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Exploring the effective reuse rate of materials and elements in the construction sector

Émilie Gobbo [a,b,*], Elham Maghsoudi Nia [c], Ad Straub [c], André Stephan [d]

[a] Louvain Research Institute for Landscape, Architecture, Built Environment, Université Catholique de Louvain, B-1348, Louvain-la-Neuve, Belgium
[b] Brussels Environment, Avenue Du Port 86C, 1000, Brussels, Belgium
[c] Delft University of Technology, Julianalaan 134, 2628 BL, Delft, the Netherlands
[d] The University of Melbourne, Parkville, Victoria, 3010, Australia

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ABSTRACT

In North-West European countries, the uptake of reusing construction elements following their first use in a building is still low. Although a large number of elements are technically reusable, they end up being recycled by crushing ormelting, or simply disposed of. This results in a high environmental impact and a net loss of economic value. This study aims to define a framework that can guide project managers, public and local authorities, as well as other organisations in setting, measuring, and reporting rates of material reuse in construction and renovation projects. To support this, a retrospective analysis was conducted on 32 construction and renovation projects that have incorporated reclaimed elements. To quantify the effective reuse rates, the data are categorised according to the types of work, functional layers, and type of projects. In summary, achievable reused targets can be determined for the structural layer (1–5% in mass), skin layer 5–15 % in mass), space plan layer (10–25 % in mass), and for outdoor surfaces (0–50 % in mass). Results confirm the contextual nature of reuse practices, emphasising that the achieved rates of reuse are linked to project types in specific layers, and depend on the overall quantity of materials in a project. It also underscores the importance of integrating reuse rate calculations proactively at the beginning of the project, particularly during the preparation of the bill of quantities. This can be accomplished by utilising appropriate procurement strategies, as-built documentation, monitoring material flows during works, and establishing a detailed record of reclaimed building elements.

1. Introduction

Minimising the environmental impact of material consumption is essential for climate change mitigation. The utilisation of materials significantly influences global emissions and contributes to the generation of substantial waste, underscoring the importance of sustainable resource consumption [1–3]. The linear economic system necessitates substantial material inputs, leading to the production of significant emissions and waste [4,5]. Therefore, it is necessary to reduce the environmental impact of our current linear system of production and consumption [4,6]. The built environment is a major driver of raw material extraction (40 %) [7] and represents the majority of all in-use material stocks. The construction industry faces a significant challenge in reducing its consumption

* Corresponding author. Louvain Research Institute for Landscape, Architecture, Built Environment, Université Catholique de Louvain, B-1348, Louvain-la-Neuve, Belgium.
E-mail address: emilie.gobbo@uclouvain.be (É. Gobbo).

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of natural resources [8]. One of the methods for achieving a circular economy in construction and decreasing the demand for new materials is the reuse of materials and treating the existing building stock as a resource, that would otherwise end up as waste [8,9]. Current practices in building design and construction rarely take into account closed-loop material systems, and incorporating reuse into building projects faces numerous challenges from both a technical and economic perspective [10]. Over the past decade, some companies have been shifting away from the linear paradigm of extraction, production, and disposal towards a more circular model, exemplified by the 9R Framework of Circular Approaches and the commonly referred to "10R ladder" of circularity strategies [11,12]. These strategies, ranked from the most to the least impactful, include R3 for reuse, R4 for repair, and R5 for refurbishing. In the circular model, even before recycling, the primary emphasis is placed on reduction and reuse, necessitating a more substantial commitment to these aspects [13]. Reuse involves dismantling existing materials without destroying them and aims to reuse these materials. This reuse process replaces materials that would otherwise need to be newly purchased. Unlike recycling, which involves chemical or physical processes to convert materials back into raw forms, reuse keeps the materials in their original state. According to legislation, reuse is also defined as: "any operation where products or components that are not waste are used again for the same purpose for which they were originally intended" (*Ordinance of 14 June 2012 of the Brussels-Capital Region on waste, B.S., 27 June 2012, art. 3, 18*) [14].

The reuse approach highlights the practicality of utilising disposable items repeatedly [15], thereby reducing the environmental impact by extending the life cycles of products, and not only reducing waste production and accumulation but also significantly avoiding the need to produce new items. The production phase notably has the most significant impact on the entire product life cycle [16,17]. The findings of a study from Norway suggest promoting reuse could greatly benefit from increased communication and collaboration among different stakeholders in the supply chain. Manufacturers can play a key role and should have a more active role in reuse processes. Effective planning and practical implementation of reuse can be enhanced by a well-established research framework [10]. In addition, public authorities, as key actors, play a significant role in increasing reuse practices.

Moreover, for a reuse strategy to be effective, essential factors need to be considered: a clear understanding of the quantities of materials in stock, their availability, and their potential for recovery in ways that are both environmentally and economically feasible [8]. However, this potential is often limited by information gaps throughout the material life cycle [9]. Moreover, there is an information gap on the potential reuse rate that can be considered in the construction industry. The Ellen MacArthur Foundation reports only 20–30 % of construction and demolition waste (CDW) that can be either recycled or reused [18,19],while there is a lack of knowledge and common methodology to report on the reuse rate specifically in the construction sector [20,21].

Therefore, this paper aims to respond to the lack of quantitative data on actual reuse achieved in construction and renovation projects that have incorporated and implemented reused elements. In a broader sense, it may also be employed as a foundation for investigating the feasibility of establishing reuse objectives within the construction industry.

1.1. Setting reuse target, monitoring and reporting on reuse rate

Reuse practices in the construction sector are not new [22]. Projects with reuse ambitions, whether qualitative or quantitative, are currently enjoying renewed interest in the current context [23]. Despite the promotion of reuse as a circular strategy, there is still a lack of consolidated data regarding quantitative analyses being carried out, particularly from an environmental point of view [16,17,24]. This applies not only to the monitoring of efforts during the construction phase but also to the assessment of the project at the end of its implementation and provisional reception, to check whether the initial ambitions have been met [25]. This raises the difficulty of quantifying reuse efforts for the project team and, at a larger scale, the lack of a harmonised method for monitoring and evaluating projects and efforts made to meet circular and environmental objectives.

In addition, reuse is often associated with the recycling or preservation of building parts [25]. If we refer to the Lansink scale advocated by the Waste Framework Directive [26], these three approaches are actually quite distinct and hierarchical in their priority for action: prevention through the preservation of buildings and reuse, preparation for reuse and finally recycling before energy recovery and landfill to be avoided. Moreover, a further distinction needs to be made concerning reuse issues. Indeed, identifying the *potential for reuse* does not necessarily lead to *effective reuse*. In a similar way to recycling, a differentiation can be made in the type and quality of reuse carried out: *equivalent reuse* is when requirements for the reclaimed components are globally comparable, whereas downcycling reuse appears when the final requirements of effectively reused elements are lower [27]. Yet, in both cases, the elements are first reclaimed and then effectively reused. This paper does not go into this level of detail but focuses on the differentiation between the reuse potential, the reclaimed elements and those effectively reused. The use of some of these terms will be clarified in Section 1.4.

The current confusion between reuse and recycling, combined with the absence of a harmonised accounting method in projects, adds a further level of complexity and difficulty in accurately calculating and reporting on reuse efforts. This can lead to several issues, such as a lack of comparability or misinterpretation of results reported by project teams, as well as a lack of transparency in the way the calculations are made [25,28,29]. Reporting on reuse efforts is important, notably to identify the contribution of reuse practices, and circular practices more broadly, to efforts to reduce environmental impacts [16,17,24,27,30]. In this sense, differentiating the *reusable potential* of an item from its *effective reuse* is essential. Achieving an effective reuse rate generally requires a prior objective or intention to reuse, either qualitative or otherwise. Finally, on a broader scale, it should be noted that the EU requires reporting on effective reuse efforts by sector [26]. A broader, more in-depth assessment, including material, economic, and environmental balances at the end of the work site, could help feed databases that are used in the reuse assessment.

1.2. Measuring reuse rate in the construction sector

This article aims to respond to the lack of quantitative data on actual reuse achieved in construction and renovation projects that have incorporated and implemented reused elements. The approach proposes the development of a clear and transparent method of analysis. The latter can be used to fuel reflection on the need to establish a common methodological framework for the quantitative analysis of effective reuse, which is currently lacking. This paper emphasises the importance of reusing materials as a circular approach. It explores the possibilities, conditions, and preparations necessary for reusing materials and components in the construction sector. The approach involves several key steps:

1. Identification of Material Flows: The initial step involves providing a comprehensive description of material flows in the construction sector. This includes a description of stock, inflow and outflow materials that have been used for this study.

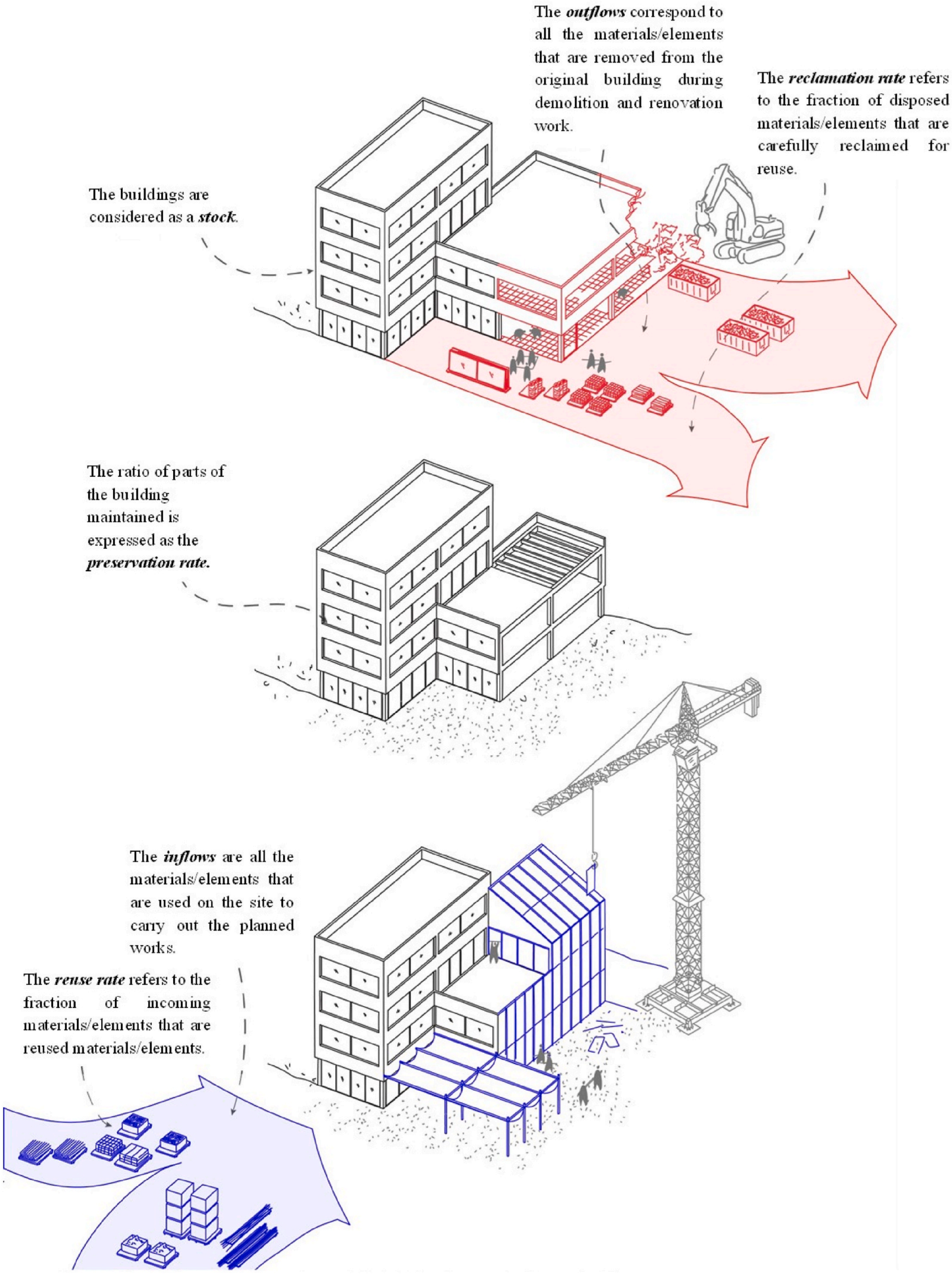

Fig. 1. Preservation, reclamation and reuse rate definition for construction work [25].

2. Reuse Rate Measurement Method: The study proposes a novel method to measure the reuse rate of materials. This involves developing a systematic approach to quantify the rate of reused materials in construction processes.
3. Analysis of case study projects: through a case study approach across Northwestern European countries, the actual amount of reused materials is explored and analysed. These case studies provide insights into real-life scenarios, considering regional variations and specific conditions.

The research question of the study is twofold: (1) What method can be developed to set, measure, and report on material reuse rates in construction and renovation projects? and (2) What material reuse per building type and layer is feasible?

1.3. Differentiation between stocks and flows, preservation, reclamation, and reuse rates

The emphasis on efficient material use and CDW management has prompted numerous countries to engage in mapping, analysing, and improving the performance of CDW-related activities through the application of Material Flow Analysis (MFA) [31]. Japan is a pioneer in incorporating material flow indicators into policy development. While the initial motivation for Japanese policy was centred around waste minimisation, it gradually expanded to adopt a more comprehensive life-cycle perspective on waste and material inputs, in line with the principles of the 3Rs (Reduce, Reuse, and Recycle). These concepts have exerted significant international influence, particularly within the G7 economies [32].

The main objective of Material Stock Analysis (MSA) is to quantify the accumulation and composition of material stock, which includes buildings and infrastructure, within a defined geographic area, considered as a system. Whereas Material Flow Analysis (MFA) seeks to track all incoming and outgoing flows within a defined geographic area, such as cities, urban regions, or countries, adhering to the principle of mass conservation. It serves as a valuable tool for modelling spatially dynamic material flows [33–35]. MFA quantifies the materials that move through a defined system within a specific timeframe [36]. However, there exists a gap in linking the assessment of available resources with the material needed for consumption or new construction. Despite significant attention and agreement within the academic community on the need to extend the life cycle of materials through reuse and the potential of upcycling reclaimed materials, its implementation has primarily been confined to recycling and downcycling. Consequently, achieving the effective reuse of reclaimed building elements requires more comprehensive information regarding the initial material stock present in the building and the material outflows resulting from partial or total demolition [1].

There is still often confusion between the terms reuse, recycling, and even preserving or maintaining parts of a building, even though they do not imply the same approaches or impacts. In this regard, this article clarifies the use of these terms and the method of quantifying the relevant rates. Hence, we have defined three terms for setting a reuse target applicable to renovation, construction, or demolition work. These are preservation, reclamation, and reuse rates (Fig. 1). These terms contribute to a structured approach in assessing and quantifying the extent of reclamation and reuse activities within the context of various construction projects.

Preservation rate (Stock). One crucial aspect is to specifically separate stock logic from flow logic. In this paper, the stock refers to what remains static. In simpler terms, it refers to the portion of existing facilities that is conserved, retained in its original position, and not put into circulation. From the standpoint of a circular economy and responsible resource management, the foremost goal should be to optimise the preservation of the existing stock. Consequently, this results in minimising the creation of flows (out and in). This preventive approach should consistently be regarded as the top priority. The preservation rate can be stated using the following formula [25]:

$$\text{Preservation rate } [\%] = \frac{\text{Quantity of retained building } [\text{kg}]}{\text{Quantity of original building } [\text{kg}]}$$

Accordingly, a complete demolition scenario would result in a preservation rate of 0 % since the mass of the non-demolished building would be equal to 0 kg. In contrast, a scenario involving light renovation, wherein the structure, envelope, and some finishes are largely preserved, can achieve a relatively high preservation rate. For instance, a project targeting a 90 % preservation rate implies that 90 % of the materials composing the original building will be conserved and remain in place during the conversion process. In the case of a new construction project on a vacant plot, the materials preservation rate becomes irrelevant as there is no pre-existing stock in-situ.

Reclamation rate (Outflow). The outflows involve all building elements extracted from the original building during demolition and renovation activities. These practices may range from rapid and destructive, resulting in the generation of more mixed waste, to preserving and cautious, facilitating the effective reclamation of building materials and elements. The reclamation rate indicates the proportion of materials and elements sourced from the original site that undergo a precise reclamation process for potential reuse in a new context. This may involve reuse on the same site or another location, with or without processing by a professional reclamation company. The reclamation rate can be stated using the flowing formula [25]:

$$\text{Reclamation rate } [\%] = \frac{\text{Quantity of material reclaimed for future reuse } [\text{kg}]}{\text{Total quantity of disposed materials } [\text{kg}]}$$

Reuse rate (Inflow). Renovation and construction activities result in an inflow of materials, involving all the materials and components used on-site to execute the planned work. What we are investigating in this paper, is the percentage of materials that have been reused during the renovation or construction. The reuse rate can be stated as follows:

$$\text{Reuse rate } [\%] = \frac{\text{Quantity of materials reused during the work } [\text{kg}]}{\text{Total quantity of materials used for the works } [\text{kg}]}$$

This rate includes materials recovered from the original building and reused on the same site, as well as materials sourced externally from other locations. However, it excludes materials and components that have been preserved in their original location as part of the efforts to maintain the existing stock. Based on the nature or origin of inflow materials, they can be subdivided into bio and geo-based materials, materials with recycled content, new materials, etc. This classification indicates that the careful selection of materials regarding sustainability and environmental considerations plays a crucial role in mitigating the overall environmental impact of construction projects.

Among the three rates defined above, this article focuses on inflows and therefore reuse rates, i.e. the proportion of reused materials compared to the total proportion of imported materials by type of functional layer.

2. Method

This paper focuses on the analysis of the reuse rate that was effectively achieved on 32 delivered construction and renovation projects in northwest Europe (geographical area of the Interreg NWE funding program), including Belgium, France, the Netherlands, Luxembourg and the United Kingdom. For this purpose, the analysis is based on a retrospective approach and concentrated on the proportion of reclaimed building elements compared to the materials needs of the projects (inflows). To ensure comparability and greater precision in interpreting the quality of the reuse rates achieved, a clear and transparent framework is defined. This includes the following main steps and their related question:

1. Definition of the scope
   - System boundaries: Does the incoming material flow refer to the entire flow or just a segment of the flow for specific applications, construction layers, or specific materials?
     - Measurement unit(s): Will the flow be assessed in terms of mass, volume, financial volume, or environmental impact?
   - Detail level: Are we aiming for a broad overview or a precise examination down to the detail?
2. Data collection includes the identification, selection, and documentation of case studies having integrated reclaimed elements:
   - Classification of projects into different clusters according to the type of work envisaged the project scale, and the function of use.
3. Restructuring and processing of data collected
   - Identification of effectively reused elements and categorisation by functional layers of buildings.
   - Systematic transposition of data into units of mass.
4. Assessment:
   - Calculating the effective reuse rates achieved by the functional layer
   - Evaluation of the CO_2 eq. savings of the operation

In the following sections, we apply the developed method and the steps described above.

2.1. *Scope of the study*

This part has already been partially introduced in section 1.4. This analysis focuses on the share of reused materials in the incoming flow of materials in construction or renovation projects. These are materials put into circulation that may come from the construction site itself (in situ reuse) or from elsewhere (ex-situ reuse). The analysis focuses on the project scale. Only the functional layers concerned by reuse elements are considered in the calculations. Consequently, the analysis excludes elements recovered from the waste stream generated by prior demolition/deconstruction, referred to as "outflow". In the case of renovation work, any parts of the existing building that have been preserved through a maintenance strategy are not included. Finally, all materials derived from recycling are also excluded from the analysis.

The determination of the reuse rate can be stated using different units, including:

- Mass of material [kg];
- Volume of material [m^3];
- Financial volume of reuse operations (in monetary units or as a percentage of a budget); or
- Calculation of environmental impacts and potential benefits, involving various units associated with different indicators.

In this paper, Mass has been chosen as a fundamental metric for several reasons:

- It is a physical property that is well-suited for quantifying material quantity and is part of the International System of Units;
- It can be measured objectively with relative ease;
- Measuring mass is a crucial step for quantifying environmental impacts, e.g. through life cycle assessment; and
- It is the reference unit used in the European report on the management and recovery of construction waste and thus results from this study are comparable to others relying on the same unit.

However, there are some limitations in using mass units. A primary practical limitation arises from the current lack of direct mass measurements for material flows in construction or renovation projects. Quantity surveys and detailed bills of quantities commonly use specific functional units for various materials, requiring conversions to express quantities in mass. Additionally, setting targets based on mass may induce bias favouring heavier elements, potentially leading to strategic behaviours by project developers prioritising the reuse of heavier materials over lighter ones. This bias may not align with broader considerations such as environmental benefits, support for innovation, market development for reclamation, and aesthetic considerations.

2.2. *Data collection*

The data collected for the study are categorised using different building layers, e.g. skin, structure. Then, the reused rates are calculated based on the mass of the elements. Both are described in the following sub-sections.

2.2.1. *Data of reused elements categorised per layer*

Realistic reuse rates are significantly influenced by the type of application within a building. For instance, structural assemblies, such as foundation footings, are rarely, if ever, composed of reused materials. Conversely, when it comes to interior finishes, substituting reused materials for new ones is often relatively easy. Given these variations, it may be beneficial to set differentiated targets for different construction assemblies. Here, we discuss three potential approaches:

1. Establish a reuse rate for the entire project: this approach involves the target rate applying to the overall flow of incoming materials.
2. Establish a specific reuse rate for each application area or layer constituting a development: the targeted rate(s) relate to specific parts of the incoming material flow. This approach allows for distinct values to be assigned to different identified materials, elements or assembly taxonomy [37].
3. Establish a reuse rate for specific batches of materials.

These three options are not inclusive, and other valid methods exist for defining the scope to which the reuse rate applies. For instance, it could be determined based on different lots within a contract, distinct phases of the works, or diverse trades involved. In

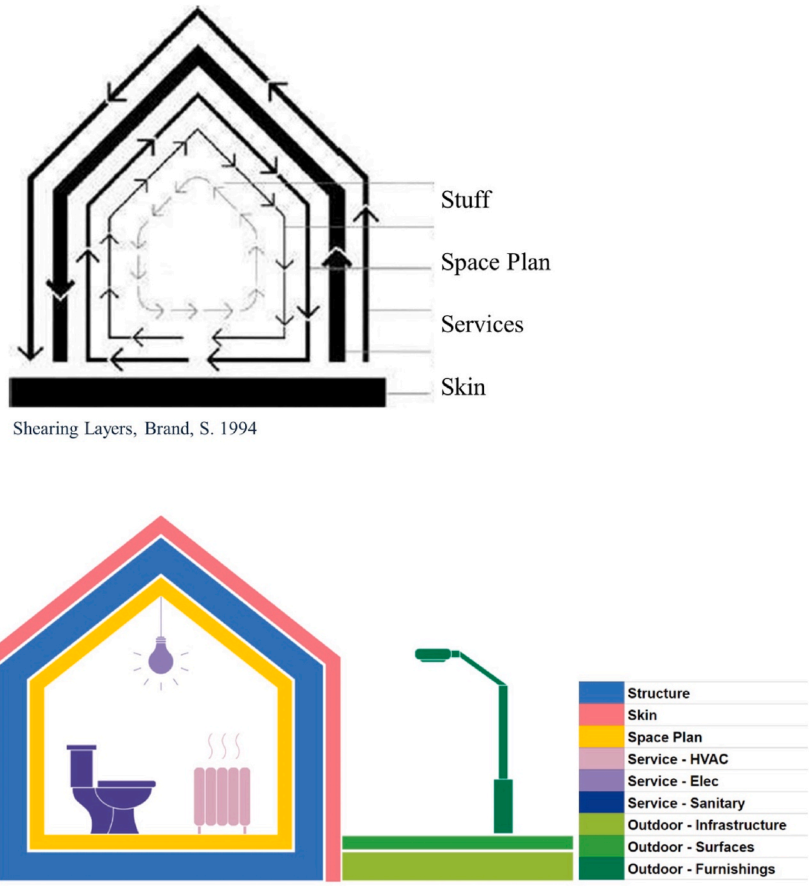

Fig. 2. Developed layers' classification based on Brand's shearing layers [29].

this paper, rates are linked to the layers option, and the broad principles can be adapted to specific cases. The reuse target rate “per layer” approach is based on a concept introduced by Stewart Brand in his book "How Buildings Learn: What Happens After They’re Built" (1994). Brand distinguishes between various component layers in the built environment, demonstrating that these layers undergo different renewal patterns. Design for Deconstruction studies have widely embraced this concept, emphasising the importance of keeping these layers independent to minimise waste during renewal operations. For instance, renewing a single internal partition should not lead to the demolition of the entire structure to which it is attached. Using this subdivision, we can establish reuse rates for different layers, allowing for the measurement of objectives based on each layer. For instance, aiming for lower rates for more complicated layers (such as the structure) and higher rates for less complex layers (such as interior finishes). The "per layer" approach is adaptable to various types of processes. For example, a new construction involves all layers, whereas a light renovation focuses only on the internal layers.

Brand’s six shearing layers serve as the benchmark for our classifications and are employed in the analysis of the 32 completed projects [38]. However, during the analysis, Brand’s layers needed to be subdivided into additional subcategories to effectively classify reused materials into their most appropriate layers. In the adaptation of Brand’s layers, the layer of “Site" was replaced with "Outdoor spaces," incorporating three additional layers (Infrastructure, Surface, and Furnishing) to better categorise materials related to the surrounding environment. Similarly, the layer of “Services” was divided into three categories: “HVAC, Electricity, and Sanitary” (Fig. 2). In the analysis, furniture, representing the "Stuff" layer in Brand’s model, has been excluded. This decision was taken since this layer falls less within the scope of the work covered by architects, as furniture is usually the responsibility of the occupant, and the information is not necessarily included in the measurements and plans, or even in the mission statement.

The following layers have been used in our analysis:

- Structure
- Skin
- Space Plan
- Services - HVAC
- Services - Electricity
- Services - Sanitary
- Outdoor - Infrastructure
- Outdoor - Surfaces
- Outdoor - Furnishings

Our approach involved utilising the bill of quantities for each project. For each line item, we specified whether the element was new or reused and identified the layer to which it belonged. While the initial subdivision of the bill of materials in some projects aligned well with our adopted layer structure, in other cases, we needed to reorganise the bill of quantities according to our layers. This reorganisation necessitated making choices, which involved some interpretative aspects. We maintained transparency and consistency with these choices throughout the process.

A detailed analysis was only conducted on layers containing reused elements. Consequently, in most cases, we could not express the reuse rate for the entire project. For instance, consider a new-build project focused on reusing 10 interior doors and 10 washbasins. In this scenario, our analysis concentrated on the layers of space planning and services sanitary. However, within each of these layers, we examined the entire material flow, including both new and reused materials. Other layers were not subjected to detailed analysis since their reuse rate was known to be 0 %.

2.2.2. Calculating the mass of reused elements

After adapting the bills of quantities to align with the layers, we proceeded to quantify the reuse rate. This involved assigning a mass to each line item in the bill of quantities belonging to a layer affected by reuse. It was decided that mass would be used as the unit of measurement in order to ensure comparability between the different elements. It is important to note, however, that this choice may introduce a certain degree of bias. For instance, the reuse of elements such as concrete, steel, or bricks may result in higher reuse rates than those observed with lighter elements, such as wood or interior finishes. It is important to note that this advantage may not be necessarily applicable or proportional when considering other units and indicators, such as economic or environmental costs. However, the impact is largely mitigated by the layer-specific approach. This decision prevents mixing elements with vastly different mass magnitudes, such as 100 m^3 of poured concrete screed with a dozen door handles, for example. In practical terms, bills of quantities rarely provide material masses directly; instead, quantities are typically expressed in various units (m, m^2, m^3, no., etc.). Therefore, a conversion process is necessary to derive the mass of materials, which is crucial for calculating reuse rates.

In our analysis, we performed the conversion using the following methods:

1. For homogeneous materials, we determined the mass by multiplying the volume by the density (kg/m^3) or, in rarer cases, the surface area by the mass per unit area (kg/m^2). If the specifications of the materials are available, the volume is generally straightforward to calculate. For instance, in the case of a masonry structure expressed in surface area with known brick thickness.
2. For composite materials and/or materials with challenging volume measurements, the mass was derived by multiplying the number of units by their unit mass.

Density and unit mass are not consistently available in quantity surveys, necessitating the search for alternative data sources. Our approach involves utilising the following elements, prioritised in the following order:

1. Technical data sheets for the components: examining plans, images, technical data sheets, and as-built documents generally provided precise data.
2. Reference databases: in cases where specific information was lacking, we turned to databases expressing the density of materials.
3. Specific assumptions: in the absence of specific or standard data, we made assumptions, often relying on data from comparable items. These assumptions and data sources are explicitly mentioned and sourced in our reference database.

Upon identifying all elements constituting a layer subject to reuse, we computed its total mass, inclusive of the mass of reused elements. A simple division then facilitated the determination of the achieved reuse rate within a given layer.

2.3. Case study overview

The process of selecting case studies and clustering each project are described in the following sub-sections.

2.3.1. Case study selection

From an initial pool of approximately sixty projects, we selected 32 construction and renovation works across northwestern European countries including Belgium, France, The Netherlands, and the United Kingdom for analysis. The primary criterion involved the successful reuse of building materials and elements within these projects. We included the reclamation rate of elements disassembled from the initial structure, intending to reuse them in the new project (i.e., scenarios involving reuse on the same site). However, in alignment with the earlier explanation, we excluded materials and components that were not dismantled, as they remained in their original location and, as a result, contributed to the preservation of the existing stock. We identified such projects through the utilisation of various information sources, namely:

- Websites dedicated to cataloguing reuse projects;
- Pilot initiatives conducted during the initial phase of the project;
- Circular calls for projects in some of the project's partner countries; and
- Literature addressing the subject of reuse.

In addition, to ensure geographic diversity, we distributed the selected projects across the distinct countries within the project area. The final selection comprised 14 projects in Belgium, 9 in France, 8 in the Netherlands, and 1 in the United Kingdom. The subsequent focus aimed at ensuring diversity within the selected projects, particularly in terms of programs. Covering a broad range of functions, we intentionally avoided exclusive emphasis on specific building types, recognising that, for instance, solely analysing office projects would lack comprehensive representation. Achieving a balance between new constructions and renovations, a critical determinant of achievable reuse rates was also considered. A focus on relatively recent projects was integral to our approach, with the oldest project, being completed in 2002. Moreover, we diversify the scale of projects, spanning from small-scale constructions to those with extensive surface areas, and even outdoor developments covering several hectares. It should be noted that our overall selection was somewhat influenced by limitations related to access to information. Most of the selected projects for analysis did not explicitly establish a reuse rate as a predefined objective at the start of the project. Nevertheless, many projects have formulated qualitative and open-ended reuse targets, which we quantify. Our goal in examining these 32 projects was to explore achievable reuse rates in diverse contexts and assess the feasibility of deriving indicative rates to assist in establishing quantitative targets for future projects.

Table 1
Clustering of the 32 case study construction projects by type, and associated details.

Code	Cluster	Number of projects	Location	Project surface area (m^2)	Number of layers with reused materials/ components[a]	Type
1–4	Social and Cultural Facilities (1)	4	FR, BE	1009–4000	1–8	Renovation
5–12	Housing (2)	8	BE, UK, FR	160–6330	1–7	Renovation/New Construction
13–20	Tertiary Buildings (Commercial/Office Buildings) (3)	8	NL, BE, FR	3334–45,120	1–5	Renovation/New Construction
21–27	Micro-Projects and Demonstrators (4)	7	NL, BE, FR	7.70–204	2–6	Renovation/New Construction
28–32	Outdoor Spaces (5)	5	NL, BE, FR	4820–130,000	1–2	Outdoor Spaces is considered neither "New Construction" nor "Renovation

Note: [a] Numbers indicate the count of the nine developed Brand's shearing layers that incorporate reused materials or components.

2.3.2. Clustering projects

To enhance comparability and refine the analysis of the results across the 32 projects [28], we categorised them into five clusters based on building types:

1. Social and Cultural Facilities;
2. Housing;
3. Tertiary Buildings (Commercial/Office Buildings);
4. Micro-Projects and Demonstrators; and
5. Outdoor Spaces.

These clusters were determined based on the initial selection of projects and were further developed during a participatory workshop involving the project partners. Factors such as program type, nature of the work, project scale, and architectural approaches were considered in grouping the projects. The classification of the 32 projects according to surface area and whether they are new builds or renovations are presented in Table 1. Projects involving the development of outdoor spaces are only classified according to surface area and not according to whether they are new builds or renovations, as this was not applicable.

2.4. Process of data analysis

2.4.1. Reuse rate calculation

As previously explained, we applied the following formula for each functional layer concerned by effective reuse elements:

$$\text{RR (Reuse rate [\%])} = \frac{\text{QReuse (Quantity of materials effectively reused in the functional layer [kg])}}{\text{QLayer (Total quantity of materials used for the works in the functional layer [kg])}}$$

2.4.2. Environmental benefits evaluation

In analysing the 32 construction and renovation projects, our information on the exact origin, age, and complete process of material reuse was occasionally incomplete. To evaluate the environmental benefits of reuse, we adopted an approach that measured the avoided impact compared to the use of new materials, without considering the previous life of the material. Following the life-cycle stages outlined in standard EN 15804 [39], reusing materials in new construction was reasoned to avoid impacts inherent in phases A1 to A3 (production phases) of the life cycle of building components. The assessment utilised reference values from a carbon database established within the Label Bas Carbone Rénovation (LBC), a French government label evaluating the greenhouse gas emissions of renovation projects at every life-cycle stage [40]. The LBC database is derived from the French INIES database [41], containing environmental and health declaration sheets for construction materials. The analysis was based on a database of embodied greenhouse gas emissions coefficients established within the Label Bas Carbone Rénovation (LBC), which provided a reference base for assessing impacts by category or product family. While the LBC approach considers that the entire life cycle impacts are avoided through reuse, our estimation focused on avoiding only the impacts of phases A1 to A3, considering that materials still need installation, maintenance, and end-of-life management similar to new components [16]. However, we did not consider processes associated with dismantling the existing assemblies.

The calculation steps for estimating avoided carbon emissions involved identifying product families in the LBC database, calculating greenhouse gas emissions (GHG) in phases A1-A3, searching for additional data for families not listed in the LBC method (INIES database [42] or other international sources), converting quantities into functional units, and calculating the total greenhouse gas emissions avoided.

Environmental benefits of reuse were expressed in kilograms of carbon equivalent (kg.CO2eq), indicating emissions avoided in each project. Negative values denoted emissions avoided through reuse. For materials with insufficiently reliable data, no information was provided. It means that the total emission avoided is underestimated in some cases, to be on the conservative side. For specific wooden elements, the total GHG emissions during phases A1-A3 may lead to a net negative result (using the $-1/+1$ criterion) [43]. This happens when certain life-cycle assessments consider the carbon sequestered in trees and plants during photosynthesis, referred to as biogenic carbon. In these instances, the amount of biogenic carbon stored in wood can exceed greenhouse gas emissions linked to its production. To subtract biogenic carbon from the total greenhouse gas emissions for the quantities of wood utilised, and to simplify this analysis, we used a default biogenic carbon content for all types of wood, provided by standard NF EN 16449 (2014), which provides an associated CO_2 capture rate of 1.637 kg.CO_2eq/kg of timber [29]. The limitations of our quantification of embodied greenhouse gas emissions are further discussed in Section 4.2.

2.4.3. Establishing reuse targets by layer

The analysis of reuse rates achieved on a series of construction and renovation projects also aims to provide a first benchmark on effective reuse practices. This would enable the identification of whether it is possible to deduce indicative rates that could be applied on a large scale to a wide range of projects. The approach developed to identify plausible reuse targets by layer is based on the cross-referencing of several data sets. We considered the following factors:

- The number of projects in the same category: the higher the proportion of projects in the same category that have reuse elements in the layer concerned, the more representative it is.

- The heterogeneity of the data by layer and category. The minimum, maximum, and average values have been calculated and considered in order to identify trends. The closer these values are, the smaller the gap between the minimum and maximum values, and the more consistent the data is considered to be. When the quantity of materials reused per layer is insufficient (on the order of a few kilograms) and the corresponding rate is also too low, it is excluded from the analysis. When the rates achieved within a category are too heterogeneous, indicating an average rate is not relevant. Similarly, it is not meaningful to express the average rate when the sample under consideration contains only two projects.
- Medians were calculated in two ways: one taking into account all the data, and the other excluding data that was too extreme (defined as more than 90 % reused mass in this case).

As shown in Table 4, the heterogeneity of the sample and the limited number of projects analysed meant that it was not always possible to identify targets for reuse.

3. Results

The results are categorised into sub-sections of achieved reused rate and environmental benefits as follows.

3.1. *Achieved reuse rate*

There are some general remarks in the analyses. For example, the projects in the Micro Projects and Demonstrators cluster achieved high reuse rates across several layers, or the category of outdoor facilities/public spaces only concerns three layers. A closer examination of the projects reveals that certain projects adopt a multi-layered approach, achieving reuse rates across most of the relevant layers. This is notably observed in projects belonging to the first cluster; the "Social and Cultural Facilities" type. Conversely, other projects concentrate their reuse actions on a more limited number of layers, a strategy often identified in housing and tertiary building projects.

Table 2 shows the maximum, minimum, and average reuse rates for each project cluster and layer. The analysis considered a few indicators, as follows:

- If the quantity of materials reused per layer was negligible (around a few kilograms) and the corresponding rate was also minimal, it was excluded from the analysis, considering the reuse in that layer to be marginal.
- In cases where the rates within a category showed significant heterogeneity, indicating average or median rates irrelevant, we decided to present only the minimum and maximum values. Similarly, expressing an average rate is pointless when the sample comprises less than three projects.
- The presentation of minimum and maximum reuse rates per layer includes only projects with actual reuse, excluding cases with a 0 % rate.

As shown, Cluster 4 (Micro Projects and Demonstrators) demonstrates a significant emphasis on material reuse across various

Table 2
Comparison of the reused rate of the different project categories for each layer.

Cluster (number of projects)	Rate (%)	Structure	Skin	Space plan	Service. HVAC	Service. electricity	Service. sanitary	Outdoor. Infra	Outdoor. Surface	Outdoor. furnishings
Social and Cultural Facilities (4)	Min	–	19.43	1.04	8.86	–	18.6	–	17.2	–
	Max	–	19.94	43.78	51.9	–	56.4	–	87.6	–
	Ave.	–	19.68 (2)	23.02 (4)	-(2)	–	38.5 (3)	–	52.4 (2)	[84.4] (1)
Housing (8)	Min	0.77	2.24	1.88	3.64	–	3.92	–	0.29	–
	Max	14.59	67.06	17.04	29.46	–	84.38	–	87.67	–
	Ave.	-(3)	23.02 (5)	7.3 (7)	-(4)	–	-(3)	–	-(2)	–
Tertiary Buildings (8)	Min	1.75	3.26	1.28	–	–	7.54	–	0.71	9.30
	Max	9.58	28.08	24.34	–	–	25.35	–	86.47	22.20
	Ave.	4.93 (3)	14.49 (4)	7.81 (7)	–	[2.34] (1)	-(2)	–	-(3)	-(2)
Micro-Projects and Demonstrators (7)	Min	1.25	28.17	9.70	4.50	6.74	1.67	–	–	–
	Max	100	100	100	28.88	10	94.42	–	–	–
	Ave.	78.69 (5)	70.73 (5)	65.30 (7)	-(2)	-(2)	54.92 (5)	–	–	–
Outdoor Spaces (5)	Min	–	–	–	–	–	–	–	4.82	0.39
	Max	–	–	–	–	–	–	–	95.55	77.44
	Ave.	–	–	–	–	–	–	[21.83] (1)	36.08 (5)	29.67 (3)

Note: Numbers in parentheses indicate the number of projects within the respective category, and rates in the brackets indicate the involvement of only one project, making it irrelevant to calculate an average.

layers (Average 67.4 %). This highlights the potential for small-scale and temporary projects to set effective reuse targets (Fig. 3). Remarkably, as illustrated in Fig. 4, outdoor spaces, alongside micro-projects, demonstrate the highest reuse rates (10,694 tons), suggesting a feasible opportunity to set reuse targets specifically for outdoor projects. A detailed comparison of the mass of reused materials across all clusters highlights that the “Outdoor-Surface” layer stands out with the highest mass of reused materials (9072 tons), containing materials and elements such as stone pavers and concrete curbs (Figs. 5 and 6). Furthermore, within Clusters 1 to 3, a notable prevalence of reused materials is observed, primarily within the “Outdoor Space” layers rather than the building layers. These findings strongly support the idea that “Outdoor Space” layers show significant potential for material reuse. Moreover, Fig. 7 provides an overview of the layers where the most materials have been reused across all clusters. These findings contribute to our understanding of the distribution and potential focus areas for material reuse in different project clusters.

3.2. *Achieved environmental benefits*

Based on the analysis of avoided greenhouse gas emissions through material reuse in our case studies (refer to Table 3 and Fig. 8), the layers related to "Outdoor Space" show both a higher reuse rate and a greater reduction in greenhouse gas emissions (177.4 tCO_2eq), particularly the “Outdoor-Surface” layer (98.9 tCO_2eq). This could be attributed to the material type or the level of interest in reuse within this layer. However, it is important to note that for materials with insufficiently reliable data, we could not provide specific information, and the total emissions reduction can be greater than what we could calculate. It is critical to highlight the significant variation in the average greenhouse gas intensity of the layers with electricity clearly dominating the others. This echoes the findings of Stephan et al. (2020) who also found significant variations in the embodied environmental flows, including greenhouse gas emissions, of different materials. This is counterbalanced by the amount of materials reused [44]. Consequently, greater attention should be given to the “Structure” and “Space Plan” layers, as they have potentially a more significant role in reducing environmental effects, considering both reuse mass and greenhouse gas emissions. This is likely due to the use of materials such as steel, cement/-concrete, glass, and aluminium [45]. Therefore, when establishing reuse targets and promoting reuse practices, it is essential to prioritise materials with a higher environmental impact (Figs. 9 and 10).

Table 4 provides data that may serve as indicative targets in scenarios closely aligned with the analysed projects. In the analysis, certain criteria were considered including excluding low reuse quantities, highly varied rates within a category and excluding cases with 0 % reuse from minimum rate calculations. The figures enclosed in parentheses correspond to assumptions elaborated upon in subsequent discussions. The results show that there is a possibility of setting a reuse target for layers of Structure (1 %–5 %), Skin (5 %–15 %), Space Plan (10 %–25 %), and Outdoor-Surface (30 %–50 %). For other layers, determining the reuse rate is challenging due to the limited number of case studies and the significant variation in reuse rates across different projects.

4. Discussion

This article aims to identify and quantify the proportion of reused materials used in projects, referring to materials reintroduced into circulation with extended lifespans through integration into subsequent projects. It is noteworthy to underscore that the primary approach in circular design and construction is prevention. At the level of extant structures, this entails renovation approaches that prioritise preservation and reduce demolitions, thereby minimising material outflows or waste generation. Regarding incoming materials, the focus is on substituting a portion of new materials with reclaimed ones that have undergone prior use. In this regard, it is important to note that the reuse rate depends on the overall quantity of materials used in a project. Absolute quantities influence the achieved rates, revealing considerable disparities in orders of magnitude among the analysed projects. Furthermore, the reuse rate is influenced by the mass of individual elements. For a given layer, the use of heavier materials essentially results in a higher rate. It is

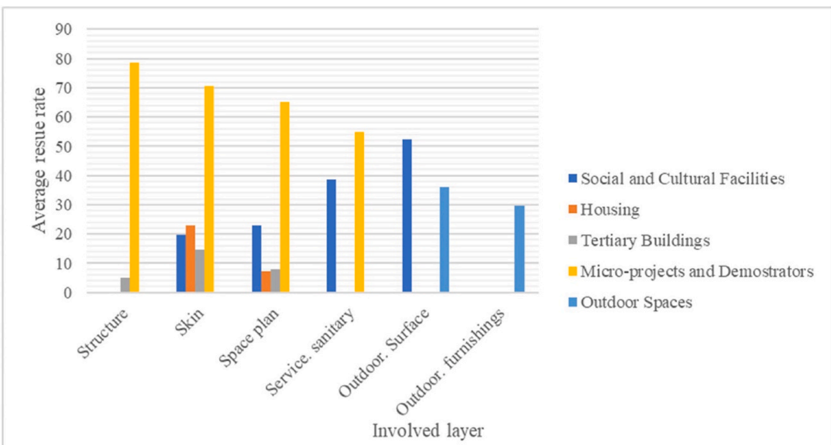

Fig. 3. The average reused rate for involved layers in each cluster.

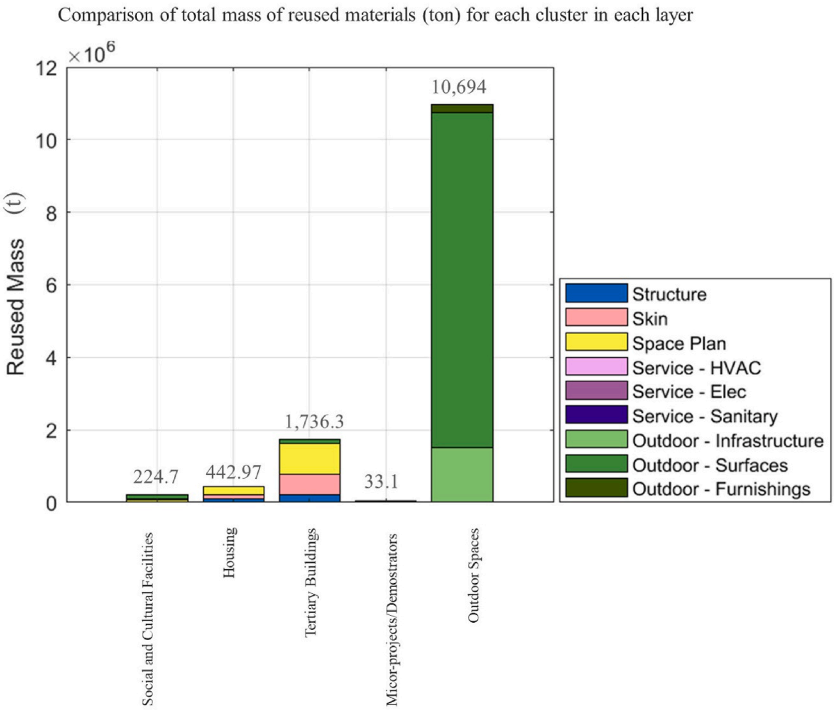

Fig. 4. Comparison of reused materials across project clusters.

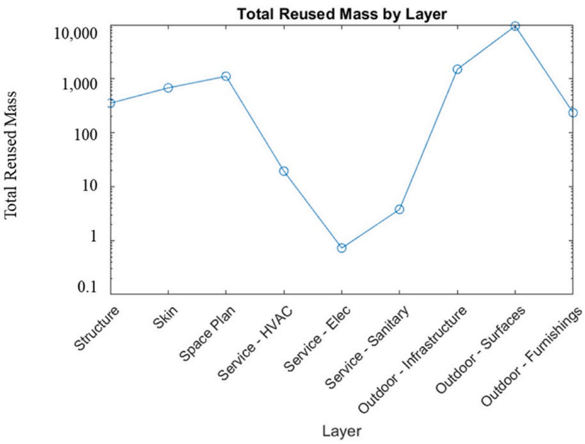

Fig. 5. The reused materials mass in each layer.

essential to recognise that these rates may not always accurately reflect the efforts made and should be considered alongside other significant indicators.

One question arising from the analysis of these reuse rates is whether it is feasible to derive indicative rates that are applicable on a broader scale for diverse projects. Addressing this question requires a detailed evaluation. Primarily, the conducted analysis suggests that generalising indicative rates for all project categories is challenging. Conversely, the analysis confirms the contextual nature of reuse practices, emphasising that the achieved rates are linked to project types (new build or renovation), material quantities, program specifics, and construction detailing as clearly demonstrated by Vandervaeren et al. (2022) [46], and more broadly, the architectural decisions made by designers and their clients. However, in specific layers and for certain project categories, certain patterns emerge, revealing potential reuse pathways, as discussed below.

4.1. Setting a reuse target

When determining a target for reuse, it is more effective to establish it separately for each layer or component of a system or

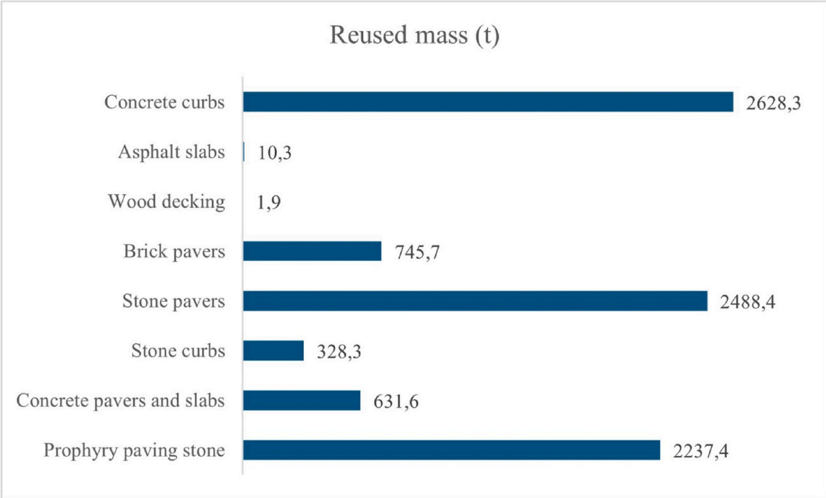

Fig. 6. Most reused materials in the Outdoor-Surfaces layer.

structure. In this context, the discussion focuses on analysing and understanding the reuse rate within each layer. This approach allows for a more detailed and tailored assessment, ensuring that the reuse target is accurately defined for each specific project.

Structure. The reuse of structural elements is not widespread overall, yet it is no longer entirely unexplored. Our analysis highlights that the reuse of structural elements often involves substantial quantities in absolute terms, leading to reductions in environmental impact. However, the structural layer, particularly in new-build projects, tends to be very heavy, resulting in relatively low reuse rates, typically ranging between 1 % and 5 % in mass. The distinction between new builds and renovations is significant, with most renovation projects retaining existing structures and achieving substantial reductions in material requirements. While it may be premature to mandate the systematic reuse of structural elements at this stage, it is an exemplary approach that merits encouragement, particularly when considered alongside efforts to preserve existing buildings. An increasing number of reuse practices can be accompanied by a gradual establishment of working methods and risk management protocols, suggesting the possibility of their widespread integration.

Skin. Efforts to reuse materials in building envelopes show promise, with various solutions available in the existing market, such as wood cladding, brick facing, and even windows. In our sample, several projects have successfully reused insulation materials, although these are less common in the reuse market. It is important to note that this layer is subject to biases inherent in the choice of mass as a unit. While elements like bricks are relatively heavy, many other components, such as wood and insulation, are lighter, and their reuse is equally attractive. This aspect should be considered when establishing a potential reuse rate. Considering the ongoing focus on improving energy efficiency, much of the upcoming work will involve the building envelope. Encouraging the use of reused materials in this context is valuable, although setting an indicative rate depends significantly on the planned construction solution. As a guide, a range of 5 %–15 % (by mass) seems achievable, especially if the project involves the application of timber cladding or brick facing a substantial part of the façade. Reusing glazing, where possible, can further contribute to meeting or exceeding this target.

Space Plan. Predictably, the space plan layer is the most frequently encountered across various projects, showcasing the broadest range of reused materials. It is also a layer relatively unaffected by the distinction between new construction and renovation projects. In many cases, the focus is on interior finishes, with renovation projects having the opportunity to retain a substantial portion of original finishes to minimise the need for new materials. Our analysis suggests indicative reuse rates within the space plan layer ranging from 10 % to 25 % (by mass). It is important to note that achieving this target across all construction projects in North Western Europe would not happen overnight, as widespread adoption of this target could have unpredictable effects on the reuse market. However, setting these orders of magnitude (and potentially higher in specific cases) can be considered a reasonable target for projects akin to those analysed, seeking to establish meaningful reuse objectives.

Services (HVAC, Electricity, Sanitary). The three layers linked with technical equipment present challenges in establishing relevant indicative rates based on the collected data. Nevertheless, several remarkable observations emerge. In our study, the reuse of technical equipment predominantly involves visible elements such as toilet bowls, washbasins, radiators, and, to a lesser extent, specific machines like water heaters and ventilation units. However, the "hidden" components of these installations, such as pipes and ducts, are scarcely reused in the analysed projects. This distinction becomes significant when comparing renovation projects, which can retain existing installations, with those necessitating the installation or reinstallation of all components from the ground up. Quantifying material flows related to technical installations poses a considerable challenge, given the complexity of obtaining detailed data in this field. However, ongoing research projects (e.g. Loreau et al. (2022) [47]), indicate a growing interest in the reuse of technical equipment, suggesting potential extensive adoption in the future.

The analysed projects currently showcase the feasibility of reusing various relatively simple technical equipment, warranting encouragement for such practices. Incentives, not solely reliant on mass-based reuse rates, would be more fitting, considering

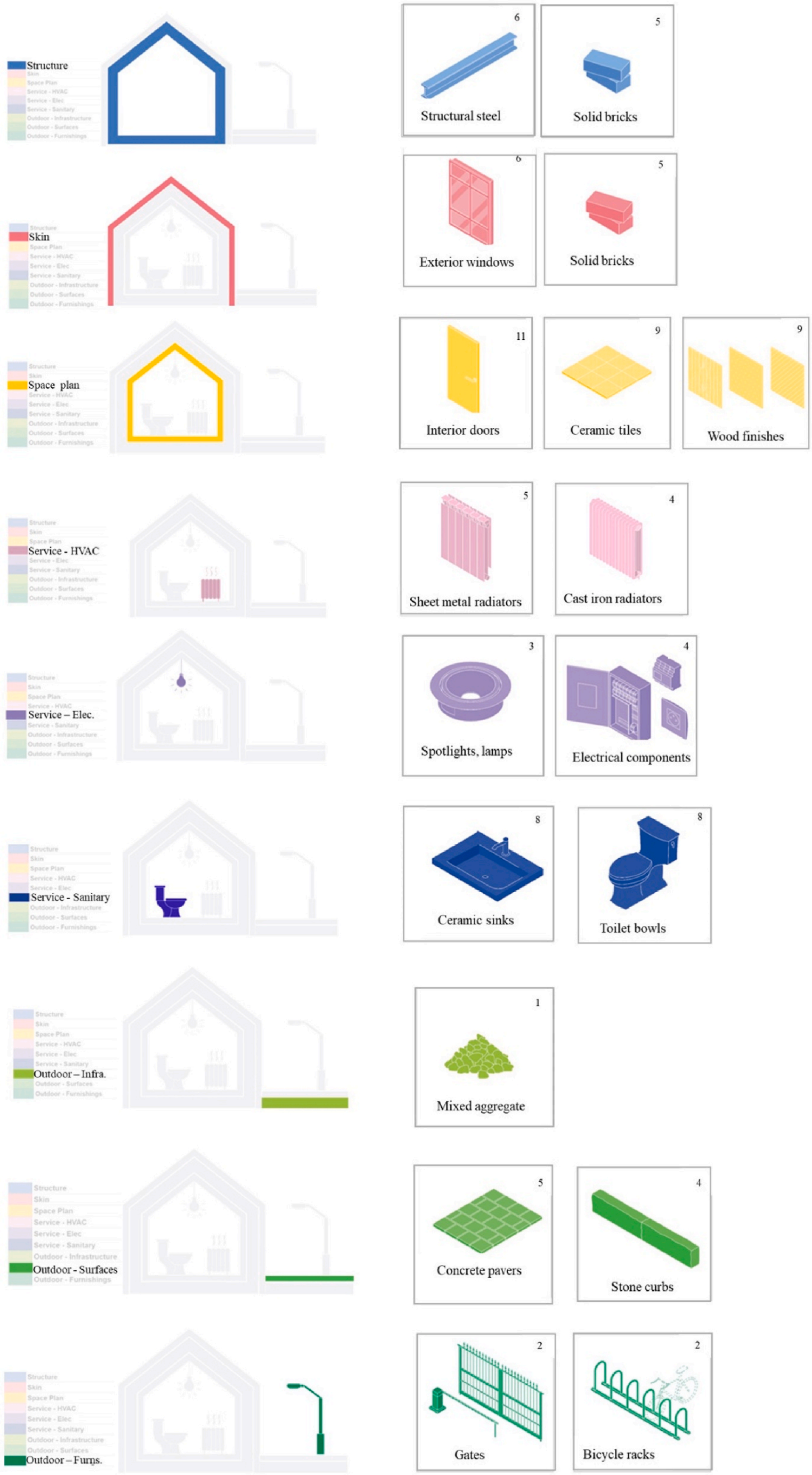

Fig. 7. Most reused materials in each layer (the digit in the top-right corner indicates the count of projects that incorporated the reuse of this specific material) [28].

Table 3
Total reused materials, avoided embodied greenhouse gas emissions, and avoided embodied greenhouse gas emissions intensity, by layer.

	Structure	Skin	Space plan	Serv. - HVAC	Serv. - Electricity	Serv. - Sanitary	Outdr. - Infrastructure	Outdr. - Surfaces	Outdr. - Furnishings
Total reused materials mass (t)	359.8	675.7	643.6	19.07	1.15	3.79	1505	9071.96	117.04
Total greenhouse gas emissions (tCO_2eq)	693.5	91.7	469.2	13.4	38.2	8.5	36.5	98.9	42
Average avoided greenhouse gas emissions intensity ($kgCO_2eq/kg$)	1.93	0.14	0.73	0.7	33.2	2.24	0.02	0.01	0.36

Table 4
Indicative targets for each layer.

Cluster / Layer	Social and Cultural Facilities	Housing	Tertiary Buildings	Micro-Projects and Demonstrators	Outdoor Spaces	Target
Structure	–	–	(5 %)	–	–	**[1–5 %]**
Skin	15 %	(23 %)	15 %	–	–	**[5–15 %]**
Space Plan	23 %	7 %	8 %	(65 %)	–	**[10–25 %]**
Service -HVAC	–	–	–	–	–	**-**
Service -Electricity	–	–	–	–	–	**-**
Service - Sanitary	–	–	–	–	–	**-**
Outdoor - Infrastructure	–	–	–	–	–	**-**
Outdoor - Surfaces	(52 %)	(50 %)	(50 %)	–	36 %	**[30–50 %]**
Outdoor - Furnishings	–	–	–	–	–	**-**

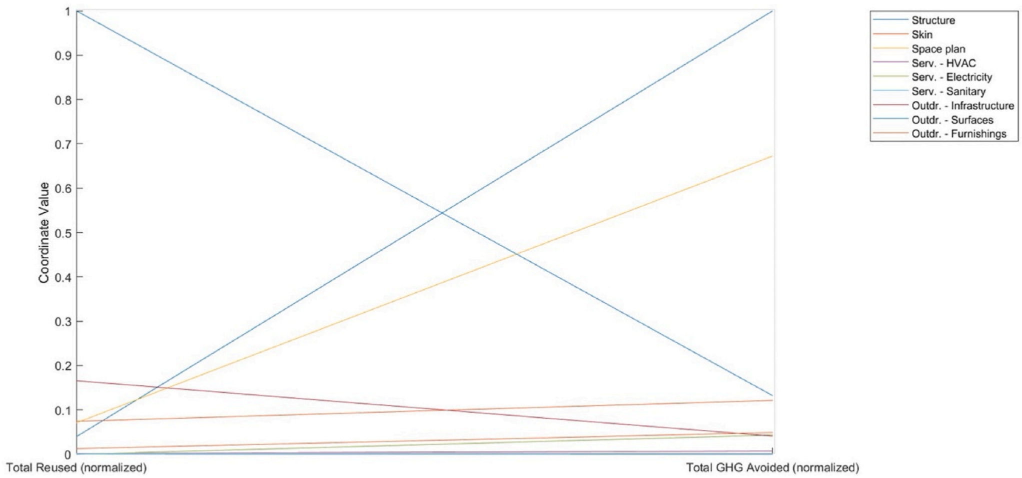

Fig. 8. Total reused materials in each layer and total avoided greenhouse gas (GHG) emissions per layer.

alternatives such as qualitative targets or targets expressed per piece.

Outdoor - Infrastructure. In road construction, there is a common practice of downcycling materials, particularly concrete and glass. In this context, concrete may be used as aggregates, while glass may be used as a filler in asphalt, rather than being fully recycled into new products. This practice highlights a prevalent trend in road construction where materials are not fully recycled or reused at their original value but instead are repurposed less efficiently. The analysis of the selected projects suggests that the reuse of infrastructural layers in road and landscaping projects remains infrequent. This tendency leans towards soil management, a critical but distinct subject from the focus of this analysis.

Outdoor – Surfaces. The data shows significant variations based on project scale, including small-scale, almost residential, landscaping projects alongside much larger-scale roadworks. Despite this diversity, there is a notable consistency in the types of reused materials, predominantly natural stone paving blocks, concrete paving blocks, and terracotta paving blocks. These materials are widely available in the reuse market, and suppliers can deliver them in considerable quantities, making them well-suited for reuse. Considering these factors, it is reasonable to propose indicative reuse rates within a range of 30 %–50 % (by mass) for projects involving landscaping and roadworks. Depending on the specific project context, this target might be subject to adjustments upwards

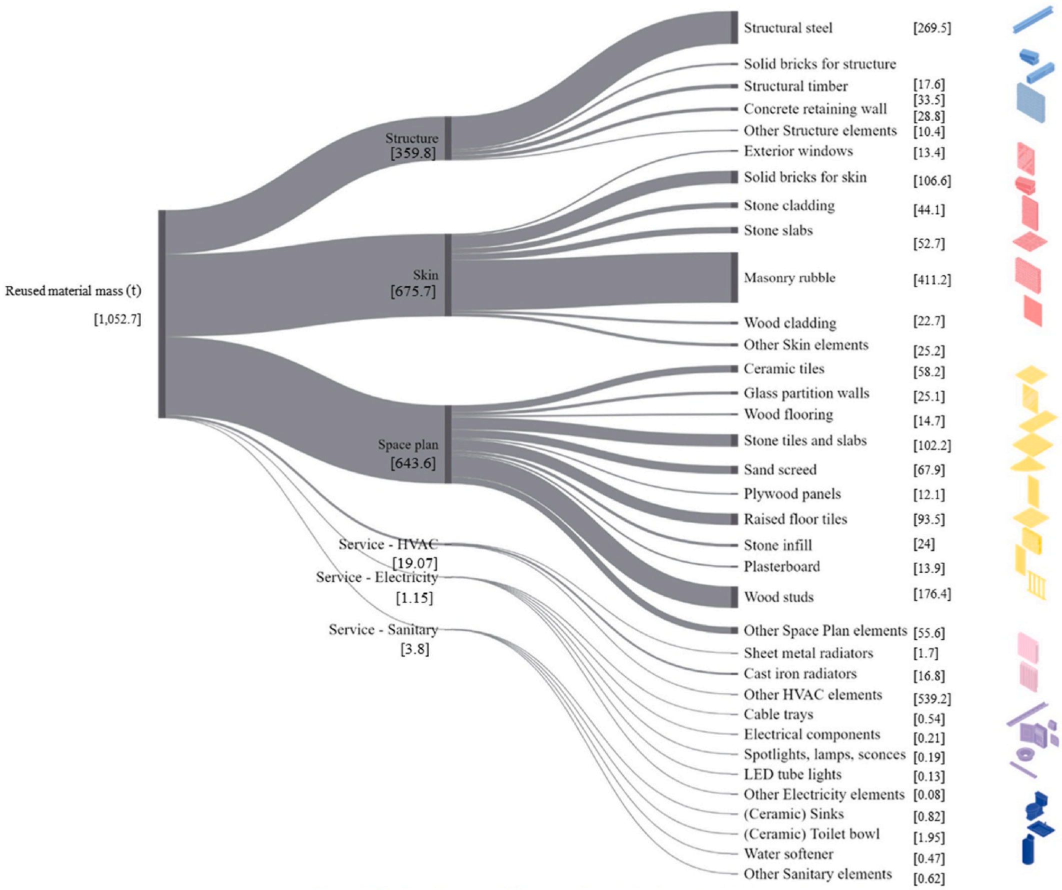

Fig. 9. Sankey diagram of the reused materials flows by layer (mass in tonne).

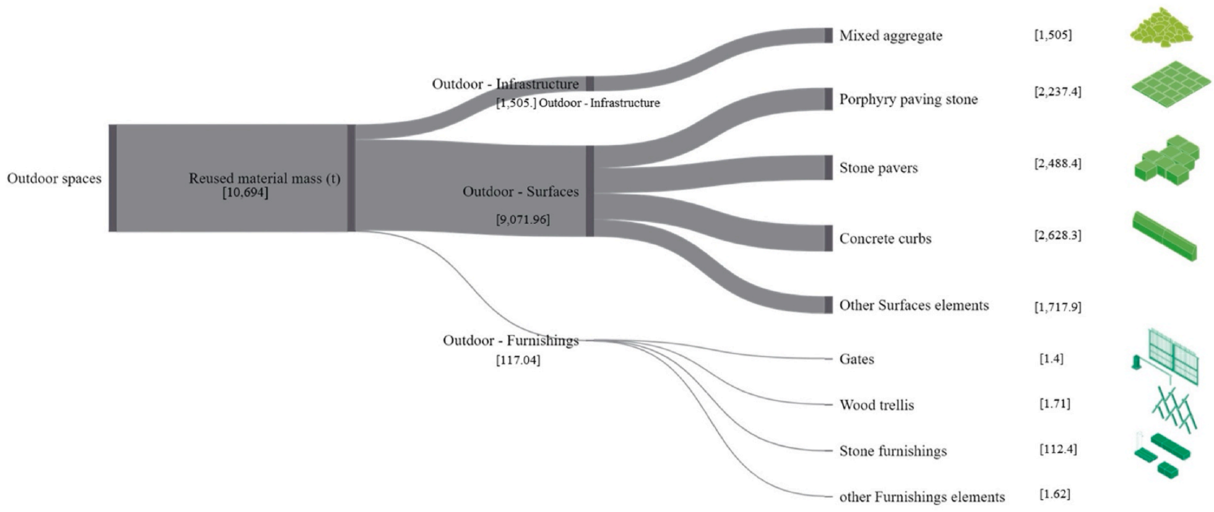

Fig. 10. Sankey diagram of the reused materials for the Outdoor Spaces layers (in tonne).

(as some projects have achieved rates exceeding 90 %) or downwards (in cases where contextual limits apply).

Outdoor – Furnishings. Based on the data collected from the analysis, establishing specific indicative reuse rates for this type of application is not currently feasible. Nevertheless, the case studies indicate the potential suitability of this application for reuse. If quantitative targets were to be planned, they would need to be grounded primarily in a thorough contextual study.

4.2. Environmental impact assessment

In terms of environmental impact assessment, heightened consideration should be directed toward the Structure layer. This recommendation stems from the observation that, in terms of environmental impacts, the Structure layer plays an important role as it represents a significant mass and has a relatively high embodied greenhouse gas emissions intensity (see Table 3). This layer, including the fundamental structural elements of a building and materials, has a substantial influence on the overall environmental footprint of construction and renovation projects [48–51]. Therefore, a targeted focus on the Structure layers is warranted for a more comprehensive and ecologically informed approach to construction practices. Reusing load-bearing building elements holds promise for advancing the circular economy within the construction industry. The complex connections between factors influencing reusability introduce a notable degree of uncertainty regarding the economic viability of reusing load-bearing structural components in the building construction sector [52]. However, there is a need to revise existing legislation in favour of reuse. For example, the study of the Norwegian construction sector shows that legislative constraints represent a major obstacle for most parties involved, but they also hold the potential to become a significant facilitator for the reuse of materials and products [10].

In addition, to set a target for reuse strategy, it is needed to consider other essential factors such as the economic feasibility and environmental impact of reclaiming elements, and the potential for diminishing returns on reuse initiatives. For example, if repairing or refurbishing costs surpass the costs of purchasing new materials, reusing the material might be avoided, or when the environmental impact of transportation or reclamation outweighs the use of the same new elements. Furthermore, the standards for the reuse process should meet acceptable material quality levels, adherence to safety regulations, and logistical considerations like the availability of storage. Similarly, the social implications of reuse could be assessed, as done in Loreau et al. (2024) [62].

4.3. Limitations of the study

The analysis of our limited cases of 32 projects may not fully represent certain layers due to the inclusion of reused elements in very few projects. This limitation is a result of constraints in time and resources during the analysis. Future endeavours are anticipated to benefit from an increasing number of projects adopting the practice of monitoring and reporting on reuse efforts, enhancing the availability of case studies. Conducting a retrospective analysis of projects demands more time and research compared to real-time participation with direct access to relevant data. Moreover, the calculation of element and material mass in our analysis was meticulous, relying on the maximum available data. However, due to the absence of precise information for some elements, assumptions, and extrapolations were necessary, potentially affecting the results. These challenges were exacerbated by the retrospective nature of our analysis, encountering obstacles such as unresponsiveness from involved organisations and difficulty accessing information. In an ideal scenario, every construction material would be thoroughly identified, recorded, and weighed before use, with a similar process for elements leaving the site. Although such comprehensive monitoring is challenging, it would enable automatic and precise calculation of achieved reuse and reclamation rates. A more practical approach involves anticipating reuse rate calculations at the project's beginning, particularly during the bill of quantities preparation. Reuse rates can be established based on procurement strategies, bill of quantities, flow monitoring during works and as-built documentation, and establishing a detailed record of reclaimed elements.

Consequently, the reuse rate, while being a useful indicator to measure efforts in material reuse, has limitations in capturing the comprehensive nature of reuse. It simplifies a complex concept that involves cultural, social, economic, and environmental dimensions, which are often challenging to measure quantitatively. While the reuse rate provides practical insights with minimal monitoring, it should not be considered a singular measure, as it may overlook crucial aspects of reuse practices. Circular economy efforts extend beyond the reuse rate, emphasising the importance of preserving existing buildings and addressing various dimensions beyond mere quantitative considerations [29].

The estimation of avoided greenhouse gas emissions through reuse suffers from several limitations, as customary in any scientific endeavour. Firstly, embodied greenhouse gas emission values for reused materials were sourced from the LBC and INIES databases, which rely on process analysis. Process analysis is known to underestimate embodied environmental flows due to the so-called "truncation error", as clearly demonstrated by various researchers [53–55]. More advanced life cycle inventory approaches, such as hybrid approaches [55], provide completed system boundaries through the use of environmentally extended input-output data while using detailed process data where available. To date, the only publicly available database of hybrid embodied environmental flow coefficients for construction materials is the EPiC database [56,57], developed for the Australian context, and therefore not applicable in this case. However, trends from the EPiC database demonstrate that process data can result in significant underestimation for some of the materials covered in this study, e.g. for embodied greenhouse gas emissions: 28.6 % for concrete-based materials, 51 % for insulation materials, and 60.7 % for timber materials. Secondly, our modelling assumes that the reused material will behave the same as a new material with its service life reset when re-used. This might not be the case with re-used materials potentially failing earlier than new materials, A sensitivity analysis on the service life of the re-used materials would provide a more nuanced understanding of the potential avoided greenhouse gas emissions, as material service life can have a significant effect on the recurrent embodied environmental flows [58,59]. Thirdly, processes associated with dismantling the existing elements to be re-used on-site are not taken into account. While embodied environmental flows associated with the construction of a building tend to be negligible compared with those associated with the production of materials [60,61], it would be interesting to develop a better understanding of the environmental flows associated with deconstructing building elements for reuse.

5. Conclusion

Setting rates for reuse, especially by public clients and local authorities, is essential to secure demand for reclaimed building products and materials, and through that drive other stakeholders to change common practises into circular practises, e.g. by recognising the value of reclaimed materials. Setting rates for preservation, reclamation, and reuse of building products and materials can be valuable in specific contexts, depending on the establishment of clear frameworks, procedures, and initial data. These details can be project-specific and may eventually become part of a broader framework adopted by public authorities. Contextual studies are essential for understanding the unique aspects of each project, and stakeholder collaboration, including market research and negotiations, can enhance the effectiveness of this approach. These rates, initially incentivised, can also be determined retrospectively during a project assessment phase, offering a comprehensive overview of the efforts and outcomes. Encouraging such practices aligns with broader goals and attention from public authorities. To set quantity for a reuse target, it is beneficial to leverage detailed and context-specific investigations. This involves understanding the knowledge of the reuse market, considering the past experiences of service providers, exploring potential supply channels, conducting an inventory of reusable materials (for on-site reuse), and conducting preliminary studies related to the targeted applications. In cases where these factors are considerably uncertain, it is recommended to establish relatively modest minimum targets and encourage bidders to exceed these. Alternatively, initial targets may be left unspecified, providing flexibility for bidders to propose their targets. Promoting general reporting on achieved reuse rates in various projects is a commendable practice, fostering positive competition and enabling continuous monitoring of progress across different scales (e.g., architectural firms, construction companies, cities, regions, or countries). However, to realise this, a standardised and consistent approach is crucial. If each project stakeholder adopts disparate calculation methods and different definitions, the accounting efforts become ineffective, hindering the ability to compare results. Public authorities can significantly contribute to this effort by establishing common frameworks and harmonised measures.

This paper highlights the importance of integrating reuse concepts at every stage, (from the bidding stage to design, construction, renovation and demolition processes). This helps prioritising reuse instead of relying on using new and critical raw materials or focusing only on recycling. This aligns with the first four steps of the 10Rs strategies: refuse, reduce, rethink and reuse. These steps emphasise the need to avoid using rpimary resources, minimise the use of critical materials, and reconsider the necessity of using new elements. It is believed that circularity in the building industry cannot be achieved unless these four steps are prioritised over the other approaches.

The study is limited by its lack of coverage of economic and social factors, as financial data for the analysed projects was difficult to access. Moreover, economic considerations, including market fluctuations due to geopolitical factors and crises, contribute to significant price instability. Integrating these dynamics presents challenges for an economic operational approach. Future studies should address these gaps by investigating the economic and social dimensions in depth, focusing on elements like taxation, and other fiscal impacts to provide a more comprehensive framework.

CRediT authorship contribution statement

Émilie Gobbo: Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Elham Maghsoudi Nia:** Writing – original draft, Visualization, Investigation, Formal analysis. **Ad Straub:** Writing – review & editing, Supervision, Project administration. **André Stephan:** Writing – review & editing.

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Acquisition: Interreg NWE programme.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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