtained from industry recommendations.

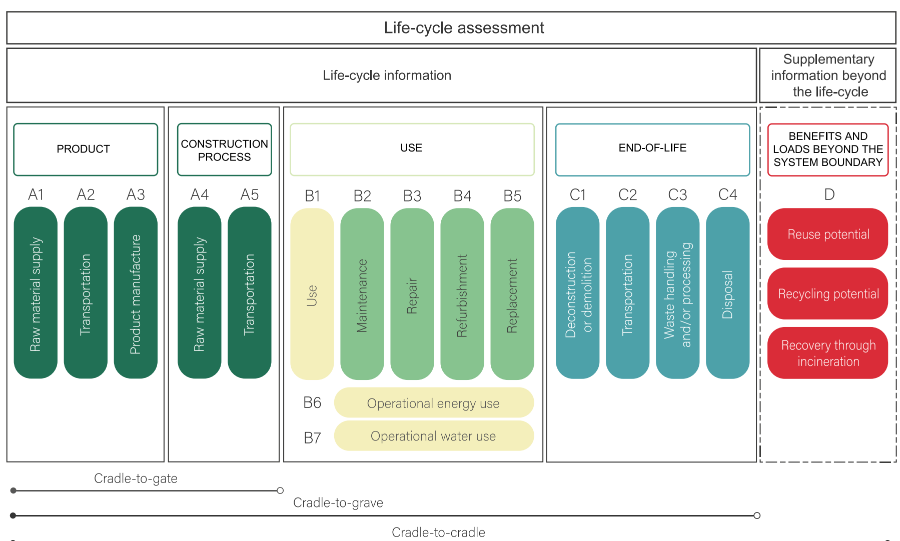


Fig. 3. Stages to include in a life-cycle assessment as specified by BSI [33].

A systematic quantitative method for understanding the influence of key design and specification decisions on resource use across multiple building life-cycles is essential.

The accounting of benefits beyond the first primary life-cycle has been the subject of recent review in academic literature. Anderson et al. [43], Eberhardt et al. [50] suggest that European standards and metrics for reuse and technical recovery are underdeveloped and call for new multi-dimensional frameworks, methods and tools to assess waste management and resource recovery that address complex value and evaluate trade-offs that arise from interventions in resource recovery. Existing LCA studies typically exclude comparisons between alternative end-of-life (EOL) scenarios/recovery methods [2,43]. A lack of knowledge and assessment methods related to the options for second use [42,49], specifically for assessing multi-component systems [38,51], means that the environmental impacts attributed to life-cycle stages C and D, and design methods to improve EOL performance are rarely investigated [43]. A review of the existing efforts to address these shortcomings is detailed in Appendix A.1. Some of the more simplistic assessments assess the reuse or recycling potential based on the initial material inputs [52,52,53], initial embodied environmental impact with [54,55], and without [56–64], the incorporation of a quality correction factor for down-cycling or performance deterioration. Eberhardt et al. [44] developed an approach to account for module D benefits across multiple life-cycles but does not account for performance deterioration. Other methods that have recently been developed outside LCA introduce an end-of-life index which considers system configuration and ease of dismantling [65–69] and taxonomies of CE indicators [70]. There is an absence of a unified assessment that adequately accounts for: data availability; design complexities in system configuration, where existing assessments typically analyse single-component mono-material systems; consideration of biological cycles; complexities of replacement cycles and uncertainties in service lifetimes; comparisons between alternative recovery scenarios; consequences of material down-cycling; and guidance for designers on how to improve [71,72]. This leads to challenges in evaluating new and existing designs based on their ability to support the circular economy and minimise waste. Recovery options that are typically considered more environmentally favourable, such as direct system reuse, may not be practical when service life and connection methods are taken

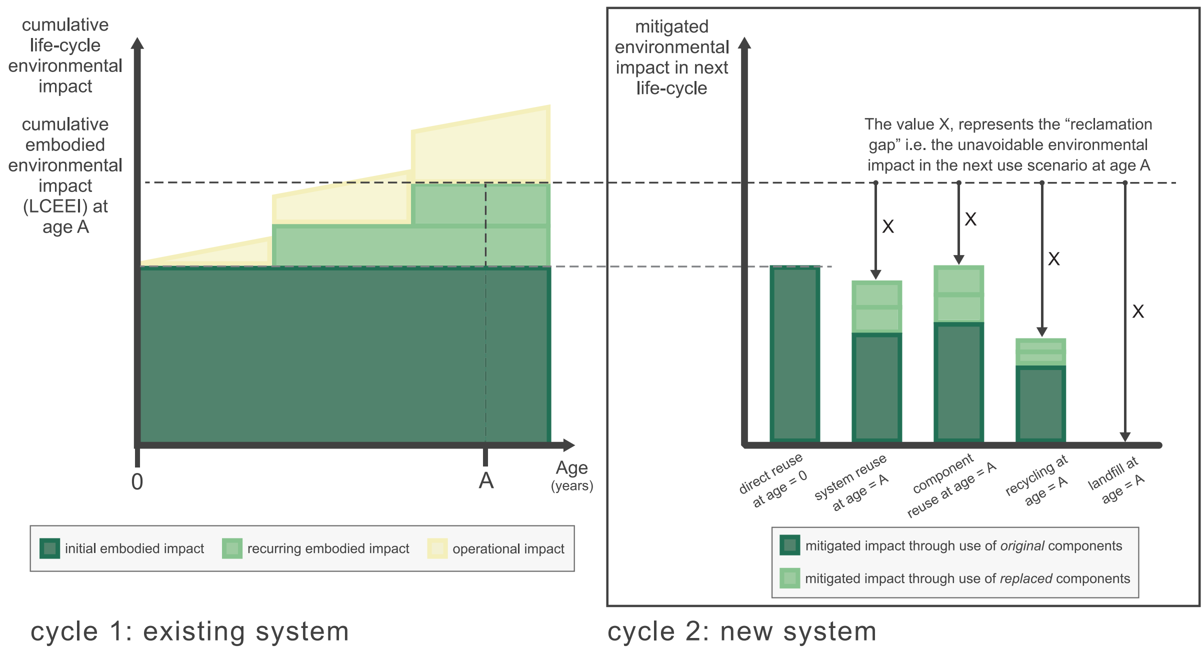


Fig. 4. Schematic representation of cumulative life-cycle environmental impact as a consequence of resource inputs across the building life-cycle in the existing system (L) corresponding mitigated environmental impact arising from the use of original and replaced components in a new system through different recovery scenarios (R).

into account. As such, it is essential to develop an approach that considers service life, specifically in the case of building components with typically long lifespans and; separation capability to enable reuse when comparing different end-of-life scenarios.

1.5. Aim of new approach

This study will explain the development of a new methodology that links the unique features of building elements with a newly developed quantity termed the *reclamation potential* (RP) to:

- Assess the impact of multi-component systems based on the service lifetimes of constituent components and connection methods on the lifetime embodied environmental impact;
- enable an understanding of how design choices, in terms of material selection and connection methods, inhibits or promotes the exploitation of certain recovery routes;
- assess and compare recovery routes based on their efficacy in promoting material efficiency;
- reflect the true value of material after its first use which could be measured in terms of environment, economics or society;
- credit "whole-life" design which accounts for durability *and* design for disassembly over multiple life-cycles with consideration for life-cycle modules A1–A5, B5, C1–C4 and D (Fig. 3);
- support decision-making at the refurbishment/end-of-life stage to promote materially-efficient recovery routes.

The overall aim is to create a robust framework to enable a quantitative assessment of reclamation potential to generate an informed environmental impact ranking of alternative recovery strategies and highlight favourable design and disassembly strategies that enable more materially-efficient designs. The outline of the new approach is described in Section 2, followed by its application to a real-world building system in Section 3. A discussion of the key findings from the application of the method is detailed in Section 4, followed by key conclusions and recommendations in Section 5.

2. New approach for measuring end-of-life reclamation potential

2.1. Outline of approach

The new end-of-life metric termed the reclamation potential (RP) is assessed with reference to the *Life-cycle Cumulative Embodied Environmental Impact* (LCEEI). The LCEEI can take the form of environmental impact categories including, amongst others: energy (MJ); global warming potential (GWP) in terms of kgCO_2-eq emissions; and abiotic depletion potential. The LCEEI is assessed based on the initial input materials prior to use (Stage A in LCA - Fig. 3) including the impacts of extraction, sourcing, processing, transportation, fabrication and construction and additional inputs related to the replacement of components throughout the lifetime of the system (Stage B5 in LCA - Fig. 3). The ability to replace components is dependent on the way in which they are connected which are categorised as 'reversible' or 'irreversible' connections. An example of the LCEEI of the first cycle of use is shown on Fig. 4.

The mitigated environmental impact (MI) in the second usage cycle of the system (Fig. 4) is evaluated as the impact of savings associated with systems, components and/or materials that could fulfil the same function in place of primary raw materials in the next product cycle. Service life uncertainty is considered by developing a probabilistic approach to assess the MI as a function of time.[1] The reclamation potential (%) is then evaluated as the net of the MI and costs associated with end-of-life management (Stage C in LCA - Fig. 3) divided by the LCEEI. The reclamation potential (RP) at a given age A, is assessed for alternative end-of-life (EOL) recovery scenarios. These scenarios are based on conceivable future recovery scenarios and take the form of system reuse (SYS-RE), component reuse (COMP-RE), recycling and energy recovery through incineration (RECYC), and landfill (LFILL). Life-cycle stages B1–B4 and B6–B7 are not considered in the proposed methodology.

[1] Probabilistic approaches to service life monitoring have been by proposed by Ellingham and Fawcett [73], Fawcett et al. [74] for assessing whole-life costing for buildings.

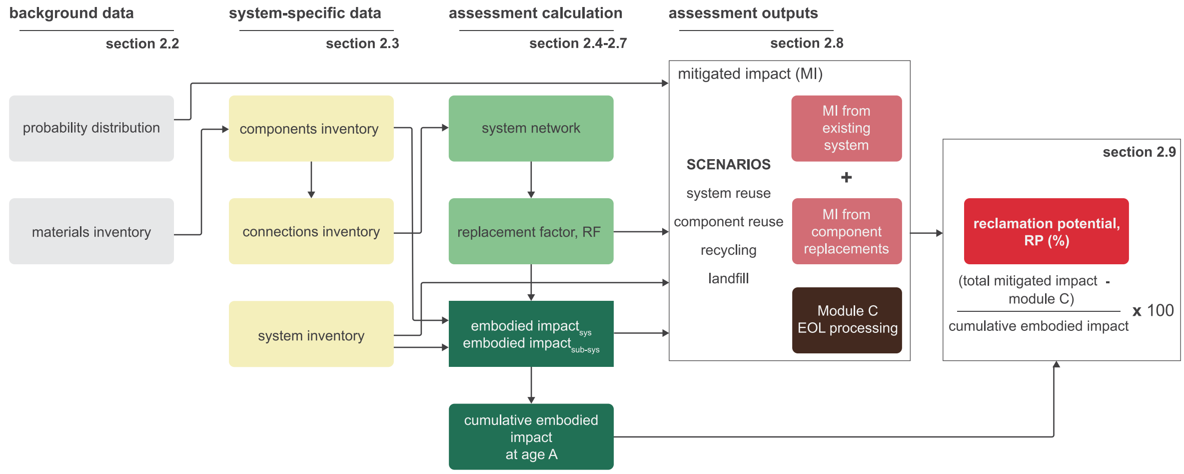


Fig. 5. Key stages in the newly developed assessment for cumulative life-cycle embodied environmental impact (LCEEI), mitigated impact and reclamation potential (RP).

The salient steps in the newly developed assessment framework are shown in Fig. 5. The inputs for background- and system-specific data are assembled based on a manual inspection of material datasets, construction drawings and system details as described in Sections 2.2 and 2.3 respectively. A bespoke Python library was developed by the authors to perform the assessment calculations. The formulas used to perform these calculations are detailed in Sections 2.4 to 2.8. Finally, an explanation of the assessment outputs is given in Section 2.9.

2.2. *Assessment inputs: Background data*

2.2.1. *Materials inventory*

The first stage of the assessment involves assembling a bespoke materials inventory which contains reference data concerning the environmental impact associated with materials and processes, recycling options, transportation, construction, demolition and deconstruction (Appendix B.1). Environmental impact inventory data related to materials and their upstream (extraction, sourcing and processing) and downstream (fabrication, transportation) processes is selected based on guidelines from ISO-14044 [75] and compliance with ISO-14040 [31]. Where geographical-specific datasets are used, care should be taken to ensure that data is representative of typical European production. Primary raw material data (EI_{PRM}), where the environmental impact coefficients are based on 0% recycled content, is used to calculate the *initial* and *recurring* embodied impacts. Each material is mapped to its second application based on the existing available recycling infrastructure. The environmental impact (EI) associated with reprocessing ($EI_{Reprocessing}$) for each material is defined as the environmental impact associated with the production of the same material with 100% recycled content. A transportation coefficient *TF*, is determined for each material which evaluates the EI per kg based on the transport mode (e.g. lorry, rail, ship) and transportation distance associated with the removal of material from the construction site to reprocessing facility as shown in Eq. (1) where DTF is the distance-weighted transport coefficient, associated with transportation by lorry, rail and ship (Appendix B.1).

$$TF\,(EI/\text{kg}) = DTF\,(EI/\text{kg.m}) \times Transport\ distance\,(\text{m}) \tag{1}$$

2.2.2. *Service life distribution*

The RP assessment accounts for deterioration in performance, by means of a service life factor, which is used to evaluate the reclamation potential in the *direct system*- or *component-reuse* scenarios. Measured real-life service life data for buildings is sparsely populated. Manufacturers typically issue a single-point estimate for the technical service life of components however exact predictions of the period of time before physical deterioration are not realistic [73]. A probabilistic approach to service life approximation based on existing mathematical distributions is utilised in this work to quantify the probability of survival over a given period of time.

Both the lognormal and Weibull distributions are often used in reliability engineering to model the probability that an item will perform to a required function without failure under stated conditions over a period of time [73,76]. The lognormal distribution provides a good fit for the performance of systems that display wear-out characteristics [76]. It corresponds to a relatively low probability of failure in the first few years of a component's service life, and a small probability of a very long service life which is similar to the empirical service life data from building components [77]. The lognormal probability distribution function and corresponding cumulative distribution function are shown in Eqs. (2a) and (2b) respectively [76].

$$f(t) = \frac{1}{\sigma t (2\pi)^{0.5}} \times \exp\left[-\frac{1}{2}\left(\frac{\ln t - \mu}{2\sigma^2}\right)^2\right] \tag{2a}$$

$$R(t)_{lognormal} = \int_{\infty}^{t} f(t)\,dt \tag{2b}$$

Where t is a specific time interval and μ, and σ, represent the mean and standard deviation of the $\ln(data)$, respectively.

The Weibull distribution is often used by reliability engineers to fit the lifetime distributions of mechanical parts [76]. The parameters of the Weibull distribution can be modified to fit the lifetime data of a system/component. The likelihood of failure may be increasing (e.g. due to wear-out failure such as fatigue), decreasing (e.g. due to burn-in rate of parts), or constant (characteristic of maintenance-induced failures of equipment) [76]. The cumulative distribution function for the two-parameter Weibull distribution can be calculated through Eq. (3).

$$R(t)_{Weibull} = \exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right) \tag{3}$$

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%.

For the RP assessment, a combined lognormal-Weibull distribution – where wear-out failures are described by the former and early failures are described by the latter – is used to model the service life of the sub-systems and components in building products. The probability of survival for systems and individual components over time t, is thus calculated through Eq. (4).

$$P_s(t) = 1 - R(t)_{lognormal} - R(t)_{Weibull} \tag{4}$$

Alternative probability distributions could be used in the RP-assessment method. This is particularly useful if empirical data on the performance of a system become available. The probability of survival of a system/sub-system is evaluated as the product of the probability of survivals of all components in that system/sub-system, as described in Eq. (5).

$$P_s(t)_{SYS} = \prod_{i=1}^{n} P_s(t) \tag{5}$$

Where i, describes the first component in the reference sub-system/system and n, is equivalent to the total number of components in the sub-system/system.

2.3. Assessment inputs: System-specific data

2.3.1. Components inventory

A functional unit must first be selected as a reference basis for the different end-of-life recovery scenarios. Construction drawings and associated bills of materials supplied by relevant manufacturers can be used to establish a list of the components that constitute the functional unit. The list of components is assembled into a *components inventory* database that details the unique component type; component mass (kg); and material type. The material type is linked to the materials inventory (Section 2.2.1).

2.3.2. Connections inventory

The construction drawings will then require systematic inspection to deduce the number and type of connections between components. All components in the system will be connected to at least one neighbouring component. The type of connections will be listed in terms of type and ease of separation - 'reversible' or 'irreversible' - in the connections inventory. The list of connection types and justification for reversibility can be found in Appendix B.2.

2.3.3. Systems inventory

Based on the selected functional unit, a system data inventory is assembled to provide environmental impact coefficients per unit mass, specific to the system for life-cycle stages A3, A4, A5, C1, C2 and C4 (Appendix B.3).

2.4. Cumulative life-cycle embodied environmental impact: Modules A1-A5, B5

The cumulative life-cycle embodied impact of a multi-component system for a specific environmental indicator (LCEEI) is calculated from:

$$LCEEI = Initial\ Embodied\ Impact_{SYS} + Recurring\ Embodied\ Impact_{SYS} \tag{6}$$

2.4.1. Initial embodied impact

The initial embodied impact is evaluated as the environmental impact associated with life-cycle modules A1 to A5. The environmental impact (EI) associated with life-cycle modules A1 and A2 for the system can be evaluated using Eq. (7).

$$Initial\ (A1 + A2)_{SYS} = \sum_{i=1}^{n} (EI_{PRM}(EI/kg) \times Mass_c(kg)) \tag{7}$$

Where c, refers to component, i, describes the first component in the reference system, n, is equivalent to the total number of components in the system, and EI_{PRM} refers to the equivalent environmental impact of life-cycle stages A1+ A2, for the reference material as listed in the materials inventory (Section 2.2.1).

$A3$ is equivalent to the environmental impact associated with the fabrication of materials and/or components into a reference system. The transportation of the system to construction site/point of use is described in life-cycle stage $A4$, where the system transport factor ($A4_{\text{coeff}}$) is evaluated based on the relevant transportation modes and distances (Eq. (1)). $A5$ is equivalent to the environmental impact associated with the construction processes on-site (Appendix C.1). Thus, the initial embodied impact of the system can be evaluated through Eq. (8).

$$Initial\ \ Embodied\ \ Impact_{SYS} = Initial\ (A1 + A2)_{SYS} + \left(Mass_{SYS} \times (A3_{Coeff} + A4_{Coeff} + A5_{Coeff}) \right) \tag{8}$$

Where $Mass_{SYS}$, is equivalent to the sum of the component masses in the reference system. The environmental impact coefficient associated with the system fabrication ($A3_{\text{coeff}}$), transportation to site ($A4_{\text{coeff}}$) and on-site construction activities ($A5_{\text{Coeff}}$) are provided in the *systems inventory*.

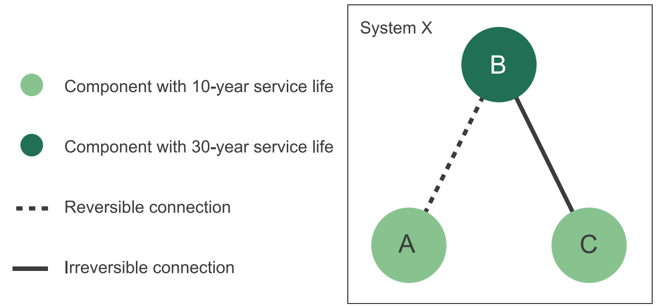


Fig. 6. Example of service life dependencies in multi-component systems.

2.4.2. Recurring embodied impact, B5

At the component replacement or end-of-life stage, the system can be deconstructed into consituent components. The ability to replace and recover parts is dependent on the ability to separate components from one another. In this way, the service life of one component, is dependent on the service life and/or deterioration of its nearest permanently connected neighbour component as shown in Fig. 6. The service life of a system/sub-system (SL_{SYS}) is therefore that of the component with the shortest service life as expressed by Eq. (9).

$$SL_{SYS} = min\{a_i, \ldots, a_n\} \tag{9}$$

Where i, describes the first component in the reference system/sub-system and n is equivalent to the total number of components in the system/sub-system.

For example, the service life of component A and component C in *system X* (Fig. 6) is equal to 10 years. Component B has a service life of 30 years. The irreversible connection between components B and C means that they cannot be separated into their individual components. Components B and C therefore remain as a sub-system of system X, with a service life equal to 10-years i.e. the service life and corresponding replacement of component B is governed by the service life of component C.

It is assumed that the components are replaced at the end of their service lifetimes. At a specific time interval or age t (years), the total number of replacements (TNR) of a specific component must be evaluated with reference to any irreversibly connected neighbours (Eq. (9)) through Eq. (10).

$$TNR = \frac{t}{SL_{SYS}} \tag{10}$$

Where the sub-system SYS, may consist of one or more components: it is the reference sub-system for the component after disassembly. The replacement factor (RF) for a specific component is evaluated based on the conditions explained in Eq. (11) where $\mathbb{W}$ denotes a *whole* number.

$$RF_c = \begin{cases} \lfloor \frac{t}{SL_{SYS}} \rfloor & if \text{ TNR } \neq \mathbb{W} \\ (\frac{t}{SL_{SYS}}) & if \text{ TNR } = \mathbb{W} \end{cases} \tag{11}$$

The recurring embodied impact of the system is evaluated as shown in Eq. (12).

$$Recurring\ EI_{system} = \sum_{i=1}^{n}(RF_c \times EI_c) + \sum_{i=1}^{n}\Big(RF_c \times Mass_c \times (A3_{Coeff} + A4_{Coeff} + A5_{Coeff})\Big) \tag{12}$$

Where c, refers to component, i, describes the first component in the reference system, and n, is equivalent to the total number of components in the system/sub-system.

2.5. Recovery routes

The four end-of-life scenarios developed in this assessment take the form of system reuse (SYS-RE), component reuse (COMP-RE), recycling and energy recovery through incineration (RECYC), and landfill (LFILL). At present, the most common end-of-life scenario within industry is either: demolition for LFILL or dismantling for RECYC. The SYS-RE and COMP-RE scenarios therefore refer to idealised situations, where reuse is made possible via the implementation of disassembly operations and suitable project-matching.

2.6. System network and component interdependencies

Connection diagrams based on the work of Lambert and Gupta [78] are particularly useful for this assessment. A connection diagram is an undirected graph where the nodes represent the components and the edges represent the connections between components. Connection diagrams can help to highlight the disassembly operations required for product recovery and any technological challenges in disassembly. Based on the component- and connections-inventory (Section 2.3), a network diagram is automatically generated for the functional unit where the nodes represent the components in the system and contain relevant material information. The edges of the network diagram represent the connections between components and their level of reversibility. The network diagram thus provides all the necessary data to evaluate the reclamation potential arising from: (i) the existing system in the component reuse recovery scenario; and (ii) component replacements over the age of the system in the system and component reuse recovery scenarios. The network diagram uses the Python *NetworkX* package [79]. In the deconstruction step, the system will be split into its constituent components and/or sub-systems based on the connection type: reversible or irreversible (Section 2.4.2). The ratio of sub-systems to individual components thus provides an early indicator into the ability to easily recover individual components.

2.7. End-of-life handling: Module C

Module C is evaluated with reference to the current system installed at time t (years), and the components that are replaced throughout the life-cycle before t. For each replacement (Section 2.4.2), there is an associated environmental impact for module C. Thus a system replacement factor (SRF), that accounts for all of the replacements of constituent components/sub-systems in the system over a specific time period, t, is calculated using Eq. (13).

$$SRF = \sum_{i=1}^{n}(RF_i \times \frac{mass_i}{mass_{SYS}}) \tag{13}$$

Where RF is equal to that calculated in Eq. (11), i, represents the first component in the system, and n, the total number of components in the system.

The relevant quantities for evaluating the end-of-life stage (life-cycle stages C1 to C4) will vary depending on the recovery scenario (Appendix C.2). The total contribution of life-cycle stages C1 to C4 for SYS-RE, COMP-RE, RECYC, and LFILL, are calculated using Eqs. (14a), (14b), (14c), and (14d), respectively.

$$Module\ C = Mass_{SYS} \times \Big(1 + SRF(C1Decon_{Building} + C2Transport_{SYS})\Big) \tag{14a}$$

$$Module\ C = Mass_{SYS} \times \Big(1 + SRF(C1Decon_{Building} + C2Transport_{SYS} + C3Decon_{SYS})\Big) \tag{14b}$$

$$Module\ C = Mass_{SYS} \times \Big(1 + SRF\ \big(C1Decon_{Building} + C2Transport_{RecycledMaterial} + C3Reprocess_{Material} + (0.1 \times C4Disposal_{Landfill})\big)\Big) \tag{14c}$$

$$Module\ C = Mass_{SYS} \times \Big(1 + SRF(C1Demol_{Building} + C2Transport_{WasteMaterial} + C4Disposal_{Landfill})\Big) \tag{14d}$$

Where $C1Decon$ and $C1Demol$ refer to building deconstruction and demolition respectively, $C2Transport$ refers to transportation, $C3Decon$, refers to system deconstruction, $C3Reprocess$, refers to reprocessing, and $C4Disposal$ refers to landfill disposal. The RECYC scenario considers a 10% yield loss of materials at the reprocessing stage, hence why Eq. (14c) includes a factor for landfill disposal.

2.8. Mitigated environmental impact: New approach to Module D

The mitigated environmental impact (MI) is a measure of the savings 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 as a consequence of component replacement (REPL) up to age t, are evaluated, as represented by Eq. (15).

$$MI_{EI} = MI[CURR]_{EI} + MI[REPL]_{EI} \tag{15}$$

2.8.1. Current system

The mitigated impact of the current system $MI[CURR]$ in the SYS-RE scenario is dependent on the service lifetimes of its constituent components and sub-systems. Eqs. (5) and (8) can be substituted into Eq. (16) to evaluate the MI of the current system in the SYS-RE scenario.

$$MI[CURR]_{SYS} = P_s(t)_{SYS} \times Initial\ Embodied\ Impact_{SYS} \tag{16}$$

The COMP-RE scenario involves splitting the system into its constituent components and sub-systems (Sections 2.6 and 2.2.2). The mitigated impact of the current system in the COMP-RE scenario is evaluated through Eq. (17).

$$MI[CURR]_{COMP-RE} = \sum_{k=1}^{m}\Big(P_s(x)_j \times Initial\ Embodied\ Impact_j\Big) \tag{17}$$

Where j, is equal to a component/sub-system of interest, x, represents the current age of a specific component or sub-system, k, is equal to the first component/sub-system in the complete system, and m, represents the total number of components/sub-systems in the complete system. At system age t, the current age x, for each component or

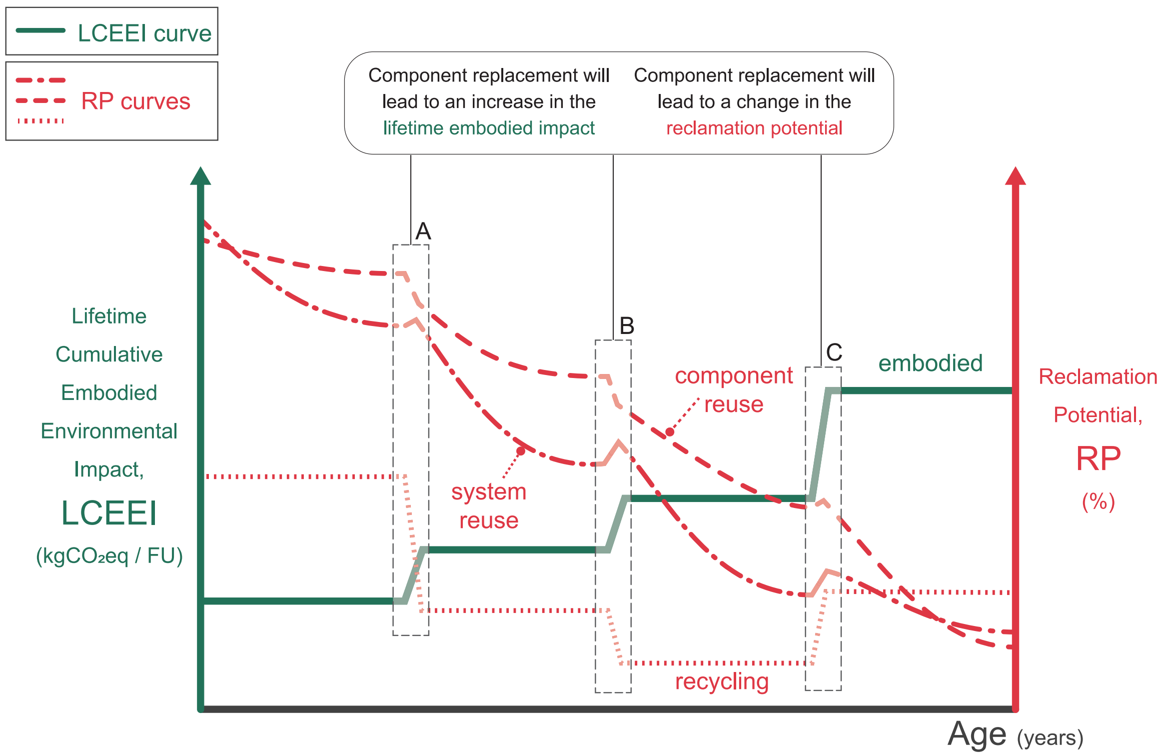


Fig. 7. Schematic RP assessment outputs showing the lifetime cumulative embodied environmental impact e.g. embodied carbon ($kgCO_2$-eq/unit) on the left y-axis and reclamation potential (%) on the right y-axis as a function of time (years). The green dashed curves represent recovery scenarios. The blue solid line represents the lifetime cumulative embodied impact.

sub-system will vary, depending on the minimum service life of the component or sub-system. For each component or sub-system, the current age x, can be calculated using Eq. (18).

$$Age\ Factor \equiv t(mod(z)) \tag{18a}$$

$$x = \begin{cases} Age\ Factor & if \text{ Age Factor } \neq 0 \\ z & if \text{ Age Factor } = 0 \end{cases} \tag{18b}$$

Where z, is equivalent to the minimum service life of the component or sub-system, as defined by Eq. (9).

The mitigated impact of the current system in the RECYC scenario is not dependent on the system age. The mitigated impact through recycling for each material is evaluated as the environmental impact of processing the secondary application of the material from primary raw materials EI_{SA}, as defined in the materials inventory (Section 2.2.1). A 90% reprocessing yield is considered. The total mitigated impact of the current system through recycling is evaluated through Eq. (19).

$$MI[CURR]_{recycling} = \sum_{k=1}^{o}\left(0.9 \times EI_{SA} \times (\sum_{i=1}^{n} Mass_c)\right) \tag{19}$$

Where i, is equal to first component of material type M, n is equivalent to the total number of components of material type M, and k, is the first material type in the system and o, is the total number of unique materials in the system.

In the landfill scenario, all materials are disposed of in landfill. Unlike the other end-of-life routes, the mitigated impact is equal to zero.

2.8.2. Replacement of components

The mitigated impact associated with replacement (REPL) is only applicable if t, is greater than the service life of the system, as expressed by Eq. (20).

$$MI[REPL] = \begin{cases} 0 & if \quad t \leq \text{ System Service Life} \\ MI[REPL] & if \quad t > \text{ System Service Life} \end{cases} \tag{20}$$

In the SYS-RE and COMP-RE scenarios, it is assumed that all replaced components/sub-systems are recovered for component or sub-system reuse. The $MI[REPL]$ is evaluated through Eq. (21).

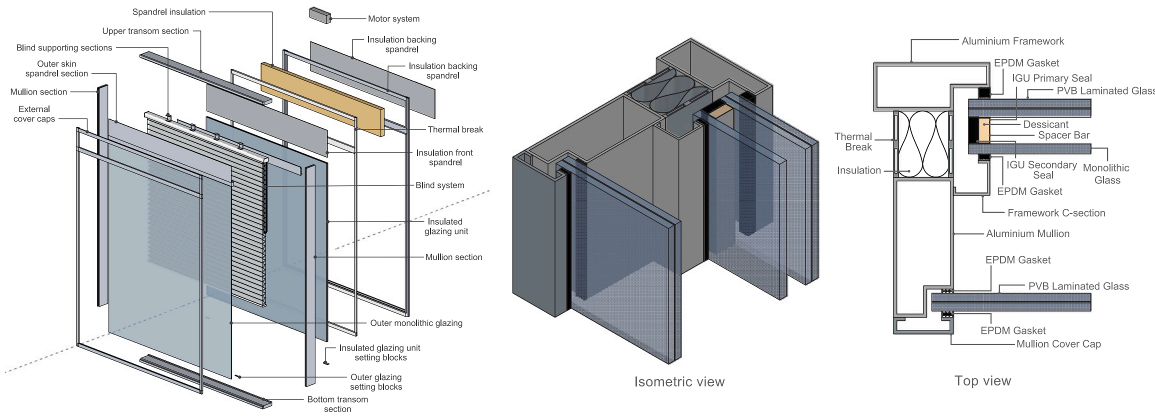
$$\sum_{j=1}^{m} MI[REPL]_j = \sum_{r=1}^{RF_c}\left(P_s(x_a)_j \times Initial\ Embodied\ Impact_j\right) \tag{21}$$

Where j, describes the first component/sub-system in the complete reference system; r, is equal to the first instance of a replaced component/sub-system; RF_c is equal to the replacement factor (see Eq. (11)); and m, is equivalent to the total number of components/sub-systems in the system. $P_s(x_a)_j$, is evaluated through Eq. (5), where the age of the replaced component/sub-system x_a, is specific to the instance of the replaced component/sub-system. For example, if $t = 35$ years, an individual component with a service life of 15-years would have a replacement factor equal to 2. The $MI[REPL]$ for the component would thus be evaluated at $x_a = 35$ and $x_a = 20$.

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 $MI[REPL]$ is evaluated through Eq. (22).

$$MI[REPL]_{recycling} = \sum_{k=1}^{o}\left(\sum_{l=1}^{p}(RF \times 0.9 \times EI_{SA} \times Mass_{component})\right) \tag{22}$$

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 material type in the system; and o, is the total number of unique materials in the system.



(a) Exploded view of double-skin dry-gasket sealed closed cavity façade

(b) Interface features of double-skin dry gasket sealed CCF (cavity blinds not shown)

Fig. 8. Schematic sketch of the double-skin closed cavity façade.

2.9. Reclamation potential, RP (%)

The *reclamation potential RP* (%), at a specific time t (years), is evaluated by substituting Eqs. (4), (6) and (15) into Eq. (23).

$$RP\,(\%) = \left(\frac{(MI - Module\ C)}{LCEEI}\right) \times 100 \tag{23}$$

To visualise the outputs of the assessment, the lifetime cumulative embodied environmental impact (LCEEI) and RP (%) is plotted against time (years) on a *RP-graph*. The RP-graph is a novel means of comparing alternative recovery scenarios for a specific functional unit, as a function of time (years). Fig. 7 shows an example of an *RP-graph*.

The LCEEI is plotted on the left y-axis of the RP-graph shown on Fig. 7. For this example, GWP (kgCO_2-eq) is selected as the environmental indicator for comparison. The cumulative embodied carbon impact of the reference functional unit over time (years) is represented by the solid green curve. The LCEEI accounts for the initial and recurring embodied impacts (Section 2.4.2). Component replacement will therefore lead to an increase in the cumulative embodied carbon impact and a resultant step *up* in the LCEEI curve as illustrated at time intervals A, B and C on Fig. 7.

The RP (%) is shown on the right y-axis of Fig. 7 and the corresponding RP curves for system reuse (SYS-RE), component reuse (COMP-RE) and recycling (RECYC) are sketched in red. The curves will start at different values of RP (Eq. (23)) at year 0, depending on the environmental impact associated with Module C (Section 2.7) - end-of-life handling and processing.

The SYS-RE and COMP-RE depend on a probability of survival factor, thus their corresponding RP curves are non-linear. The RP is a function of the embodied impact of the current system plus that of those components and/or sub-systems that are replaced. Therefore the RP for the SYS-RE and COMP-RE scenarios will decrease over time due to the decreasing probability of survival of the existing system/components – up until the time they are replaced – and the decreasing probability of survival of components after they have been replaced. The system reuse curve is likely to decay more rapidly than the component reuse curve because the RP is a function of the *product* of the probability of survivals for system reuse in contrast to the *sum* of the probability of survivals for component reuse. In this way, the decay in the system reuse curve is highly dependent on the number of components in the system.

The SYS-RE and COMP-RE curves may exhibit an increase (step up) or decrease (step down) in RP at certain time intervals corresponding to the time when a component is replaced. The RP is a function of the added value of a new component/sub-system compared to the deteriorating value of replaced components/sub-systems and the added impact associated with disassembly/assembly operations. Component replacement will therefore affect system reuse and component reuse curves differently. A step up in the SYS-RE curve (intervals A, B and C on Fig. 7) implies that the positive effect associated with the increased probability of survival of the existing system (due to component/sub-system replacement) is more significant than the negative effect of decreasing probability of survival of replaced components/sub-systems and environmental costs of disassembly/reassembly of replaced components. Similarly, a step up in the COMP-RE curve (interval C on Fig. 7) implies that the effect of replacing of a new component and/or sub-system with a high probability of survival is greater than the effect of the decreasing probability of survival of replaced components/sub-systems. A step down in the curve (intervals A and B for COMP-RE on Fig. 7) would indicate the contrary and/or signify that the added impact associated with disassembly/assembly operations for replacing components outweighs the added value of the new replaced components.

The RP for the recycling recovery scenario follows a linear curve with steps up and down that correspond to the material type and mass of components in the original system and any component replacements that occur over time. At year 0, the RP (Eq. (23)) through recycling will depend on the: material type and mass of the components in the original system (Eq. (19)); and environmental impact associated with end-of-life handling and processing the materials in the original system (Eq. (14c)). At a time interval beyond year 0, the RP through recycling is proportional to the total RP of the existing system *and* the components that are replaced up until that point. Therefore, the resulting change in the RP curve for recycling will depend on whether the components that are replaced at a specific time interval have a total RP (Eqs. (19), (23) and (14c)) that is higher or lower than the RP through recycling of the current system plus that of the previously replaced components. As an example, we could consider a system composed of components that constitute 80% aluminium and 20% glass. Aluminium would typically exhibit a higher RP through recycling compared to glass (Section 3.1.4). Therefore, with all other things being equal, the replacement of a glass component would lead to a step down in the RP curve (interval A and B on Fig. 7) and the replacement of an aluminium component would lead to a step up in the RP curve for recycling.

The RP graph is an effective visual representation of the RP assessment and could be particularly useful in decision-making for example: (i) to identify the recovery scenario of an existing system that yields the greatest environmental benefit and (ii) visualise the impacts of alterations to a prospective design with reference to: material selection; component service lifetimes; and connection types between components.

Table 1
Properties of dry-gasket sealed double-skin closed cavity façade.

System	Total number of components	Total number of connections	Total number of sub-systems	System mass	System service life
Double-skin closed cavity façade	125	257	105	793.0 kg	15 years

3. Application of method

3.1. Functional unit

3.1.1. System overview

The new RP assessment method was applied to evaluate the reclamation potential of a dry-gasket sealed "double-skin" closed cavity façade (Fig. 8). The system consists of a thermally-broken aluminium frame with an 80% glazing ratio, an inner insulated glazing unit with an inner 10.76 mm-thick laminated glass pane and outer monolithic 6 mm-thick glass pane, an outer 10.76 mm-thick laminated glass pane, mineral wool insulation (within the aluminium frame), and motorised Venetian blinds installed inside the cavity.

3.1.2. System-specific quantities

The lifetime environmental impact in terms of total primary energy (renewable and non-renewable) and global warming potential (GWP-100) in terms of carbon dioxide equivalent (CO_2-eq) emissions was evaluated using the new method.[2] Material data inputs for life-cycle stages A1, A2 and C3, were taken from the *materials inventory* (Appendix B.1) and system-specific data inputs for life-cycle stages A3, A4, A5, C1, C2, C3 and C4, including transportation distances, are listed in (Appendix B.3).

3.1.3. Service life distributions

Technical service life data for each material was obtained through consultations with façade manufacturers (Appendix B.1). These values were used to define the parameters to fit the probability distributions that were evaluated through Eq. (4). For multi-component systems, distribution parameters for the lognormal and Weibull distributions were adjusted to fit a cumulative lognormal-Weibull distribution that produced a close fit to the [80] study on the failure of insulated glazing units over time. The selected parameters for the lognormal and Weibull distributions for multi-component systems and individual components are listed in Appendix D.

3.1.4. Second application routes

The second application for each material recovered for the RECYC recovery scenario (Section 2.6) was selected based on a review of existing available recycling infrastructure in Europe (Fig. 9). The material-specific mitigated impact based on the recycling route, excluding reprocessing losses, is presented in Appendix E.

3.2. Processing: System networks

The system network for the functional unit is shown in Fig. 10(a) and Table 1 presents the properties of the system in terms of: total number of components; total number of connections; total number of sub-systems after the deconstruction step i.e. once all reversible connections are removed; system mass; and system service life. Fig. 10(b) presents the system network for one of the resulting non-deconstructable sub-systems - an insulated glazing unit (IGU) - which arises after the deconstruction step has taken place.

[2] Global warming potential (GWP) can be measured over different time periods. The 100-year time period is typically used in literature.

3.3. Results

3.3.1. Initial embodied energy and carbon

The assessment outputs for the double-skin closed cavity façade show that material life-cycle stages A1 and A2 are found to be the most significant contributor to stage A life-cycle emissions, contributing 92% to the A-stage total. Unit fabrication (A3) constitutes 5% of emissions associated with stage A. Transportation of the unit from the point of fabrication to the site of construction (A4) contributes <1% of stage A life-cycle emissions.

The distribution of the initial embodied energy and carbon by material type for life-cycle stages A1 and A2, is shown in Figs. 11(a) and 11(b), respectively. The remaining 2% is attributed to on-site construction activities (A5). Glass and aluminium components account for 45% and 47% of the embodied carbon, respectively. Polymer components collectively account for up to 4% of the initial embodied carbon.

3.3.2. Reclamation potential

The total embodied energy and carbon increase over time as a consequence of additional material inputs associated with the replacement of components at the end of their respective service lifetimes. The cumulative embodied energy and carbon at 25-, 50- and 75-years is presented in Table 2. The replacement of blind system motors (DSFs) and gaskets represent a minimal contribution to the cumulative embodied carbon and energy. Every 25 years the glass embedded in the insulated glazing unit is replaced. At 25 years the cumulative embodied carbon is 62% higher than the initial embodied carbon. Anodised aluminium framework materials are replaced at 50-years. At 50-years, the cumulative embodied carbon increases by 254%. This margin increases to 322% at the 75-year time interval at which point all components in the system have been replaced at least once.

The reclamation potential (RP) for each recovery scenario at 0-, 25-, 50-, 75-, and 100-year intervals is detailed in Table 2. The added CO_2-eq emissions associated with life-cycle stages C1-C4 in the landfill recovery scenario at the 0-, 25-, 50-, 75-, and 100-year intervals are detailed in Table 2. All recovery scenarios show a reclamation potential well below 100 percent at year 0 because the environmental impact arising from re-fabrication, transportation, end-of-life handling and reprocessing are unrecoverable.

The reclamation potential (RP) graph is shown in Fig. 12. The mitigated impact and resulting RP in the LFILL recovery scenario are equal to zero and therefore not plotted in Fig. 12.

SYS-RE yields the greatest RP at year 0. From year-2, COMP-RE exhibits a higher RP than SYS-RE. In the first 25-year period, there is a rapid drop in the RP of SYS-RE. By year-14 i.e. the year before any components have been replaced, the RP has decreased from 91% (year-0) to 58% (−33%) in the SYS-RE scenario. In this same period, there is a marginal decrease in RP from 86% to 85% (−1%) in the COMP-RE scenario. After 25-years, the RP of COMP-RE decreases at a rate that is closer to that associated with the deterioration of RP in the SYS-RE scenario. Beyond the 25-year time interval, the *margin* in RP between the SYS-RE and COMP-RE scenarios varies between 3% and 28%. The margin widens in the time intervals between component replacements, and narrows at the year in which a component replacement occurs. The RP through RECYC fluctuates between 22%–36% over the 100-year period. The RP for SYS-RE remains higher than RECYC up to year-78, where the RP of SYS-RE falls to 22%. From year-2, the RP of COMP-RE remains higher than SYS-RE and RECYC across the 100-year period.

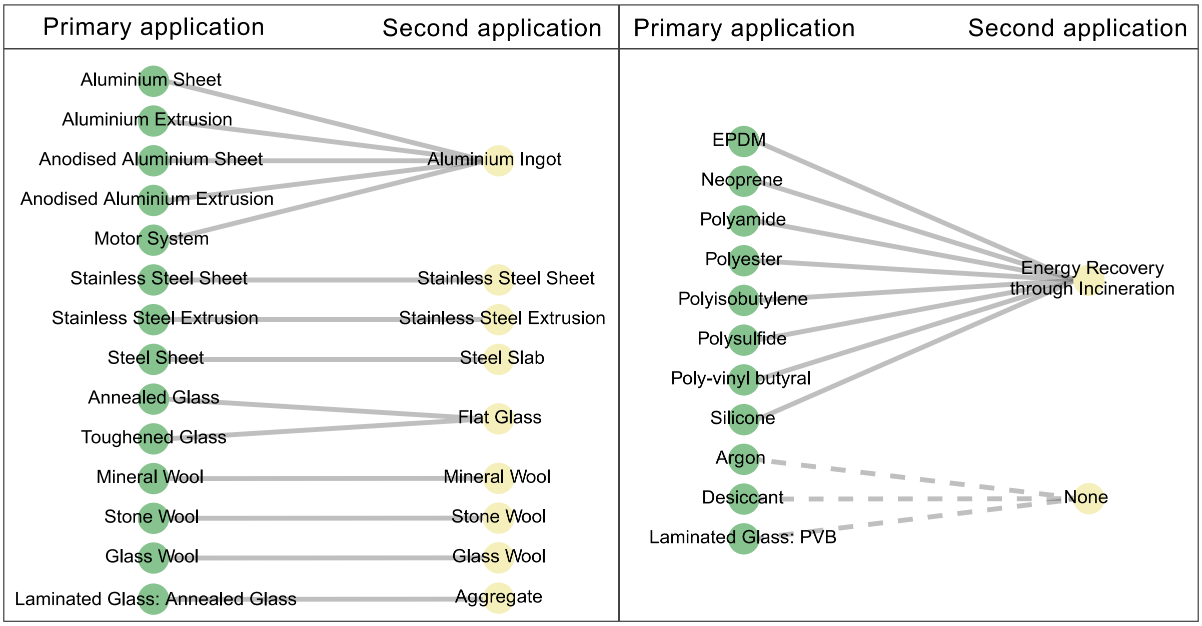


Fig. 9. Recycling routes for materials in the RECYC recovery scenario. The dark-shaded nodes represent the primary application and the light-shaded nodes represent the second application.

Table 2
Cumulative embodied energy and carbon (CEI) per m^2; reclamation potential for system reuse, component reuse and recycling; and additional CO_2 emissions for landfill disposal, at 0-, 25-, 50-, 75-, and 100- years.

Age	CEI GJ/m^2	CEI kg CO_2-eq/m^2	RP (%)				Added kg CO_2-eq/m^2: (LFILL only)
			SYS-RE	COMP-RE	RECYC	LFILL	
0-year	3.1	2.0×10^2	91%	86%	36%	N/A	2.1×10^0
25-year	5.1	3.2×10^2	65%	83%	23%	N/A	3.8×10^0
50-year	7.9	5.0×10^2	37%	46%	25%	N/A	5.7×10^0
75-year	10.2	6.4×10^2	25%	31%	22%	N/A	7.5×10^0
100-year	13.1	8.2×10^2	23%	26%	23%	N/A	9.4×10^1

4. Discussion

4.1. Findings from application: Embodied impacts

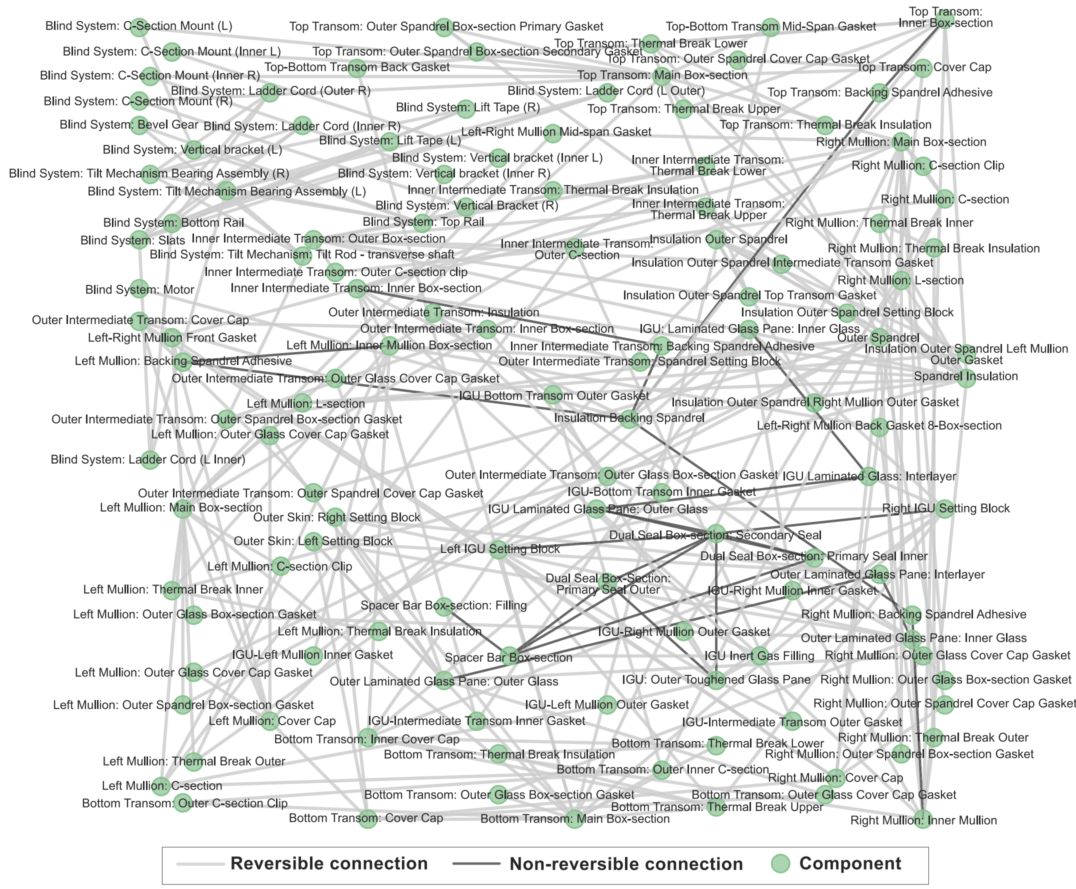
The initial embodied energy and carbon impacts (A1 to A5) for the double-skin closed cavity façade equates to 3.1 GJ/m^2 and 200 kgCO_2/m^2 respectively (Table 2). This is consistent with [36,81] and [82], the latter of which evaluated an initial embodied carbon equal to 210-350 kgCO_2/m^2 for glazed double-skin façades (DSFs) with stainless steel framework. This is almost double that of single-skin façade (SSF) typologies evaluated in literature [35]. DSFs typically perform better in operation compared to SSFs [83,84], though this can vary depending on climatic conditions [85]. Future investigations on the trade-offs between functional design factors [86] and the cumulative embodied energy/carbon, operational performance and reclamation potential would be highly valuable to evaluate the extent to which the additional embodied energy and carbon is offset by improved operational performance over the whole building life-cycle [87–89].

Glass and aluminium are the most energy- and carbon-intensive materials in the DSF, thus highlighting the need to increase levels of post-consumer recycled content in new production, to minimise their relative contribution to the upfront embodied impacts in buildings. The electrical motor systems are fitted outside the façade unit, meaning that they can be easily replaced without affecting neighbouring components or requiring complex disassembly operations. Therefore, their replacement has a very small effect on the cumulative embodied impact despite their 15-year service life. The replacement of insulated glazing units (IGUs) presents a different outcome. The individual glass panes in the IGU, have a reference service life of 60-years. Due to the nature of the IGU design, glass panes are permanently fixed within the IGU subsystem. Consequently, it is found that the replacement of the IGU at 25-year intervals has a significant impact on the cumulative embodied energy and carbon of the façade system (Fig. 12), thus highlighting the value in designing for shorter service life components to be easily accessible at the replacement stage and developing new protocols for efficient disassembly.

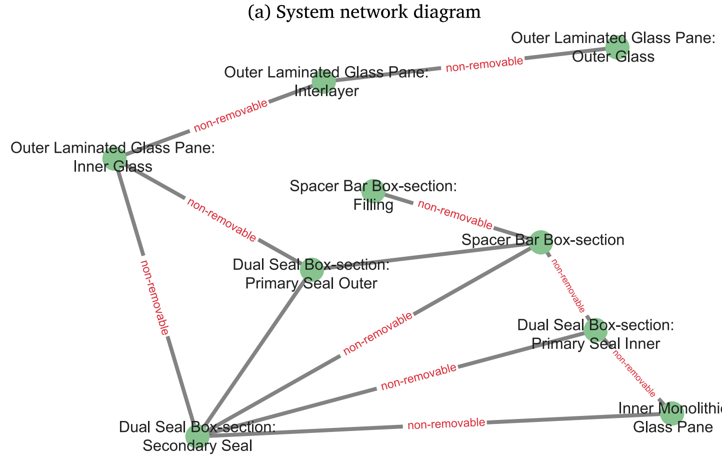
At 75-years, the cumulative embodied carbon exhibits a 322% increase compared to the initial embodied carbon. The magnitude of this increase is striking in the context of building design. Whilst primary load-bearing structural elements (e.g. structural floors, beams, columns) may contribute a greater proportion of the upfront embodied impacts associated with buildings, their design lifetimes may be 100 years or more. By contrast, it is evident through this work, that the complexity of service lifetimes in building envelopes can lead to lifetime embodied carbon impacts that are up to 4.1 times the initial embodied carbon impact over a 100-year time-frame.

4.2. Findings from application: Reclamation potential

Despite marginal relative year-on-year increases at certain time intervals, the RP through RECYC shows a general decreasing trend over the 100-year time period. This trend may be explained by the fact that the components with shorter service lifetimes (such as polymers and laminated glass) typically have a lower reclamation potential through recycling than components which typically exhibit longer service lifetimes (such as aluminium, steel and non-laminated glass). The RP through RECYC is never greater than 40%. This is due to the fact that



(a) System network diagram



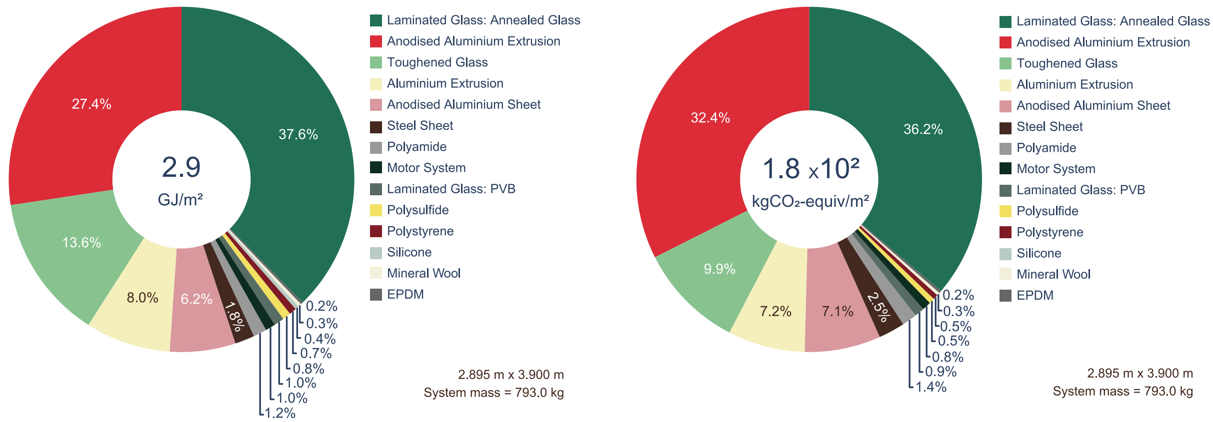
(b) Network diagram of IGU sub-system after deconstruction step where remaining constituent components can not be further disassembled

Fig. 10. System and sub-system network diagrams of dry-gasket sealed double-skin closed cavity façade.

the energy and CO_2 emissions associated with the *manufacture* of façade systems and constituent components will not contribute to avoided energy and CO_2 emissions in the secondary application through recycling. Based on the results for RP, from year-2, COMP-RE is the preferred recovery route for the double-skin façade assessed in this work. The RP for SYS-RE drops rapidly after the first few years. This is due to the fact that in contrast to COMP-RE, in SYS-RE the probability of survival of the system is governed by the lowest probability of any of its components (weakest link analogy). A key implication of this finding is that the recovery of *components* for reuse is more environmentally favourable than *direct system reuse* in the absence effective reconditioning methods.

4.3. Reclamation potential: Review of method

End-of-life impacts and benefits beyond the first life-cycle of building products are often overlooked. The assessment approach presented in this work provides a novel methodology for evaluating a newly defined quantitative value, reclamation potential (RP), to compare designs based on their end-of-life recovery potential in different scenarios. The evaluation of RP has been developed to handle multi-component systems based on their connection types and service lifetimes: life-cycle interventions related to component replacements are not only dependent on the service life of the independent component, but also that



(a) Initial embodied energy of system (GJ/m^2) (b) Initial embodied carbon of system ($kgCO_2/m^2$)

Fig. 11. Initial embodied energy and carbon per m^2 of double-skin closed cavity façade for life-cycle stages A1-A2.

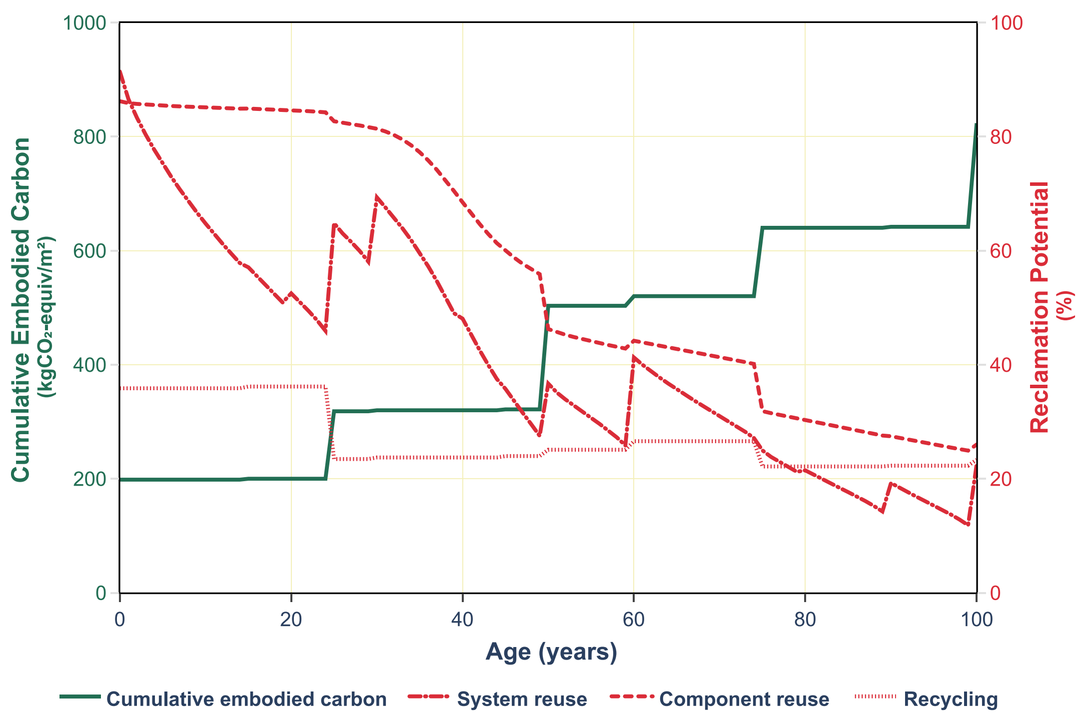


Fig. 12. RP-graph highlighting the life-cycle cumulative embodied carbon impact (LCEEI) per m^2 and reclamation potential (RP) for double-skin closed cavity façade. The solid curve represents the lifetime embodied carbon. The dashed lines represent the reclamation potential for the different recovery scenarios: system reuse, component reuse, and recycling over the 100-year reference study period.

of their permanently connected neighbours. Four key factors are evaluated in the course of the assessment of RP: the cumulative life-cycle environmental embodied impact (LCEEI) based on life-cycle stages A1-A5 and B5, environmental impact from end-of-life recovery operations (life-cycle stages C1-C4), mitigated environmental impact (MI), and the resulting reclamation potential (RP). In the evaluation of reclamation potential, the embodied impacts of materials are evaluated based on 0% recycled content to avoid double-counting energy or emission savings. The calculated value for MI goes beyond the basic evaluation of module D deployed in generic LCA, and considers a probability of survival factor for reuse options, that accounts for the service life of components and their parent systems. The mitigated impact through RECYC takes into account *material-specific* secondary applications based on available recycling infrastructure. In this way, the negative impacts of down-cycling are quantified. With the new RP method, it is possible to identify which recovery scenario is more environmentally favourable at a specific point in time. This enables a more comprehensive approach for seeking realistic design strategies and recovery scenarios that yield the highest RP, rather than assuming benefits through a more generic hierarchy.

4.4. Limitations and future work

The RP assessment developed in this work would benefit from further application to alternative façade typologies, structural systems and mechanical & electrical services, where a broad range of material palettes and construction techniques are deployed. The deconstruction of the system into sub-systems in the RP method described in this work is based on a binary measure for the reversibility of connections (reversible or irreversible). As such, no additional information is provided on other factors affecting ease of disassembly such as time and labour costs, or sequence of disassembly operations, which could be key factors in determining the viability of reusing components. Future development of the RP method could incorporate existing methods for evaluating connection types based on their disassembly potential and disassembly sequencing in the evaluation of reclamation potential [90–95].

The RP in the reuse scenarios on the example façade system is by no means conclusive. The sensitivity of SYS-RE and COMP-RE to the probability of survival factors used in this study highlight the need to develop improved test methods that quantify performance deterioration over time. For example, performance deterioration could be measured in terms of thermal performance for building envelopes, load-bearing capacity for primary load-bearing structural systems, or capacitance for electrical components. Data from performance tests could be incorporated into this assessment, such that each component and/or sub-system has its own probability of survival function that best represents selected performance indicators over time.

The reference materials inventory was selected based on ISO-14044 guidelines [75]. Various data sources were reviewed, including manufacturer-specific environmental product declarations, the Inventory of Carbon and Energy [96,97] and the EcoInvent database [98] (Appendix B.1). LCA remains a relatively new research field; new manufacturer-specific data continues to grow in accessibility. Future work should look to build a dynamic materials inventory that handles uncertainty based on: proportion and type of recycled content; variations in manufacturing yield losses; and reference energy sources for all materials [42,47,99–101]. Considerations for these factors were made when assembling the material inventory, to ensure that the data was representative of current European production. More research is necessary to examine the life-cycle implications of on-site construction and deconstruction activities. This may call for enhanced monitoring and reporting of on-site energy use and corresponding CO_2 emissions. Future development of the assessment would benefit from accounting for the generation and handling of material waste produced at the fabrication and construction site which can increase resource use by 10%–15% [102]. Given the comparative nature of the research presented in this work, the aforementioned data assumptions are considered valid. The output of this assessment should be handled with consideration for these assumptions.

All impacts evaluated in this study were based on the energy efficiency of existing manufacturing processes and relevant fuel/electricity supplies. In this way, it disregards future decarbonisation of electricity supply and assumes that the energy used and equivalent CO_2-eq emitted today generate negative impacts of climate change equal to those caused by future energy use and CO_2-eq emitted in the future. The first assumption may be considered reasonable, in light of the known technological challenges associated with improving supply-side efficiency to a level that matches growing energy demand [103–105]. Future development of the assessment may include a factor that considers the second assumption, often referred to as the *time value of carbon* [106].

Alternative design and recovery options, such as promoting deconstruction practices or enhancing recycling facilities, are likely to significantly influence existing supply-chains, infrastructure and employment [107]. The skeleton of the new assessment method allows for other indicators such as the scarcity of raw materials (abiotic depletion potential), financial costs associated with necessary transportation / deconstruction infrastructure, environmental shadow costs and social factors which are often missed in circular economy measurement indices [71,108,109]. Future research would benefit from placing greater focus on these impacts to enable comprehensive recommendations for policy and practice.

5. Conclusions & recommendations

The novel method developed in this study enables the evaluation of the reclamation potential (RP) of multi-component systems in different recovery scenarios. The RP metric, provides a quantitative measure of the ability for systems, components and materials to be re-deployed through reuse or recycling. This allows for preferential design strategies and recovery scenarios that minimise negative environmental impacts to be identified. The potential of the newly-developed assessment was demonstrated on a representative double-skin aluminium-framed closed cavity façade. Based on the findings, the following conclusions and recommendations can be made:

1. The RP-metric has the potential to signal the most environmental favourable recovery route for components embedded in the existing building stock. The findings confirm that landfill disposal generates environmental burdens higher than any other recovery scenario and should thus be avoided. Based on the double-skin façade studied in this work, it was evident that system reuse is not always the best recovery option for multi-component systems. In the absence of viable reconditioning processes, other recovery routes, such as component reuse and/or recycling, may be more feasible. The measured values of RP highlight the urgent need for reconditioning processes that increase the probability of survival of components and systems. In this way, functional performance could be restored and the original environmental value could be maintained for longer time periods. Future development of the assessment method should include variability in disassembly tasks and sequences and options for reconditioning.
2. The RP-metric provides a useful measure to evalute the future environmental value of *new* designs with consideration for material selection, construction methods and service life dependencies on neighbouring components. There is a growing trend towards the use of permanent fixing methods such as adhesives in place of mechanical dry connections. The impact of these design choices on RP and the development of durable connections that also enable rapid disassembly are important issues for future research. In this work, the IGU seal was assumed to be irreversible leading to premature replacement of glass and higher lifetime embodied carbon. Some small-scale initiatives are developing processes to technically separate IGU seals for glass reuse. Future studies on efficient disassembly processes are essential to eliminate the detrimental life-cycle impact of irreversible connections. The appraisal of connection types must be continually revised to reflect existing recovery infrastructure and disassembly methods.
3. Application of the assessment to a wider range of building elements (e.g. structural components such as floor systems; mechanical and electrical services; and advanced technologies such as photovoltaic devices) should be explored to investigate the sensitivity of the total number of components, material selection, and ability to readily remove components on the reclamation potential for building elements that serve alternative functions. The assessment could be enriched through the collection of service life data relating to product performance and deterioration over time. Such empirical data could be used to define probability distributions that are specific to the building element under study (e.g. load-bearing capacity for structural elements or thermal performance for cladding systems).
4. The contribution of recurring embodied energy and CO_2-eq emissions (B5) over time were found to be significant over the 100-year time period for the double-skin façade evaluated in this study. The development of double-skin façades was a direct response to improve building operational energy performance of buildings whilst maintaining transparency, with limited consideration for the effects on embodied carbon/energy. Future uses of this RP-assessment to a wide range of building products and systems could allow the consequences of other material efficiency strategies to be evaluated such as material substitution, light-weighting components, more intensive product use and

manufacturing/reprocessing yield improvements. These factors should be evaluated alongside operational performance to assess the *whole-life* environmental performance during the design of the next generation of building products.

CRediT authorship contribution statement

Rebecca Hartwell: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mauro Overend:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

Rebecca Hartwell reports financial support was provided by Permasteelisa Group. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.111866.

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