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Reuse of Aluminium Structural Components in Circular Construction: A Life Cycle Assessment of a Portal Frame Tent Structure

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Abstract

Aluminium is one of the most carbon-intensive structural materials, making the direct reuse of aluminium members a highly effective strategy for reducing environmental impacts by avoiding primary production. Despite this potential, the reuse of aluminium structural members has received far less attention than steel reuse. This study addresses that gap through two complementary contributions. First, it develops a reuse pathway for aluminium structural members based on existing steel reuse frameworks while addressing aluminium-specific technical challenges. Second, it evaluates the environmental implications of this approach through a life cycle assessment of an aluminium portal frame tent structure in accordance with EN 15804+A2 and the EF 3.1 method, covering Modules A1–A5, C1–C4, and D. Three end-of-life scenarios are considered: a cut-off baseline, a recycling scenario, and a reuse scenario. Aluminium production accounts for 37.6% of the cradle-to-gate impact while representing only about 3.3% of the mass. Direct reuse lowers the net global warming potential by about 22% relative to recycling and is the lowest-impact option across all 16 impact categories. The results identify direct reuse as the environmentally preferable end-of-life route, although wider implementation depends on design for disassembly and a dedicated technical framework for reclaimed aluminium.

Keywords: aluminium structures; structural reuse; circular economy; life cycle assessment; sustainable construction; greenhouse gas emissions; design for disassembly

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1. Introduction

Climate change and resource depletion are becoming major challenges today, which is why the need for sustainable construction is increasing. The construction sector significantly contributes to this problem; it is estimated that the construction industry causes 37% of CO_2 emissions, consumes 36% of energy, and generates one-third of waste globally [1,2]. As a result, the concept of circular economy in construction (circularity) has started to develop rapidly, which, instead of the current linear approach, aims to extend the lifespan of a building and reduce waste by reusing and recycling structural parts [3]. Within a circular economy framework, reusing structural members is prioritised over recycling. Recycling returns the material to its raw form, and the reprocessing itself consumes additional energy and resources. Reuse, on the other hand, keeps structural components in their original state, leading to substantial savings in both CO_2 emissions and resource consumption. Aluminium and steel stand out as materials with high potential for reuse due to their durability, longevity, and the possibility of relatively simple assembly and disassembly using suitable connections between members. Aluminium has proven to be a material with a very long lifespan in construction applications. An example is the dome of the church of San Gioacchino in Prati in Rome (Figure 1a), made of aluminium in the late 19th century, as well as the Arvida Aluminium Bridge (Quebec, Canada), an aluminium arch bridge that has been in use since 1950 (Figure 1b) [4]. Such examples indicate that aluminium components, with minimal maintenance, can retain their mechanical properties, visual appearance, and high corrosion resistance for decades.

(**a**) (**b**)

Figure 1. Early applications of aluminium in construction: (**a**) Dome of San Gioacchino in Prati, Rome, one of the first uses of aluminium in architecture; (**b**) Arvida Bridge, Quebec, the world's first all-aluminium long-span arch bridge [4].

Beyond their longevity, metal structures offer an important advantage over concrete structures due to the possibility of assembling members using mechanical fastening systems, which allows disassembly without significant structural damage. This approach is consistent with circular economy principles, specifically design for disassembly (DfD), which encourages the use of reversible and standardised connection systems.

Aluminium is characterised by its corrosion resistance, high strength-to-weight ratio, low density, and full recyclability, which make it particularly suitable for lightweight and reusable structures [5,6]. The primary aluminium production produces very high CO_2 emissions, so recycling and especially the reuse of aluminium are very important from an environmental and financial perspective. Recycling steel cuts production emissions by roughly 80–85% compared to primary production, while direct reuse achieves over 95% [7]. The same logic applies even more strongly to aluminium. Primary aluminium production emits about 14.8 t CO_2e per tonne (2023 global average), against 2.18 t CO_2e per tonne for primary steel (2024) [8,9], which makes the potential carbon savings from the reuse of aluminium components even more significant. Although the reuse of aluminium structural components involves technical and regulatory challenges, its potential environmental benefits are strong enough to justify further investigation. Recent research has increasingly focused on the reuse of structural members, primarily in the field of steel structures [7]. Methodologies for structural member assessment, requalification, and reliability verification of reused steel members are being developed within CEN/TC 250, with the aim of integrating reuse into Structural Eurocode frameworks. However, research focused on the reuse of aluminium is still limited. The main technical challenges are the fatigue limit,

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which, in aluminium, is not defined, as well as the compatibility of connections, residual stresses, and variability of the mechanical properties of aluminium alloys.

From an environmental standpoint, a life cycle assessment (LCA) provides a most robust method for quantifying the benefits of reuse in comparison with recycling and primary production. Several LCA studies have already been carried out for structural steel reuse in buildings, demonstrating substantial reductions in embodied impacts when reclaimed members are used instead of newly produced steel [10,11]. However, comparable LCA studies focusing on the reuse of aluminium structural components are still scarce, so the full environmental and practical implications of aluminium reuse remain insufficiently researched.

As a first step of the literature analysis, a bibliometric network was constructed using VOSviewer 1.6.20 and the co-occurrence of authors' keywords as the type of analysis to map the main research themes related to the reuse of aluminium in construction. Figure 2 illustrates the connections between the main topics identified in the collected literature, with circular economy emerging as the central research theme. In the network, each node represents an author keyword, node size is proportional to the number of occurrences, and node colour denotes the cluster to which the keyword was assigned by VOSviewer. The links indicate co-occurrence between keywords, with their thickness proportional to the co-occurrence strength. Distinct clusters link aluminium, recycling, post-consumer scrap, and decarbonization, showing the connection between aluminium secondary production and the reduction of embodied carbon. Other significant links include design for disassembly, buildings, and sustainable construction, indicating that end-of-life design strategies and building-level circularity are among the most active research directions. The link between Eurocode 3 design rules and sustainability shows a regulatory dimension and current lack of an equivalent framework for aluminium structures.

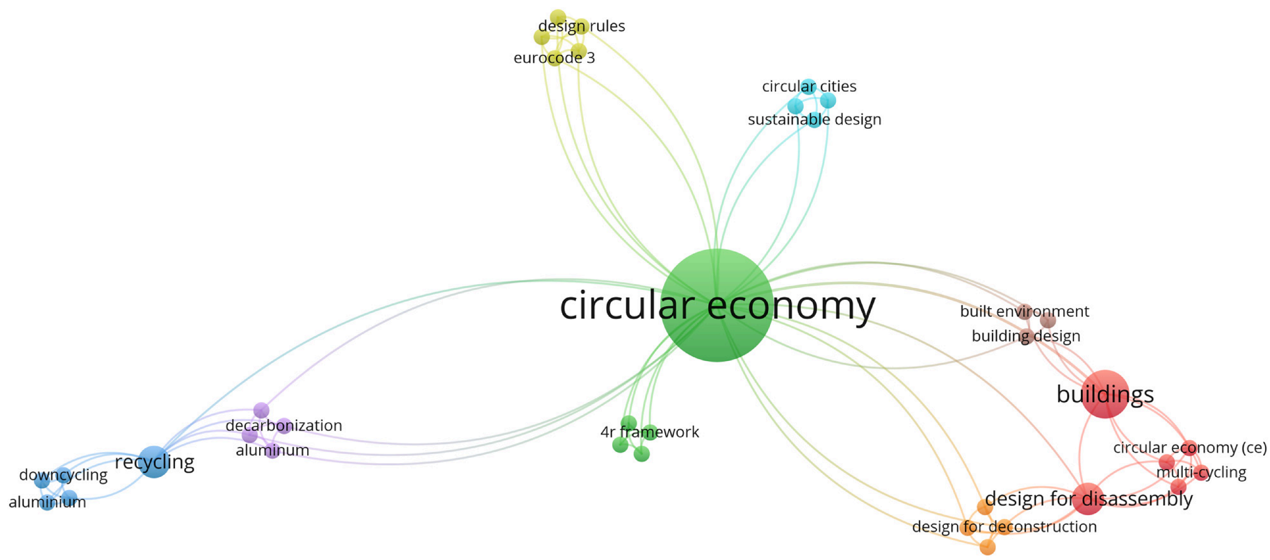


Figure 2. Co-occurrence network of author keywords related to aluminium reuse in construction, generated with VOSviewer 1.6.20.

The referenced literature, comprising 42 sources, together with the bibliometric map, indicate that although the circular economy in the construction sector has been extensively researched, only a limited number of studies explicitly address the reuse of aluminium structural components. The categorisation of publications according to their relevance to the research questions shows that while many sources engage with related themes, only a small subset directly aligns with the focus of this study, forming the basis for the subsequent analysis.

Despite well-developed frameworks for structural steel reuse, such as the provisions of CEN/TS 1090-201 [12], design guidelines being developed within CEN/TC 250, and projects such as PROGRESS [13], no equivalent methodology currently exists for structural aluminium reuse. This gap is particularly important because aluminium has a substantially higher environmental footprint than steel and presents additional material-specific challenges for reuse. At the same time, quantitative evidence on the environmental advantages of reuse over recycling remains limited.

This paper addresses this scientific gap by developing an aluminium-specific approach to structural reuse and by providing quantitative evidence of its environmental benefits. In contrast to much of the circular-economy and steel-reuse literature, the study adapts established structural-steel reuse pathways to aluminium-specific requirements and quantitatively assesses the environmental impacts of a real aluminium tent structure across three end-of-life scenarios.

This study is structured around two interconnected objectives. The first concerns the application of circularity principles at both the material and structural level, examining the reuse potential of aluminium as a structural material and developing guidelines for connection design, disassembly, and structural component recovery within modular construction systems adapted from existing frameworks for structural steel reuse [7,13]. The second objective addresses the environmental dimension by applying a life cycle assessment tool to evaluate the benefits and feasibility of reusing aluminium structural members through a case study of an aluminium portal frame tent structure. Further to a reference scenario (Scenario 1), two end-of-life scenarios are analysed for the same structure and use pattern: a recycling scenario (Scenario 2), in which all aluminium members are sent to remelting at the end of their service life, and a reuse scenario (Scenario 3), in which the aluminium members are recovered and transferred to a reuse hub for future application instead of being recycled. By combining design-oriented reuse strategies with a comparative environmental assessment, the study contributes to addressing the current lack of LCA-based evidence for aluminium structural reuse and supports informed decision-making beyond conventional recycling approaches. The remainder of this paper is organised as follows. Section 2 reviews the principles of circularity in the construction industry and examines the material-specific challenges that differentiate the reuse of aluminium structural components from that of structural steel. Section 3 proposes a structured reuse pathway for aluminium structural members, encompassing the stages from pre-redevelopment audit and deconstruction to assessment, storage, design verification, and reinstallation. Section 4 presents the LCA framework adopted in this study, including the Goal and Scope definition, system boundaries, life cycle inventory and impact assessment methodology, applies it to a real aluminium portal frame tent structure, and reports the comparative LCA results for the three end-of-life scenarios. Section 5 discusses the findings and evaluates their robustness, while Section 6 summarises the main conclusions.

2. Circularity

Circular construction (circularity) represents principles of the circular economy in the construction industry to preserve the value of materials, reduce waste, and reduce carbon emissions throughout the entire life cycle of buildings. In that context, aluminium takes an eminent position due to its corrosion resistance and stable mechanical properties over time, and retains its functionality even after long-term use, making it suitable for multiple life cycles [4]. The literature frequently addresses that the term circular economy is often reduced to recycling, although the key difference is that the circular economy seeks to "close the loop" through changes in design, business models, and asset management [14]. As the largest consumer of material resources and generator of waste globally, circularity in the construction sector represents one of the key pathways for greenhouse gas reduction, decreasing the use of primary raw materials and preserving the environment [3].

The implementation of circular economy principles in the construction sector faces multiple challenges, including legal, technological, regulatory, economic, and cultural barriers. Uncertainty regarding liability and warranties, the lack of standardised criteria for reused structural components, and the belief that reused components involve greater risk reduce their attractiveness among investors and designers [15]. Therefore, clear technical procedures for reuse are needed to define the testing, certification, and design of reused structural components, thereby supporting the wider implementation of reuse strategies. The circular economy in construction is not only an environmental protection concept but a systematic transformation of design practices and resource management. The following sections examine circularity principles at the material level through reuse and recycling strategies for metals and then at the building level through design principles that enable multiple life cycles.

2.1. Circularity at Material Level: Reuse, Recycling, and Aluminium Specific Challenges

Globally, steel remains the dominant construction metal; approximately 1900 million tonnes of steel are produced annually in comparison to 70 million tonnes of aluminium [16,17]. Despite differences in production volumes, both materials are highly recyclable and increasingly included in circular economic strategies. In Europe, 88% of structural steel is recycled at the end of life, while reuse accounts for only around 11% [7]. Comparable data for aluminium are limited, but the pattern is similar: recycling is well established, whereas direct reuse of structural members remains uncommon. Although aluminium can theoretically be recycled indefinitely, in practice, the material quality often deteriorates as a result of alloy mixing and impurity accumulation. Secondary aluminium is frequently used in applications with lower technical requirements than the original product, as precise control of chemical composition becomes more difficult [18]. One such example is its use as an additive in concrete [19]. In addition, material losses during melting processes represent a further limitation [20]. At high temperatures, aluminium oxidation and dross formation occur, resulting in mass loss. From a circular perspective, the most favourable strategy is the direct reuse of aluminium members as finished products, without melting or significant reprocessing.

Reuse preserves both the material value and the embodied energy used during primary production. Given the advantages, the question is not whether reuse is preferable, but why it remains so rarely implemented in practice. For structural steel, the barriers are primarily regulatory, but standardisation efforts are underway, and methodologies are being developed. While the general methodology of structural reuse is transferable from steel to aluminium, there are several material-specific challenges that need to be addressed when considering reusing aluminium structural components. The material-specific challenges that explain this gap can be grouped into five main categories: fatigue behaviour, heat-affected zones, alloy identification, galvanic corrosion, and geometric vulnerability [7,21].

Although the fatigue behaviour of aluminium and steel is determined by the same physical principles, there are some important engineering differences that need to be considered, especially for the reuse of structural members. The fatigue strength of aluminium is substantially lower than that of steel. Particularly, higher crack growth and lower fracture toughness at room temperature result in a shorter critical crack length and a shorter fatigue life. Furthermore, while EN 1993-1-10 [22,23] specifies minimum fracture toughness requirements for structural steel, no equivalent regulation exists for aluminium, which makes the documentation of alloy and loading history particularly important for reused aluminium members [24].

In addition, heat-affected zones (HAZ) are another consideration in reuse, as aluminium alloys, especially heat treatable series like the 6xxx series, commonly used in structural applications, experience a permanent reduction in mechanical properties in the heat-affected zone near welds [25]. For structural members intended for reuse, welded joints should therefore be avoided wherever possible. If welded joints are unavoidable, welded details should be classified conservatively. Structural aluminium includes a wide variety of alloys (mostly from the series 5000, 6000, and 7000) with significantly different mechanical properties, weldability characteristics, and corrosion behaviour [26,27]. Within every alloy series, the temper designation (T5, T6) further defines material properties. This variety of series and tempers makes alloy identification particularly a challenge, unlike steel, where a relatively small number of standardised grades covers most of the use cases. The use of XRF (X-ray fluorescence) or OES (optical emission spectrometry) techniques is essential, but these methods may not always distinguish between closely related alloys or identify the temper condition [28].

Aluminium is more reactive and anodic than most common structural metals. Direct contact with a dissimilar material, such as steel, in the presence of an electrolyte, can lead to galvanic corrosion. Standard prevention measures include insulating inserts, compatible fasteners (e.g., stainless steel or aluminium screws), and protective coatings. For reused aluminium members, this risk must be assessed in two stages: first, assessment of possible galvanic corrosion damage from previous use (especially at connections with steel fasteners), and second, the design of new connections that prevent galvanic corrosion in the new structure [29].

Lastly, aluminium members are usually extruded as relatively thin-walled sections. This geometry makes them more susceptible to local damage during deconstruction, such as dents, permanent local deformations, and edge damage, which can significantly reduce the effective capacity of the cross-section. Deconstruction and handling procedures must therefore be adapted to minimise such damage [30].

These challenges specific to aluminium do not prevent aluminium reuse but rather require adapted procedures for inspection, classification, and design. The reuse pathway presented in Section 3 addresses these considerations at each stage of the process chain.

2.2. Circularity at Building Level: Design for Disassembly (DfD)

Designing for longevity and adaptability involves creating load-bearing systems that can accommodate changes in function, loading, and layout throughout the building's lifespan, lowering the risk of premature demolition. Decisions regarding structural grid, floor height, and cross-sections have long-term implications for the building's adaptability and potential for repurposing and are therefore crucial for the successful implementation of a circular strategy [3].

Design for disassembly refers to the design of structures so that members can be disassembled in a predictable sequence, using standardised tools, with minimal damage and while maintaining the load-bearing function of the member. Existing guidelines highlight several principles: avoiding permanent connections wherever possible (e.g., welds or bonded joints that prevent clean separation), prioritising reversible mechanical connections, ensuring access to connection zones, and planning tolerances and disassembly logistics (including sequence, storage, and labelling) in advance [31]. ISO 20887 [32] is frequently referred to as a framework for the DfD approach and its integration into the design process. Reviews of connection systems in metal frame structures further emphasise that the type of joint is critical for successful disassembly and reuse. The connection defines if the member can be removed without cutting, how many cycles of assembly–disassembly it can withstand, and the risk level of damage to edges, bolt holes, and contact surfaces. Bolt holes are particularly prone to elongation under bearing stress after repeated assembly. Once they exceed the tolerances of EN 1090-3 [33], the hole can be re-drilled to the next bolt size with re-verification of bearing resistance, or the member is recycled rather than reused. Since bolt threads and contact surfaces are the parts most affected by repeated handling, bolts are treated as consumables and replaced at each assembly cycle. Recent literature argues that improving reuse rates is contingent on a fundamental shift in connection design, as current solutions often prioritise rapid assembly over future disassembly [34].

2.3. Standardisation and Development of Regulations

The main obstacle in structural reuse lies in the regulatory and certification framework. According to the European Construction Products Regulation (CPR, Regulation (EU) 2024/3110) [35], every construction product placed on the European market must carry a CE (European Conformity) marking together with a Declaration of Performance and Conformity (DoPC) that demonstrates compliance with the applicable standards. For steel and aluminium structural components, this falls under the EN 1090 series: EN 1090-1 [36] for conformity assessment, EN 1090-2 [37] for steel execution requirements, and EN 1090-3 [33] for aluminium execution requirements. Standards are primarily developed for the assessment of new structural components (members and joints). Reused structural components are generally not covered by existing standards and rarely come with full documentation on their manufacturing history, alloy composition, or past loading, resulting in technical and legal uncertainties. Work is underway at the European level to close this gap. Technical Committee CEN/TC 135 has developed the technical specification CEN/TS 1090-201 [12], which provides complementary provisions to EN 1090-2 for the use of reclaimed structural components, covering deconstruction, reusability and quality assessment, including tiered testing protocols selected according to documentation availability [12]. Currently, CEN/TS 1090-201 [12] applies only to structural steel and does not cover aluminium, which presents its own set of material-specific challenges and clearly requires an equivalent technical specification. In parallel, Technical Committee CEN/TC 250 is developing guidance for the integration of reused components into the Eurocode 3 framework, while Eurocode 9 remains outside the current scope of this work [38]. Studies have identified the absence of design provisions for reused components in standards as the main obstacle to the wider application of reuse in practice [39]. The lack of an equivalent specification for structural aluminium is therefore a significant regulatory gap; unlike steel, aluminium brings additional issues such as alloy identification, fatigue behaviour, and HAZ effects, none of which are addressed by current standards.

3. Reuse Pathway for Aluminium Structural Members

In this study, the term "reuse pathway" for aluminium structural members is defined as a sequence of technical, regulatory, and organisational steps by which a member from an existing structure (permanent or temporary) is transferred to a new function, while ensuring safety, traceability, and acceptability according to regulations. These steps are not only technical issues, but social-technical processes, which include investors, designers, contractors, logistics intermediaries (such as a reuse hub), and depending on the jurisdiction, quality control and approval bodies [7]. Guidelines for design emphasise that designers must adopt a design approach covering the entire life cycle of the structure. This involves understanding who will be responsible for future adaptation, disassembly, reuse, or recycling, and incorporating these requirements into the design from the outset. The following subsections outline the process chain for the reuse of aluminium structural components, Figure 3. The methodology for this process chain is based on a systematic review of the literature on the reuse of structural steel components [7,10], taking into consideration the specificities of aluminium described in Section 2.1.

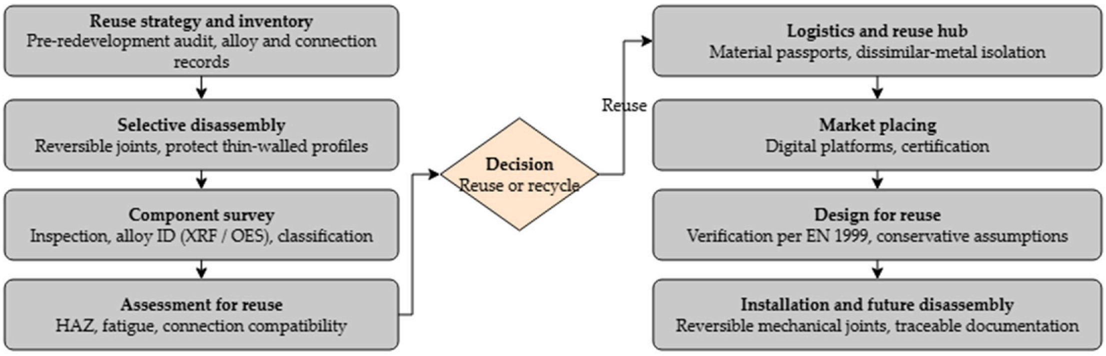


Figure 3. Proposed reuse pathway for structural aluminium members.

3.1. Defining Initial Reuse Potential and Reuse Strategy

Research on the reuse of steel structural components has established scenario-based classifications that, with appropriate material-specific checks (alloy, heat-treatment, welded joints, and contact/galvanic corrosion), can also be applied to aluminium structures. It is important to differentiate between types of reuse because requirements and risks vary significantly depending on whether reuse takes place as in-situ reuse (member stays in the same position), on-site reuse (member stays at the same location but in a different position), or ex-situ reuse (member is transferred to a new location). It is recommended that a pre-redevelopment audit be conducted to identify suitable members for reuse and plan selective disassembly [3]. In this phase, all available data about the structure are collected (drawings, structural calculations, alloy and material specifications, certificates, maintenance records), and an initial inventory of members is created with basic geometrical properties, position in the structure, connections, and accessibility for disassembly [7]. The inventory forms a basis for the decision on which type of reuse strategy will be conducted, as well as a decision on the required testing and the level of processing of members. At this stage, it is useful to start thinking "backwards", which means beginning the design of a new structure from available structural components. The concept of "form follows availability" is recognised as one of the key shifts in the design of structures, instead of the usual "design first" approach [40]. The designer optimises the solution around the available stock of members while verifying load-bearing capabilities and functionality [41]. This approach is compatible with aluminium members, which are usually modular, but it requires reliable data on material properties and the intended use case of the structure.

3.2. Reclaim of Members: Deconstruction Planning and Selective Disassembly

The reuse of structural members generally requires planned disassembly rather than conventional demolition. Reports about circular design and LCA methodology emphasise design for deconstruction as an approach in which a structure is designed (or an existing object is analysed) so that members can be disassembled and reused multiple times, with clearly defined disassembly sequences [42]. Guidelines further highlight that prefabrication and modular structures facilitate disassembly, as does the design of reversible connections. Even though many recommendations in the literature refer to steel, the basic principles are easily transferable to aluminium: avoiding permanent, non-separable joints wherever possible, ensuring access to connections, and reducing "hybrid" composites that make disassembly more difficult [3,42]. In addition, for aluminium members, the reclaim phase must minimise damages that can degrade load-bearing capabilities, including controlling contact with incompatible metals (galvanic corrosion), and protecting against localised impacts that can cause permanent deformation of thin-walled profiles [3]. The result of this phase is a preserved member with unique identification, together with a record of initial placement, orientation and type of connection, as well as any observed damage (photos and logs), which is a prerequisite for subsequent traceability.

3.3. Component Survey: Inspection, Material Identification, and Classification for Reuse

Following disassembly and the reclamation of reusable components, a component survey is conducted. Systematic reviews of reuse emphasise the need for standardisation of testing protocols and classifications to reduce uncertainty and increase the confidence of designers and investors. Within the project "Provisions for a Greater Reuse of Steel Structures (PROGRESS)" [13] guidelines for quality and traceability are ensured through a unique member ID and a suitability classification system-three material classes are defined. For Class A, original test certificates are available and serve as evidence of conformity. For Class B, the original documentation is missing, so re-certification is required through a comprehensive testing program covering mechanical properties and chemical composition, supported by quality checks. Class C comprises structural steels for which material properties and composition cannot be reliably identified; consequently, design and verification must be based on the most conservative assumed steel grade [13].

Applied to aluminium, a typical component survey should include:

- visual inspection (including damage, dents, permanent deformations, traces of corrosion, and damage to protective layers);
- a check of dimensions and geometric tolerances;
- identification of the alloy (e.g., portable PMI/XRF, spectrometry) and verification of whether joints and thermal effects (welding) are compatible with the new function.

Non-destructive testing of cracks may be required, especially for members exposed to cyclic load, vibrations or dynamic influences. As aluminium lacks a fatigue limit, the loading history of members is relevant, and remaining fatigue life should be checked according to EN 1999-1-3 [43] if load history is documented. Otherwise, conservative load assumptions should be used instead. It is important to emphasise that, for aluminium, in addition to the general condition, the risk of an "unknown alloy" must also be considered. The issues of mixing alloys and the accumulation of impurities are key causes of downcycling in recycling; similarly, in reuse, unreliable identification of alloys can limit member design to a more conservative approach or demand additional testing [20]. While portable XRF identifies the alloy, it does not distinguish the temper condition, so hardness testing is therefore used as a complementary check. Therefore, in practice, it is recommended that reused members be sorted by alloy, and that identification results be recorded in their unique ID or digital passport. The component survey can also be carried out before dismantling (in situ) when this is reasonable and necessary.

3.4. Assessment

The assessment phase involves evaluating whether an aluminium member is suitable for reuse based on previously defined properties. Taking into consideration safety, serviceability, and durability at a level of reliability equivalent to new construction products [38]. In this way, a reused member is treated equally to a new member in design terms. The assessment includes classification of the member considering available documentation, the condition of the cross-section, connection compatibility, and the intended new use, in line with the recommended European process chain (reclaim-assessment-classification-design) [13]. A member can be: (i) acceptable without further intervention, (ii) acceptable with limitations or minor modifications, or (iii) unsuitable for direct reuse [7]. For aluminium components, particular attention is needed to potential changes in the heat-affected zone, local damage of thin-walled sections, and compatibility with new connection details, especially in the context of long-term durability and future disassembly, in line with design-for-disassembly principles [32]. The final decision between reuse and recycling is based on technical feasibility and the extent of necessary interventions, while also considering the construction circularity hierarchy [3].

3.5. Logistics, Storage, and "Reuse Hub" Models

A systematic literature review highlights the importance of dedicated infrastructure development, including storage facilities, digital marketplaces, and "reuse hubs" that can bridge the time gap between dismantling and installation in a new structure [44]. The method of transport, whether directly from one construction site to another or via intermediate storage, has a direct impact on both cost and environmental performance [10]. In the case of aluminium, storage must simultaneously protect the members from mechanical damage and prevent unwanted corrosion resulting from contact with other materials; quality storage is not just an operational detail but an integral part of the proof that the members have retained their properties for reuse. Digitalisation at this stage has a dual purpose: (i) it allows the management of supply and connects suppliers with buyers; and (ii) it serves as a basis for traceability and credibility. The concept of material passports has been developed to ensure that data about geometry, mechanical properties, connection details, load and use history are reliably documented [45,46]. For aluminium members, material passports should also include alloy identification, thereby reducing risk and facilitating design decisions.

3.6. Market Placing

The market-placing stage refers to how reclaimed members are offered for reuse, whether through internal procurement chains, intermediaries, digital platforms, or reuse hubs. A transparent market, supported by standardised descriptions and certifications, together with a digital inventory with material passports and the development of regional reuse hubs, would significantly contribute to the wider application of reuse [45,46]. In practice, the material passport forms the basis of the market-placing phase.

3.7. Design

Reused components must be designed and verified in accordance with the standards for new structures, as European guidance and pre-standardisation documents for the reuse of metal structural components are currently under development [38,39]. In the case of aluminium, the design stage must address several aspects simultaneously:

- verify structural resistance and serviceability, considering the actual geometric tolerances and the condition of the reclaimed components;
- manage uncertainties (e.g., by adopting conservative assumptions where documentation is incomplete);
- avoid detailing choices that would hinder future disassembly and reuse.

3.8. Installation, Verification and Future Disassembly

The installation of aluminium members into a new structure requires a combination of conventional structural design in accordance with standards and additional verification due to uncertainties. The literature suggests that reuse is most effective when the design is tailored to available members and supported by digital tools and optimisation methods that identify structural configurations capable of maximising the use of existing components [47]. This approach can be especially effective for modular structures, but it demands disciplined documentation and clear modification boundaries (e.g., permissible modifications to components, limitations on connecting different alloys, and criteria for acceptable damage). At the European level, research aimed at establishing design rules for reused metal members highlights the need to catalogue typical members and details for reuse and to align them with a standardised approach to verification. Although most research has so far focused on steel, there is growing recognition and a need for the reuse of aluminium members, and to transfer and adapt the methodology to other metals [39].

4. Environmental Quantification of the Reuse Strategy: A Case Study

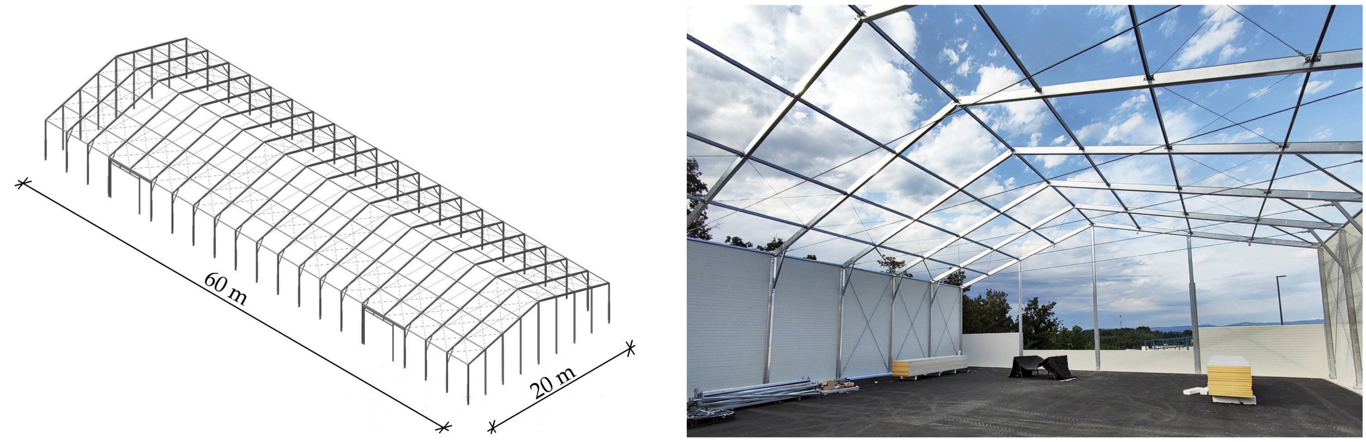
After the reuse pathway for aluminium components has been defined, the next essential step is to quantitatively demonstrate the environmental justification of such a strategy through a structured life cycle assessment. LCA is a standardised approach for evaluating the environmental impacts of products or systems across their entire life cycle. According to EN ISO 14040 [48] and EN ISO 14044 [49] the LCA framework includes (i) the Goal and Scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation of results [42]. These phases together ensure a consistent and transparent assessment approach. Two main standards cover LCA application in the construction sector: EN 15804 [50], which focuses on the construction product (material) and is used for declaring the environmental properties of products, and EN 15978 [51], which evaluates the building at the whole-building level and covers all relevant phases of the building's life cycle, from material acquisition to end of life. EN 15804 [50] and EN 15978 [51] structure the life cycle into standardised modules A1–A3 (production), A4–A5 (construction site), B1–B7 (use phase), C1–C4 (end of life), and D (benefits beyond system boundaries) [51].

One of the key methodological challenges in the reuse of structural members is the correct allocation of end-of-life credits. In the modular approach, environmental burdens of deconstruction and processing at the end of life (C1–C3) are attributed to the existing building, while the potential future benefits of reuse or recycling are typically reported in Module D (beyond the system boundary). This allocation can complicate result interpretation and comparability, particularly if system boundaries and reuse scenarios are not clearly defined [11,52].

4.1. Goal and Scope of the Study

Following the LCA framework and standards outlined in the previous section, this part of the paper focuses on the application of LCA to a real case study, Figure 4. The primary objective of the LCA is to quantitatively compare the environmental impacts of alternative end-of-life scenarios for the aluminium load-bearing members of the structure, with particular attention to reuse and recycling pathways.

The case study structure is a real aluminium portal frame tent of 20 × 60 m (1200 m^2) with a double-pitched roof [53]. The primary load-bearing system consists of transverse aluminium portal frames with a tension-tie cable, spaced at 3.00 m centres. Columns and rafters are executed as extruded hollow sections with cross-sectional dimensions 230 × 90 mm, manufactured from EN AW-6082-T6 alloy [54]. Global stability is provided by roof and vertical bracings, consisting of galvanised steel cables. Joints incorporate internal hollow section inserts made of S235JR steel, connected using galvanised steel bolts. The galvanised coatings on the steel inserts and bolts also help limit galvanic corrosion at the aluminium–steel interfaces. These contact surfaces are inspected during the component survey, since galvanic damage accumulated during service may affect the suitability of components for reuse. All connections are mechanically fastened and fully demountable, and therefore consistent with DfD principles and the reuse-oriented assumptions adopted in the LCA. As no members are welded, no heat-affected zones are present in the structure, and HAZ softening does not need to be considered for this case study. The portal frame tent is predominantly statically loaded and not subjected to significant cyclic actions; fatigue is not a governing consideration for the case study structure.



(**a**) (**b**)

Figure 4. (**a**) 3D structural model; (**b**) interior view of the partially assembled structure.

The study is conducted as a comparative "cradle-to-grave" LCA with extended system boundaries, including potential benefits beyond the life cycle of the reference structure (module D). In accordance with EN 15978 [51], the assessed life cycle stages include Modules A1–A5 (product and construction stages), C1–C4 (end-of-life stages), and Module D, while use-phase modules (B1–B7) are excluded [55], Figure 5.

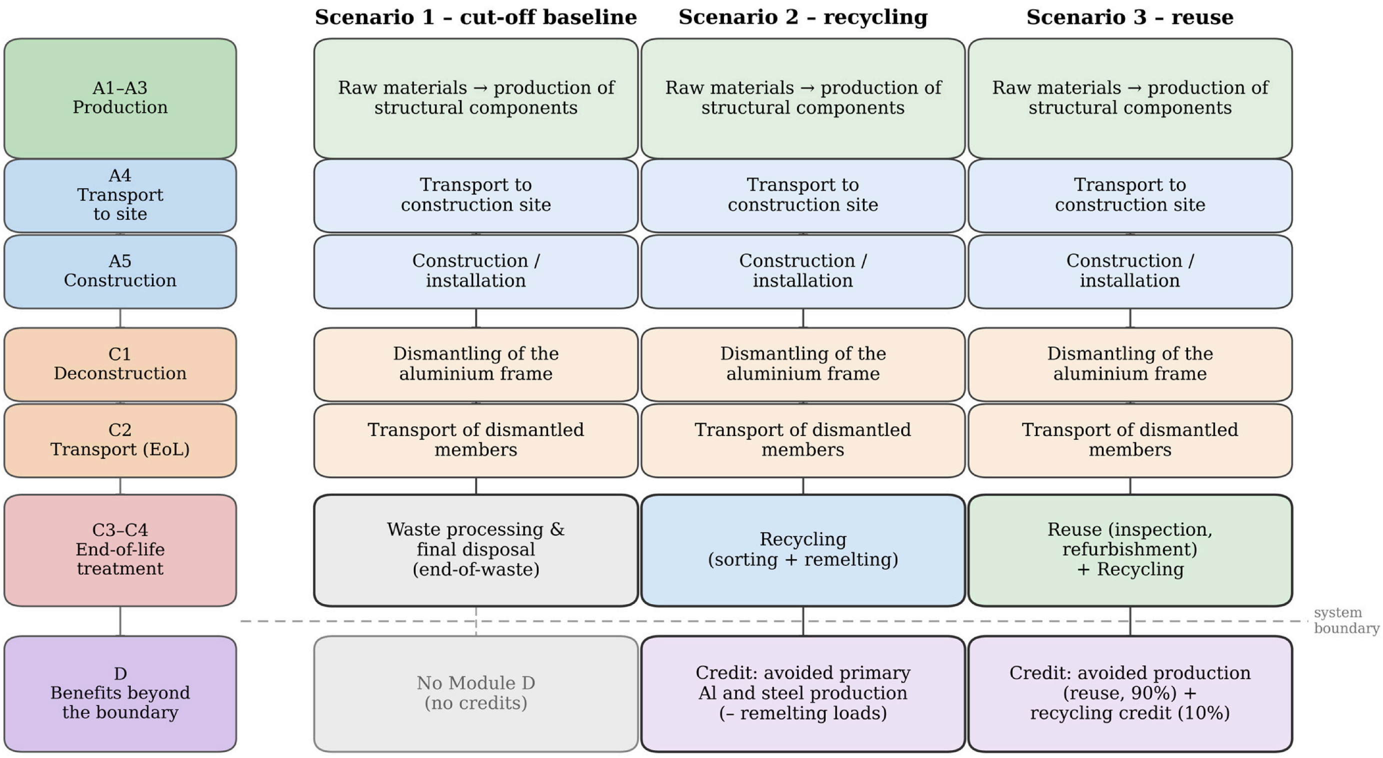


Figure 5. System boundary of the comparative LCA.

The impact assessment focuses primarily on Global Warming Potential (GWP), expressed in CO_2-equivalent emissions (tCO_2e), reflecting the current decarbonisation priorities of the construction sector and the environmental relevance of aluminium production and processing.

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In this study, three alternative end-of-life scenarios are evaluated for the aluminium structural system, as follows:

The construction phase is identical in every scenario. The structure is built from the same quantities and quality of materials, so Modules A1–A5 produce the same impacts in all three cases.

Scenario 1: Cut-off Baseline (no Module D Credits): Once the building reaches the end of its service life, the structural members are disassembled and assumed to leave the system boundary at the end-of-waste stage, with no credits or loads attributed to Module D.

Scenario 2: End-of-Life Recycling (100% Recycling with Module D Credits): In the second scenario, all aluminium and steel members are disassembled and sent to recycling. Module D credits are attributed for the substitution of primary aluminium in the next life cycle.

Scenario 3: End-of-Life Reuse (90% Reuse, 10% Recycling with Module D Credits): In the third scenario, 90% of aluminium and steel frame members are assessed as suitable for direct reuse based on the component survey and assessment described in Sections 3.3 and 3.4 and are transferred to a reuse hub for use in the next life cycle without remelting. The remaining 10% of members, assessed as unsuitable for reuse, are sent to recycling. Module D credits are attributed for both the reused and recycled members, reflecting avoided production impacts in the next life cycle.

4.2. Functional Unit

The functional unit is defined as one portal frame tent structure with a covered plan area of 1200 m^2. This definition enables all scenarios to be compared based on the same load-bearing function, under identical geometrical and mechanical requirements.

4.3. Life Cycle Inventory

The life cycle inventory (LCI) analysis involves quantifying all relevant material and energy inputs and outputs associated with the modular tent structure across the defined system boundary. Within the LCA framework, LCI establishes the baseline for impact assessment by defining material flows through production, construction, end-of-life treatment, and potential benefits beyond the system boundary.

4.3.1. Structural System and Material Quantities

The structural system consists of an aluminium frame comprising extruded aluminium columns, beams and steel inserts, supported by in-situ reinforced concrete foundations, and complemented by tension steel cables and rectangular hollow section (RHS) steel inserts. The building roofing and cladding consist of a PVC technical textile membrane. The structure is designed for repeated assembly and disassembly using bolted reversible connections, consistent with the principles of DfD [56].

The material inventory was obtained directly from the project documentation of a realised structure, including design drawings and structural calculations. The aluminium frame members are extruded profiles with 31% recycled content. The concrete foundations are designed to remain permanently in place, while structural frame members and textile envelope are fully disassemblable.

The complete material inventory is presented in Table 1. The total aluminium frame mass is 4156 kg. The steel members consist of 960 kg of tensile cables and 8288 kg of RHS steel inserts. The foundations comprise 108,000 kg of concrete and 3546 kg of reinforcing steel. The PVC technical textile membrane has a total mass of 900 kg. A reference service life of 30 years is assumed for the structural components, while the textile membrane has a replacement interval of 10 years.

Table 1. Material inventory of the structure-Modules A1–A3.

Material/Type	Structural Component	Mass [kg]
Aluminium frame	Frame-columns, beams	4156
Steel inserts	Frame reinforcement inserts-columns, beams	8288
Steel cables	Structural frame-tensile members	960
Concrete-in situ C25/30	Foundations	108,000
Steel-reinforcing bar	Foundations	3546
PVC membrane	Roof and wall cladding	900
Total		**125,850**

Transport distances were estimated based on a typical European supply chain for construction materials and are summarised in Table 2, corresponding to Module A4 (Transport to Site). Aluminium extrusions, steel sections, and cables are assumed to be delivered from production facilities to the construction site over a distance of 500 km by road freight, using a 16–32 t EURO 5 lorry. The PVC membrane and concrete are assumed to be transported over shorter distances of 100 km and 50 km, respectively, reflecting their more localised supply chains.

Table 2. Material inventory of the structure: Module A4 (Transport to Site).

Material/Type	Mass [kg]	Distance [km]	[tkm] *
Aluminium frame	4,156	500	2078
Steel inserts	8,288	500	4144
Steel cables	960	500	480
Concrete + reinforcing bar	111,546	50	5577
PVC membrane (per replacement)	900	100	90

* tkm-tonne-kilometre (mass × distance), the activity unit for transport in the LCA inventory.

The environmental impact of the construction phase (Module A5) was calculated based on a total of 80 working hours of mechanised equipment used for the assembly of the aluminium frame, reinforcement steel inserts (RHS members), cables, and PVC membrane cladding. The workload includes erection of the primary frame (17.5 h), secondary members and cables (31.5 h), membrane installation (6 h), and forklift operation (25 h). The workloads per material type are summarised in Table 3.

Table 3. Material inventory of the structure: Module A5 (Construction phase).

Material/Type	Workload [h]
Aluminium frame	17.5
Steel inserts and cables	31.5
Membrane installation	6.0
Forklift operation	25.0

End-of-life deconstruction activities are modelled within Module C1 (Deconstruction/Demolition) for the different end-of-life scenarios, Table 4. For the recycle scenario (Scenario 2), the environmental impact of the end-of-life process is assumed to be 60% of the construction-phase impacts, reflecting the fact that dismantling operations are faster and less labour-intensive, as component preservation is not required.

For the reuse scenario (Scenario 3), the deconstruction effort is assumed to be 100% of the original assembly effort, reflecting the need for careful, non-destructive disassembly to avoid damage to reusable components. Each member must be recovered intact; therefore, the process is at least as demanding as the original erection. In addition, the reuse scenario includes extra processing activities at the reuse hub, such as inspection, cleaning and minor refurbishment, which are modelled as additional post-deconstruction processes [7].

Table 4. Material inventory of the structure: Module C1 (Deconstruction phase).

Material/Type	Scenario 1 (Cut-Off) Workload (h)	Scenario 2 (Recycling) Workload (h)	Scenario 3 (Reuse) Workload (h)
Aluminium frame	10.5	10.5	17.5
Steel inserts and cables	18.9	18.9	31.5
PVC membrane	3.6	3.6	6.0
Forklift operation	15.0	15.0	25.0

Transport processes at the end of life are modelled within Module C2 (Transport) and reflect the different end-of-life pathways considered. For the reuse scenario (Scenario 3), the same transport distances as those assumed for Module A4 are applied, representing the transfer of reclaimed aluminium and steel members from the existing site to the reuse hub and subsequently to the new construction site, resulting in a total transport distance of 200 km. For the recycling scenario (Scenario 2), a shorter distance of 100 km is assumed, representing transport of dismantled aluminium and steel members from the site to the nearest recycling facility (Table 5).

Table 5. Material inventory of the structure: Module C2 (EOL transport).

		Scenario 1 (Cut-Off)		Scenario 2 (Recycling)		Scenario 3 (Reuse)	
Material/Type	**Mass (kg)**	**Distance (km)**	**(tkm) ***	**Distance (km)**	**(tkm) ***	**Distance (km)**	**(tkm) ***
Aluminium frame	4156	100	415.6	100	415.6	200.0	831.2
Steel inserts	8288	100	828.8	100	828.8	200.0	1657.6
Steel cables	960	100	96.0	100	96.0	200.0	192.0

* tkm-tonne-kilometre (mass × distance), the activity unit for transport in the LCA inventory.

4.3.2. Allocation Methodology and End-of-Life Modelling

As outlined in the Goal and Scope definition, the allocation of environmental impacts at the end of life represents a key methodological issue in the life cycle assessment of reusable building components. This section details the implementation of the chosen allocation approaches and their application to the defined end-of-life scenarios. In this study, two allocation variants were applied: the cut-off approach (100:0) and the cut-off approach with Module D.

The cut-off 100:0 approach includes environmental burdens from production (Module A) and end-of-life processes (Module C). The system boundary ends at the end-of-waste point, and no credits beyond this boundary are considered. This approach is included to reflect current construction practice, where the reuse of components—although increasingly promoted—is not guaranteed due to long service lives and uncertainty regarding future end-of-life pathways.

The cut-off approach with Module D additionally accounts for potential benefits beyond the system boundary by assigning credits for recycling and reuse. Recycling credits are calculated as the difference between the impact of primary material production and the impact of the recycling process, multiplied by the mass of material sent to recycling and adjusted by the quality correction factor Qs/Qp [47]. For aluminium and steel, the quality correction factor is assumed to be 1.0, as there is no significant degradation of mechanical properties after recycling. This value corresponds to closed-loop recycling, in which sorted members of a known alloy are returned to the same application [57,58]. This is a conservative choice for the present case study as a factor of 1.0 assigns the maximum possible recycling credit to the recycling scenario, so any downcycling penalty (Qs/Qp < 1.0) would reduce that credit, increase the net impact of the recycling scenario, and widen the margin in favour of reuse. Reuse benefits are calculated as the avoided impact of primary material production, minus the impact associated with the value-retention processes, such as inspection and transport.

The three end-of-life scenarios introduced in the Goal and Scope share identical production (Modules A1–A3) and construction phases (Modules A4–A5), as the structure is initially assembled from new materials in all cases. Differences between scenarios are limited to end-of-life treatment (Module C) and the resulting benefits beyond the system boundary (Module D).

In Scenario 1, the deconstructed aluminium and steel members are assumed to leave the system boundary at the end-of-waste stage, and no credits or burdens are reported in Module D. This scenario represents the pure cut-off 100:0 allocation approach.

In Scenario 2, aluminium and steel members are sent to recycling facilities for remelting at the end of service life. A 100% recycling rate is assumed for all frame members, reflecting high recyclability rates of structural metal components. Module D credits are allocated to account for the substitution of primary aluminium and steel production with recycled secondary material. Environmental loads associated with the recycling process, such as transport to the recycling facility, sorting, processing, and remelting energy, are accounted for in Modules C3–C4 and subtracted from the Module D credits. The net Module D credit for aluminium recycling is calculated as:

$$D_{Al,recycling} = m_{Al} \times R_c \times (Q_s/Q_p \times I_P - I_{rec}), \quad (1)$$

where m_{Al} is the mass of aluminium sent for recycling, R_c is the recyclability rate (1.0), Q_s/Q_p is the quality correction factor (1.0 for aluminium), I_P is the impact of primary aluminium production, and I_{rec} is the impact of the recycling process; similar methodology can be applied to steel recycling [47].

In Scenario 3, aluminium and steel members are assumed to be reused following deconstruction. Based on post-use inspection, 90% of members are considered suitable for reuse, while the remaining 10% are sent to recycling facilities. Module D credits are therefore allocated to both the reused fraction (90%) and the recycled fraction (10%). The net Module D credit for the reuse fraction is calculated as:

$$D_{Al,reuse} = m_{Al,reuse} \times (I_P - I_{VRP}), \quad (2)$$

where $m_{Al,reuse}$ is the mass of aluminium transferred for reuse, I_P is the impact of primary aluminium production, and I_{VRP} is the impact of the value-retention processes. A summary of the end-of-life treatment pathways and the corresponding Module D allocation rules for the three scenarios is provided in Table 6.

Table 6. Summary of end-of-life treatment and Module D allocation.

Parameter	Scenario 1: Cut-Off Baseline	Scenario 2: 100% Recycling	Scenario 3: 90% Reuse
EOL treatment	Deconstruction → end-of-waste	100% recycling (remelting)	90% reuse +10% recycling
Module D	None	Credit for avoided primary production (minus remelting loads)	90%: credit for avoided production; 10%: recycling credit
Allocation method	Cut-off (100:0)	Cut-off with Module D	Cut-off with Module D

4.4. Life Cycle Impact Assessment

Following the definition of the system boundaries, inventory, and allocation procedures, the environmental performance is evaluated using the Environmental Footprint

(EF) 3.1 method, which implements the complete set of impact categories prescribed by EN 15804+A2. All calculations are performed using SimaPro 10.3.0.3 software [59]. The analysis mainly focuses on the climate change impact category, quantified by the global warming potential over 100 years (GWP_{100}), expressed in CO_2-equivalent emissions. Although climate change is used as the primary indicator, all 16 EF 3.1 impact categories were calculated for every scenario, so that the comparison between end-of-life routes does not rely on a single indicator.

The assessment was carried out step by step; production processes were first defined for each material, followed by transportation and installation. Three alternative end-of-life scenarios were then formulated, including reuse and recycling pathways together with disassembly and transportation to the corresponding treatment or reuse facilities. The results were then analysed through a material-level breakdown of the production stage, a comparison of the three end-of-life scenarios across all 16 impact categories, and additional analyses of the sensitivity to the reuse rate, the influence of transport distance, and the statistical uncertainty of the background data using Monte Carlo simulation.

4.5. Results of the Analysis and Interpretation

Based on the impact assessment methodology described above, this section presents the results of the LCA for an aluminium portal frame tent structure and compares the environmental performance of the three defined end-of-life scenarios for the same structure and functional unit. As all scenarios share identical production (Module A1–A3), the environmental impacts associated with these stages are identical across scenarios.

4.5.1. Production-Stage Impact

The production stage (Modules A1–A3) generates 66.8 t CO_2e for the complete structure (Table 7). Most of it is concentrated in structural metal members. Aluminium accounts for 37.6% and the steel inserts for 30.9% of the production stage GWP_{100}. Taken together, the three metal components (aluminium, steel inserts and cables) represent 72%, even though they make up only a small share of the total mass. The remaining components contribute less than 30% combined. This makes structural metals an environmental hotspot and the main reason why end-of-life strategies that preserve metal carry the greatest potential for improvement.

Table 7. Contribution by material: Modules A1–A3 (same for all scenarios).

Material	GWP_{100} (kg CO_2e)	Share
Aluminium	25,098	37.6%
Steel inserts	20,650	30.9%
Concrete	11,845	17.7%
Reinforcing bar	3773	5.6%
PVC membrane	3113	4.7%
Steel tension cables	2307	3.5%
Total	**66,787**	**100%**

Figure 6 shows the contribution of individual life cycle stages and materials to the overall climate change impact and confirms that aluminium production carries the largest environmental burden for this type of structure. The main difference between the analysed scenarios appears in the end-of-life phase, where reuse provides higher environmental credits, thereby reducing the initial carbon footprint originating from production.

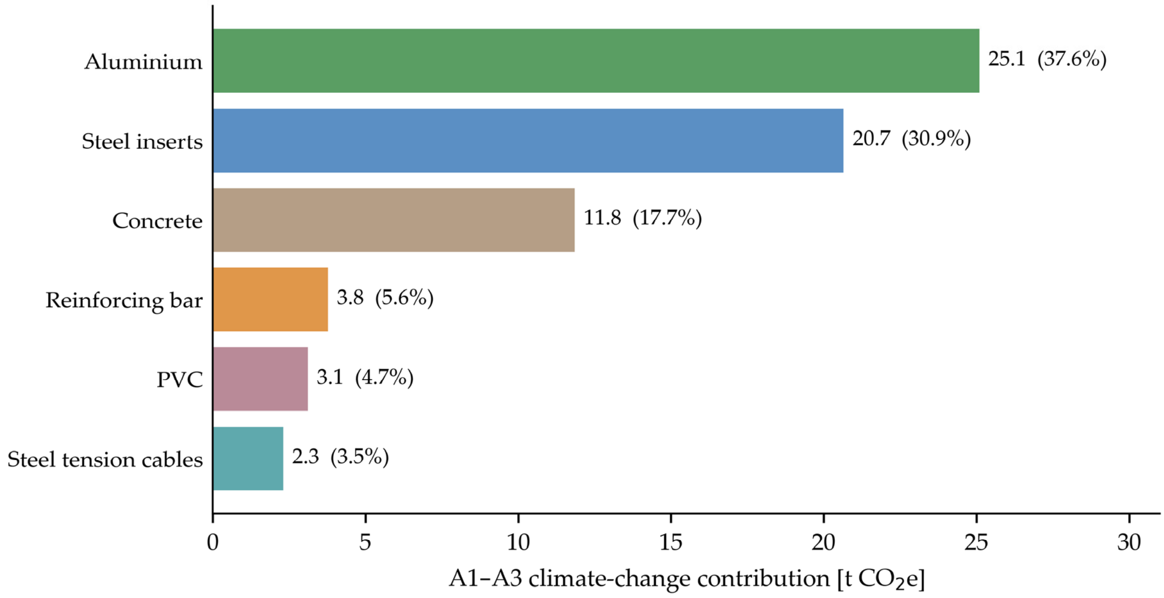

Figure 6. Relative contribution of individual material groups to the global warming potential (GWP_{100}) of the structure.

4.5.2. Comparison of the End-of-Life Scenarios (Climate Change)

In Scenario 1 (cut-off), no end-of-life credits are accounted for, and the total climate change impact amounts to 89.5 t CO_2e.

In Scenario 2, aluminium and steel members are sent to recycling facilities for remelting. Even though recycling requires less energy than primary production, it remains an energy-intensive process. The total net global warming potential for this scenario is 56.6 t CO_2e (37% below the cut-off).

In Scenario 3, aluminium members are dismantled and transferred to a reuse centre for direct reuse, preserving the embodied energy of the primary production and avoiding emissions from the remelting process. The total net global warming potential for this scenario is 44.2 t CO_2e, which is 51% below the cut-off baseline and 22% below recycling.

Figure 7 compares the total climate change impacts across the three end-of-life scenarios. Although Scenarios 2 and 3 share the same initial carbon footprint of the production phase and both deliver significant environmental savings at the end of life, the results clearly demonstrate the advantage of reuse. Implementing the direct reuse strategy reduces the overall carbon footprint by almost 22% compared with conventional recycling, confirming reuse as a substantially more environmentally favourable option for circular construction practice.

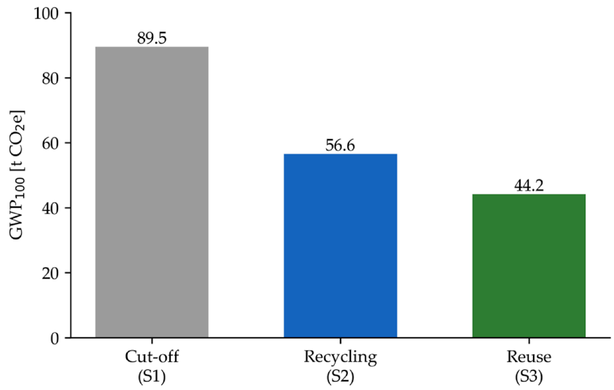

Figure 7. Climate change impact (GWP_{100}) of the three end-of-life scenarios.

4.5.3. Robustness Across Impact Categories

To verify that the scenario ranking is not specific to climate change, the three scenarios were compared across all 16 impact categories of the EF 3.1 method (Table 8, Figure 8). The reuse scenario (S3) has the lowest environmental impact in every category, with reductions relative to the cut-off scenario ranging from 8% for ozone depletion to more than 80% for ionising radiation, human toxicity, and resource use of minerals and metals. By contrast, the recycling scenario (S2) shows less consistent performance, providing only marginal benefits for ozone depletion, water use, and non-cancer human toxicity, while performing worse than the cut-off baseline for resource use of minerals and metals.

Table 8. Life cycle impact of the three scenarios for all 16 EF 3.1 categories, and the saving of reuse (S3) relative to recycling (S2).

Impact Category	Unit	Cut-Off (S1)	Recycling (S2)	Reuse (S3)	S3 Benefit Over S2
Acidification	mol H^+ eq	352	202	108	47%
Climate change	kg CO_2 eq	89,498	56,590	44,200	22%
Ecotoxicity, freshwater	CTUe	694,452	631,259	208,559	67%
Particulate matter	disease inc.	0.00429	0.00141	7.89×10^{-4}	44%
Eutrophication, marine	kg N eq	99.7	72.1	57.6	20%
Eutrophication, freshwater	kg P eq	30.1	17.1	6.42	63%
Eutrophication, terrestrial	mol N eq	719	453	298	34%
Human toxicity, cancer	CTUh	9.48×10^{-5}	3.85×10^{-5}	1.79×10^{-5}	54%
Human toxicity, non-cancer	CTUh	0.00106	0.00102	3.43×10^{-4}	66%
Ionising radiation	kBq U-235 eq	8437	3336	1013	70%
Land use	Pt	231,639	194,607	115,200	41%
Ozone depletion	kg CFC11 eq	0.007	0.00665	0.00645	3%
Photochemical ozone formation	kg NMVOC eq	255	150	105	30%
Resource use, fossils	MJ	857,695	425,218	265,079	38%
Resource use, minerals and metals	kg Sb eq	1.7	1.94	0.263	86%
Water use	m^3 depriv.	21,650	21,168	9897	53%

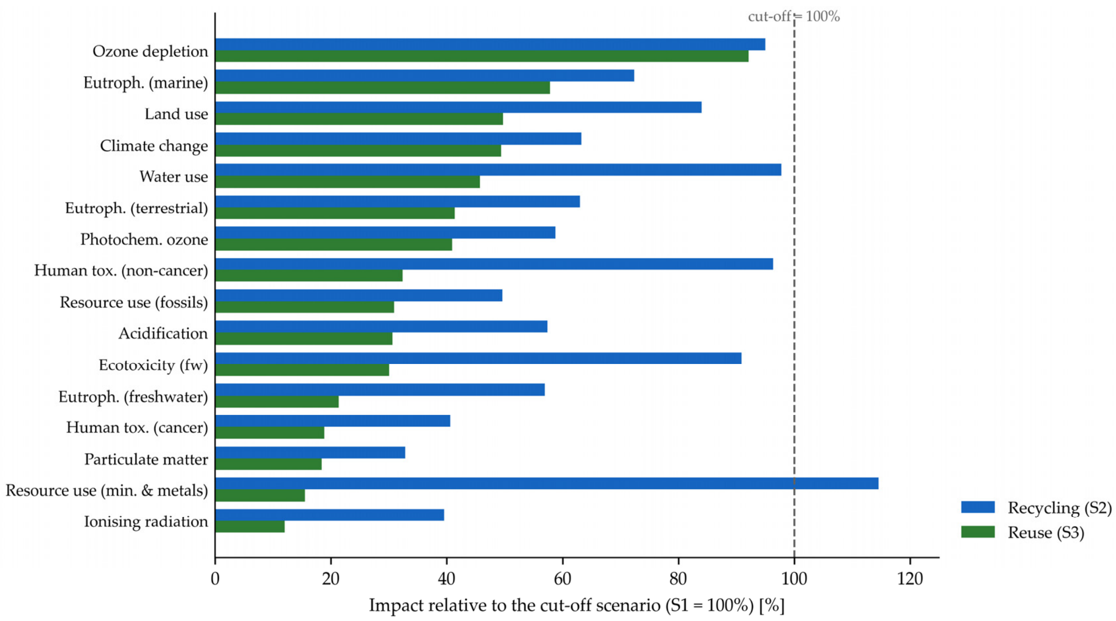

Figure 8. Impact of the recycling (S2) and reuse (S3) scenarios expressed as a percentage of the cut-off scenario (S1 = 100%) for all 16 impact categories.

4.5.4. Influence of the Reuse Rate

The reuse scenario (S3) assumes that 90% of the members are recovered for direct reuse and the remaining 10% are recycled. This is an ambitious assumption, but it is supported by the fact that the case study structure was designed with reuse in mind as a demountable, reusable frame with bolted connections and standardised members chosen specifically to allow disassembly and redeployment rather than demolition. A 90% recovery rate is therefore realistic in the context the structure was designed for. Whether this reuse rate can be achieved in practice depends on the post-service condition of the members and the extent to which careful deconstruction is carried out. To assess the sensitivity of the results under less favourable conditions, the analysis was therefore repeated for reuse rates ranging from 100% to 50% (Table 9).

Table 9. Climate change impact of the reuse scenario as a function of the reuse rate.

Reuse Rate	GWP_{100} (kg CO_2e)	Saving vs. Recycling	Saving vs. Cut-Off
100%	42,938	24.1%	52.0%
90%	44,200	21.9%	50.6%
80%	45,462	19.7%	49.2%
70%	46,724	17.4%	47.8%
60%	47,986	15.2%	46.4%
50%	49,249	13.0%	45.0%

Reuse remains the lowest-impact option across the full range of reuse rates considered. The impact varies almost linearly with the reuse rate, with each 10% increase in reuse corresponding to a change of approximately 1.3 t CO_2e. Even at a 50% reuse rate, the impact remains 13% lower than that of the recycling scenario (S2), Figure 9. These results indicate that the environmental benefit of reuse does not depend on achieving high recovery rates; even partial reuse of the structure performs better than complete recycling.

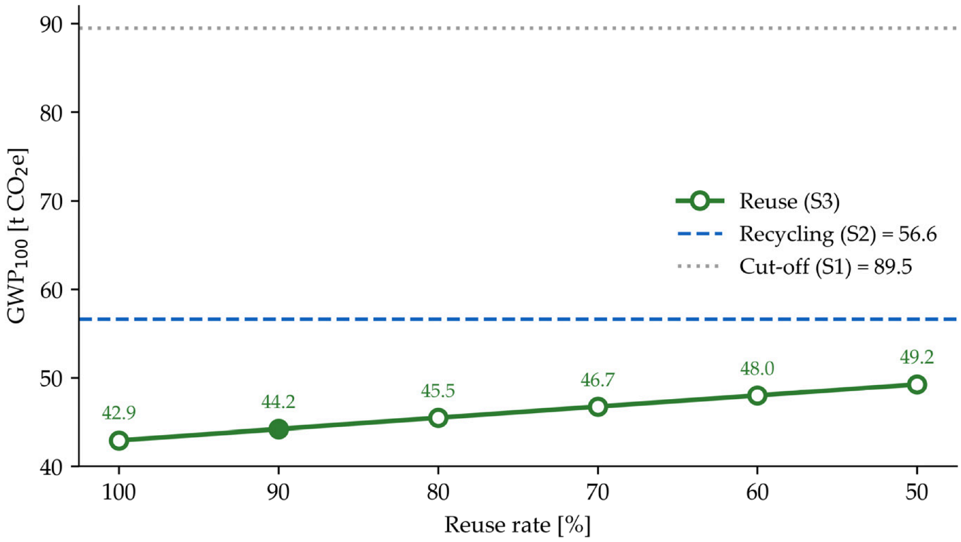

Figure 9. Climate change impact of the reuse scenario as a function of the reuse rate, compared with recycling (S2) and cut-off (S1).

4.5.5. Influence of the Logistics Distance

Reuse generally involves longer transport than recycling. Reclaimed members may either be transported directly to a new construction site or pass through a reuse hub, whereas scrap is typically sent to a nearby recycling facility. This raises the question of whether the additional transport required for reuse could offset its environmental savings (Table 10 and Figure 10).

For 12.1 t of reclaimed metals and an emission factor of 0.106 kg CO_2e per tkm, each additional kilometre adds 1.28 kg CO_2e, resulting in a break-even distance of approximately 9700 km. The red dot marks the break-even point, where the reuse scenario (S3) and recycling (S2) reach equal climate change impact. This distance is far beyond any realistic scenario; therefore, transport cannot reverse the environmental advantage of reuse.

Table 10. Climate change impact of the reuse scenario as a function of the additional transport distance of the reclaimed members.

Additional Distance (km)	GWP_{100} (kg CO_2e)	Saving vs. Recycling
0	44,200	21.9%
1000	45,478	19.6%
2500	47,396	16.2%
5000	50,593	10.6%
7500	53,790	4.9%
9689 (break-even)	56,589	0.0%

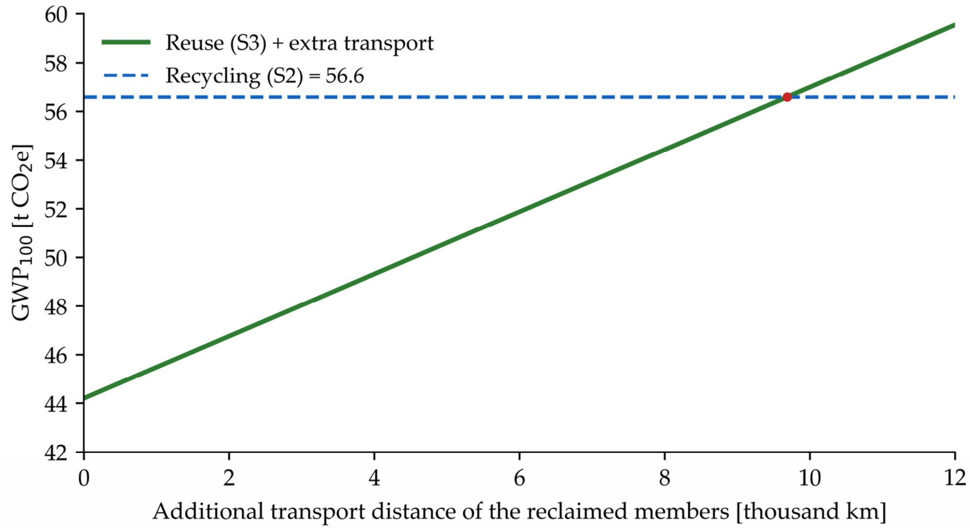

Figure 10. The climate change impact of the reuse scenario as a function of transport distance.

4.5.6. Uncertainty of the Results

To assess the influence of statistical uncertainty in the background data, a Monte Carlo simulation with 10,000 iterations was performed for each scenario in SimaPro 10.3.0.3 [59]. The resulting climate change distributions are summarised in Table 11 and shown in Figure 11. The distributions occupy distinct ranges, with coefficients of variation of approximately 5%. The 95% intervals for reuse (40.2–49.4 t CO_2e) and recycling (51.1–63.4 t CO_2e) do not overlap, with the upper bound of the reuse interval below the lower bound of the recycling interval. Across the full simulation, reuse has a lower climate change impact than recycling in 99.9% of the runs, with the few exceptions occurring only in the distribution extremes outside the 95% intervals.

In addition, the reuse scenario has a lower impact than the cut-off scenario in 100% of the runs. This estimate is conservative because the three scenarios were simulated independently. Since the scenarios share the same production stage, their impacts would in practice be positively correlated, which further reinforces the statistical robustness of the reuse advantage.

Table 11. Monte Carlo statistics of the climate change impact (10,000 runs per scenario) in t CO_2e.

Scenario	Mean	SD	CV (%)	95% Confidence Interval
S1–cut-off	89.5	4.1	4.6	82.1–98.4
S2–recycling	56.6	3.2	5.6	51.1–63.4
S3–reuse	44.2	2.3	5.3	40.2–49.4

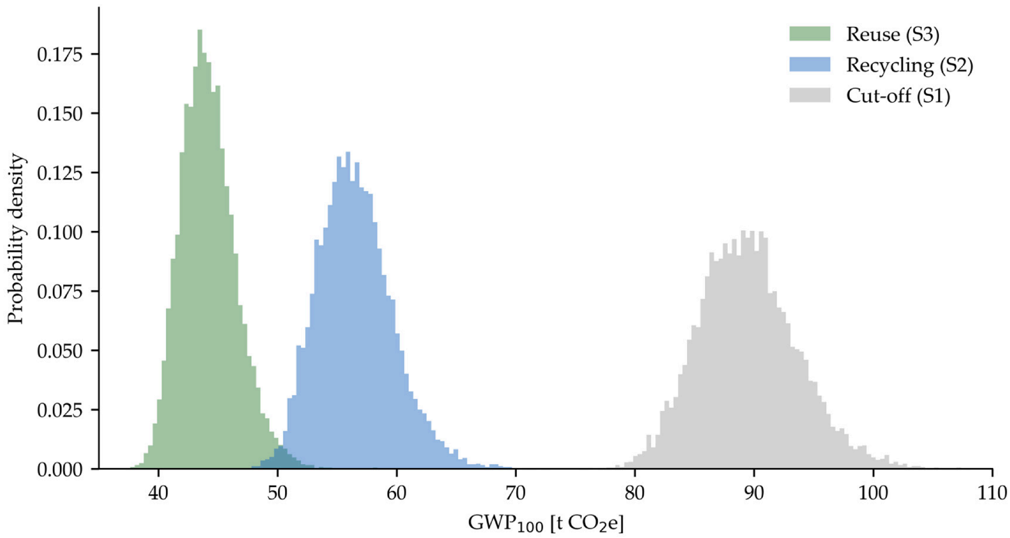

Figure 11. Probability distributions of the climate change impact of the three scenarios from the Monte Carlo simulation (10,000 runs each).

5. Discussion

The three end-of-life strategies are clearly ranked: direct reuse outperforms recycling, and recycling outperforms the cut-off baseline. For climate change, reuse of the aluminium structure results in 44.2 t CO_2e, corresponding to reductions of approximately 22% compared with recycling and 51% compared with the cut-off scenario. Although both circular scenarios perform favourably, the additional benefit of reuse compared with recycling is significant. This benefit arises because reuse preserves both the primary energy and the manufacturing effort already embedded in the extruded profiles.

The contribution analysis explains why the end-of-life strategy is particularly important for steel and, especially, aluminium. These metals account for almost three-quarters of the production-stage GWP_{100}, despite representing only a small proportion of the total mass. Retaining metal components rather than scrapping them is, therefore, where the largest environmental benefit lies, placing reuse ahead of recycling in a circular construction strategy.

Several analyses confirm the robustness of this ranking. It holds for reuse rates as low as 50%, indicating that the results do not depend on the optimistic 90% baseline assumption. It also holds across all 16 impact categories. In addition, the transport contribution is negligible, with a break-even distance of approximately 9700 km, while the Monte Carlo simulation ranks reuse as the lowest-impact option for climate change in 99.9% of 10,000 runs. The advantage of reuse is therefore not the result of a single assumption but represents a robust case for prioritising structural reuse in the transition to a circular economy. The limited influence of transport is encouraging from an engineering perspective, as it suggests that regional and even cross-border networks of reuse hubs can be environmentally justified.

Some limitations remain. The functional unit covers a single service life, whereas crediting multiple consecutive use cycles of a demountable system would likely further favour reuse. The assessment is attributional and static, and the end-of-life credits depend on the cut-off-with-Module-D allocation approach adopted here. Finally, the number of assembly–disassembly cycles that demountable aluminium connections can sustain has not yet been quantified experimentally. In this paper, this limitation is addressed by treating bolts as replaceable consumables and by inspecting the connection zones during each component survey.

6. Conclusions

This paper examined the environmental and technical feasibility of reusing aluminium structural components in circular construction by combining a reuse pathway that accounts for aluminium-specific challenges with a comparative life cycle assessment of a portal frame tent structure under three end-of-life scenarios, carried out in accordance with EN 15804+A2 and the EF 3.1 method. The proposed reuse pathway demonstrates that the direct reuse of aluminium structural members is technically feasible, provided that key material-specific challenges are systematically addressed, namely: the absence of a fatigue endurance limit, irreversible property loss in heat-affected zones, the identification of alloy and temper condition, the risk of galvanic corrosion at connections with dissimilar metals, and the susceptibility of thin-walled extruded profiles to local damage during deconstruction.

The life cycle assessment results quantitatively confirm the environmental benefits of aluminium reuse. The cradle-to-gate impact of the reference portal frame tent structure amounts to 66.8 t CO_2e and is dominated by aluminium production, which contributes 37.6% of the total production-stage global warming potential despite representing only approximately 3.3% of the total structural mass and together with the steel inserts and cables contribute to roughly 72% of emissions. This disproportion between material mass and environmental impact identifies aluminium as one of the most impactful materials for the implementation of circular strategies in structures.

Among the three end-of-life scenarios assessed in accordance with EN 15804+A2, the reuse scenario (Scenario 3: 90% direct reuse, 10% recycling) achieved the lowest net life cycle impact, at 44.2 t CO_2e, about 22% below recycling (56.6 t CO_2e) and about 51% below the cut-off baseline (89.5 t CO_2e). Reuse is also the lowest-impact option in all 16 EF 3.1 categories, whereas recycling benefits only some indicators. The results show that the reuse of aluminium structural components is both technically feasible and environmentally advantageous. The barrier to wider adoption is not the material itself or any physical barrier, but the lack of dedicated technical specifications, clear certification pathways, and organised regional supply chains for reused components.

Future work should focus on the factors that determine realistic reuse rates, as these have a dominant influence on the environmental outcome. In addition, the durability of connections under repeated assembly–disassembly cycles should be investigated experimentally to establish how many reuse cycles bolted aluminium joints can sustain. Further research should also extend the functional unit to the multiple consecutive life cycles for which demountable systems are intended, as this would further amplify the benefits of reuse. Complementing the environmental assessment with life cycle costing would help confirm the economic feasibility of reuse, while additional experimental evidence is needed to support the development of an aluminium-specific technical specification analogous to the provisions that currently exist for structural steel.

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