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Reuse of reclaimed steel components in construction: A systematic review of potential, challenges and future directions

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ABSTRACT

This review paper investigates the state-of-the-art potential, challenges, and future directions for the reuse of reclaimed steel components in construction. A comprehensive literature review was conducted, encompassing over 130 publications focused on keywords related to reuse, steel, components, construction, and circular economy. The paper analyses the potential benefits of reusing steel, particularly in terms of carbon savings. The findings also identify several barriers to reuse, including the high costs associated with reclaiming steel components, the lack of design regulations in Europe, as well as logistical challenges. Detailed examinations of the processes involved in the reuse of reclaimed steel components highlight current challenges at various stages. Furthermore, the paper presents several design examples that demonstrate the practical potential for reuse in real-world applications. Looking ahead, the importance of steel reuse as a sustainable alternative to recycling is expected to grow in the context of sustainable construction.

1. Introduction

The construction industry, especially the production of steel for construction, significantly contributes to global resource consumption and environmental impact [1]. In response to the demand for more sustainable practices, the circular economy has become a promising model that focuses on waste reduction and the continuous reuse of materials [2]. Due to its durability and recyclability, steel is well-suited to this model. In the context of the European Union’s 2050 climate goals, which aim for carbon neutrality and a 90 % reduction in CO_2-emissions from the construction sector, the reuse of steel components plays a crucial role [3]. Meeting these ambitious targets requires a shift from traditional linear economic models to more circular practices. However, the potential for directly reusing steel components, without melting them down, remains largely unutilized in practice.

Currently, only 11 % of steel in Europe is reused, while 88 % is recycled [4]. Although recycling makes an important contribution to reducing the need for primary raw materials, the reuse of steel components is even more efficient in terms of lowering CO_2-emissions and conserving resources. Reusing steel components offers numerous benefits, including a reduction in environmental impact by up to 95 % compared to primary production [5]. However, despite its potential, the reuse of steel faces several technical, logistical, economic, and regulatory barriers.

Through a systematic literature review, this study investigates the current state of research on the reuse of reclaimed steel components in the construction industry in Europe, concentrating on design-related aspects. It examines methods, evaluation techniques, and regulatory frameworks that are currently in place or needed for practical implementation. While numerous studies address individual challenges and potentials, there is a notable lack of a comprehensive and actionable implementation strategy for the reuse of reclaimed steel components. Addressing this gap, the paper analyses current knowledge and derives initial approaches for practical integration of reclaimed steel components into construction processes. By reviewing existing methodologies and documented case studies, critical insights into the opportunities and barriers for steel reuse are given, laying the basis for future implementation.

2. Methodology of structured literature review

In the initial stages of the preparation phase, the research questions have been elaborated, the inclusion and exclusion criteria for the studies have been defined, the criteria for assessing the quality of the studies have been defined, and finally the data to be extracted from the studies was defined.

The objective of this study is to provide a comprehensive overview of the current state of research, as well as main developments and

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emerging trends in the context of reusing steel components. The following research questions were formulated:

- **RESEARCH QUESTION RQ1:** How are the terms “Recycling”, “Reuse” and “Retrofitting” classified?
- **RESEARCH QUESTION RQ2:** How exactly is reuse linked to the circular economy?
- **RESEARCH QUESTION RQ3:** What are the prerequisites for the implementation of reuse?
- **RESEARCH QUESTION RQ4:** Which design examples of steel reuse have already been documented?
- **RESEARCH QUESTION RQ5:** On which topic has research on reuse focused on so far?

Based on the research questions, inclusion and exclusion criteria were outlined to select relevant literature, see Table 1. First, the articles included in this study must have been published between 2000 and 2024 in order to give current results. In addition, the articles should be available in English, though German articles have also been accepted. The full text of the article must be available for review. Next, a search strategy is defined, identifying keywords for the search that are closely related to the research questions. The following keywords have been used:

(a) reuse,
(b) steel,
(c) components,
(d) construction, and
(e) circular economy.

Subsequently, the initial search results have been subjected to a series of filters based on the pre-defined inclusion and exclusion criteria. Next, the filtered results are subjected to a review, during which the abstracts of the selected studies are screened to further narrow down the number of relevant publications. For the remaining articles, a full-text assessment is conducted to ensure that they fulfil all inclusion criteria and are relevant to the research questions.

In addition to the comprehensive structured search and manual review, a "backward snowballing" technique is used to find articles not identified by the first method. Backward snowballing uses reference lists to identify new, relevant articles [6]. The combination of both techniques increases the likelihood of including all relevant articles in the given research area. In this step, all databases are permitted. Additionally, data from previous own research were included if relevant.

Once the protocol for the review had been set, the actual literature search was accomplished in 2024. Fig. 1 illustrates the results in terms of the number of articles selected in each phase of the review study. The first search, an automated process, identified 447 articles based on the defined keywords. The filters were then applied, resulting in 70 articles being sorted out, including 38 duplicates. This was followed by a manual review including title and abstract. As part of this process, 219 articles were removed, leaving 158 articles. Those articles that were deemed insignificant after the full-text evaluation were removed. Backward snowballing led to adding 54 articles. The results left a total of 137 articles for analysis.

Table 1
Inclusion and exclusion criteria.

Criteria	Inclusion	Exclusion
Publication date	Articles that were published between 2000 and 2024	Articles published before 2000
Database	Articles listed in Google Scholar, Scopus, Web of Science, ProQuest or Science Direct	unpublished Articles
Language	Articles written in English or German	Articles not written in English or German
Subject relevance	Focus on “reuse of steel”	Articles that do not relate to the context of “reuse of steel”

Table 2 illustrates the final number of publications that were selected as part of the systematic literature review on the reuse of steel components in the construction industry and related topics. Additionally, Fig. 2 shows the publication dates. Most papers have been published in the last 5 years, showing that the topic of reuse and circular economy have become increasingly important lately.

As a first step of the analysis, links between the various topics in the context of reuse have been established in terms of a bibliometric network [7]. Fig. 3 illustrates the links between the main topics of the collected literature: The central topics *reuse*, *circular economy* and *sustainability* are clearly recognizable as main research fields. Additionally, links between *recycling*, *steel*, *design*, *deconstruction,* and *design for deconstruction* show that *reuse* is often discussed in connection with the handling of building materials, especially steel, as well as with *planning for deconstruction and reuse*. Other significant links are *environmental impact* and *energy*, which shows the relevance of reuse to *ecological issues* such as *energy consumption* and *environmental impact*. These terms are also strongly linked to *deconstruction* and *demolition*, putting the focus on the end of the life cycle of buildings and deconstruction processes.

A main finding of this analysis is that although there are numerous studies on reuse, only a few explicitly deal with the *design of reclaimed steel components*. The categorization of publications according to their relevance to the research questions also reveals that many of the sources examined deal with related topics: Although a large proportion of reviewed literature shows relevant contributions, only some of it directly addresses the research questions. The most important sources provide important insights into the topic of *reusing reclaimed steel components*.

3. Circular economy in steel construction

The circular economy represents a sustainable economic system that is intended to replace the current linear economic model, which is typified by the "take, make and dispose" approach [8]. The fundamental objective of this transformation is to minimize waste and, consequently, mitigate material loss [9,10]. The principle of the circular economy is the extension of the life cycle of materials through the processes of recycling, reuse, and reprocessing, thereby creating a closed-loop system for product life cycles [11].

Steel is 100 % recyclable without any mayor loss of quality, so that unlimited circular economy is possible [12]. Due to its durability and strength, steel can be used in a variety of applications, which in turn reduces the frequency of new production and overall material consumption. The steel industry is therefore already making a significant contribution to a circular economy.

Fig. 4 illustrates the cycles created by recycling and reuse of steel from dismantled buildings. The following stakeholders can be identified within the value chain:

- Manufacturers, including steel mills that produce steel.
- Service centres, which assume the function of storage and processing.
- Fabricators, who prepare the steel for projects by drawing, cutting, and drilling.
- Fitters, who assemble the steel parts into a structure on site.
- Engineers, who design the steel components.

The roles of the stakeholders within the value chain are subject to change. The reuse of steel components has the potential to create new positions in the structural steel cycle, thereby complementing the recycling process, examples of such process chains with newly created positions are given in chapter 6. The newly created roles include, for instance, the testing and the refurbishment of the components [13–15].

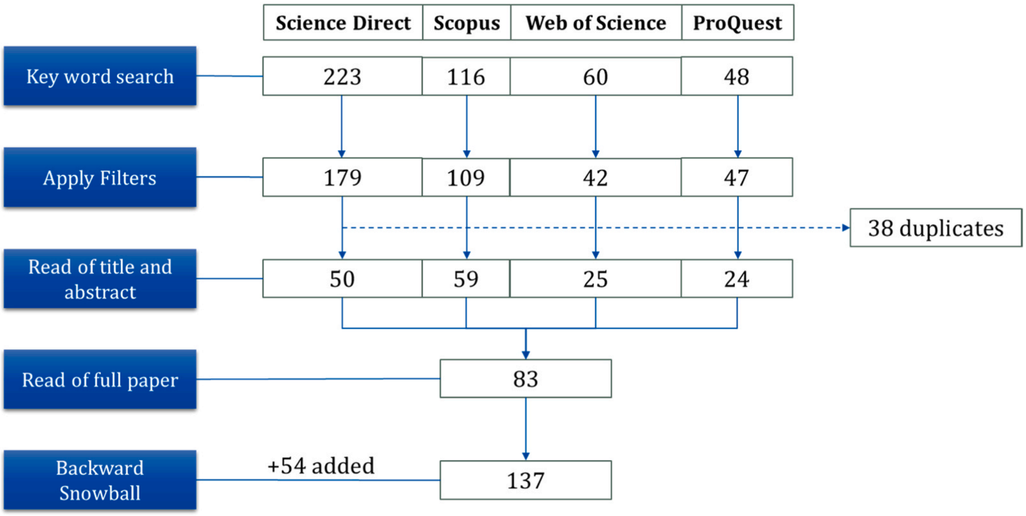


Fig. 1. Results of systematic literature review.

Table 2
Literature search results.

	Structured Search		Manual Search		Backward Search	Final Results
	1st Strategy Keywords Results	2nd Strategy Appling Filters	3rd Strategy Reading Abstracts	4th Strategy Reading Full Articles	5th Strategy Backward Snowball	
Science Direct	223	179	50	26		
Web of science	60	42	25	9		
Scopus	116	109	59	30		
ProQuest	48	47	24	18		
Total	447	377	158	83	54	137

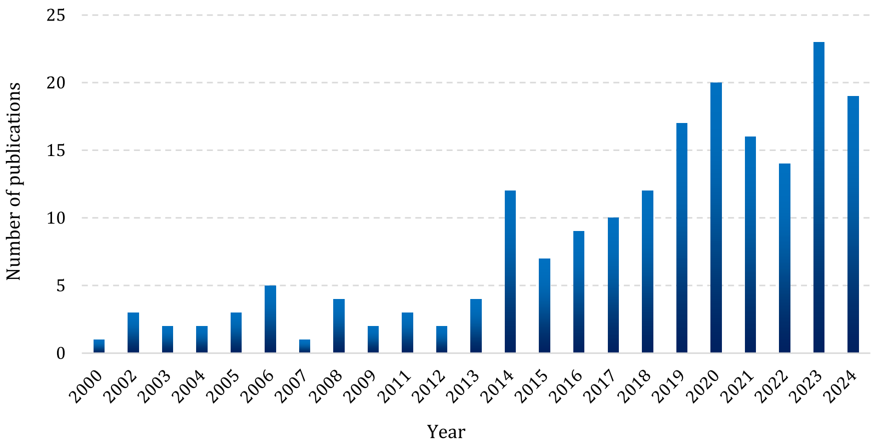


Fig. 2. Number of publications per year.

In addition to sustainability incentives, political measures and targets are formulated to implement the circular economy. The circular economy is a main component of the European Union’s 2030 Action Plan to achieve the 17 Sustainable Development Goals of the United Nations [16], in particular goal 12, which ensures sustainable consumption and production patterns [17].

The practical implementation of circular economy in the steel sector is still limited. One reason for this is the persistent gap between conceptual ambition and practical feasibility. There is a lack of reliable data in the literature and experience on life cycle costs, CO_2 emissions and logistical handling in order to integrate reused components into the circular economy. This makes it difficult to compare reuse with established processes such as recycling – the steel industry has so far largely focused on recycling rather than on direct reuse when implementing the circular economy [18]. This is because, despite the advantageous properties of steel for reuse, the dismantling of steel components from existing buildings poses technical challenges. The components are in some cases found as composite structures made of steel and concrete, which makes dismantling more difficult [19]. Also, not 100 % of steel components will be reusable, while they will be recyclable.

In addition, the demolition phase in particular presents a major challenge, both technically and organizationally, which is why much of the existing literature focuses on this aspect. Incorporating reuse considerations in the early planning phase could significantly simplify the dismantling process and close material loops more effectively, if suitable framework conditions and incentives are developed. In particular, the

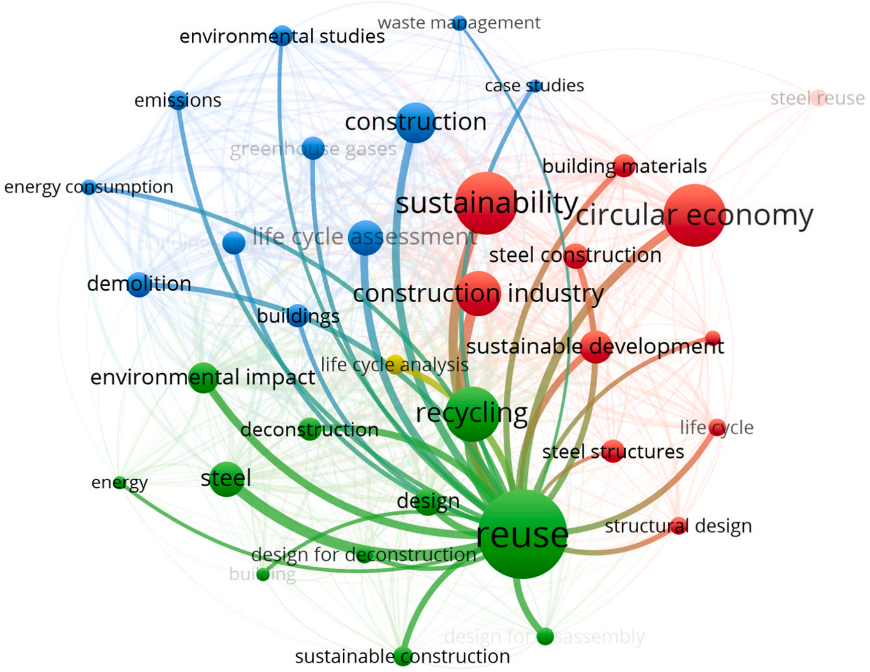


Fig. 3. Reuse bibliometric network.

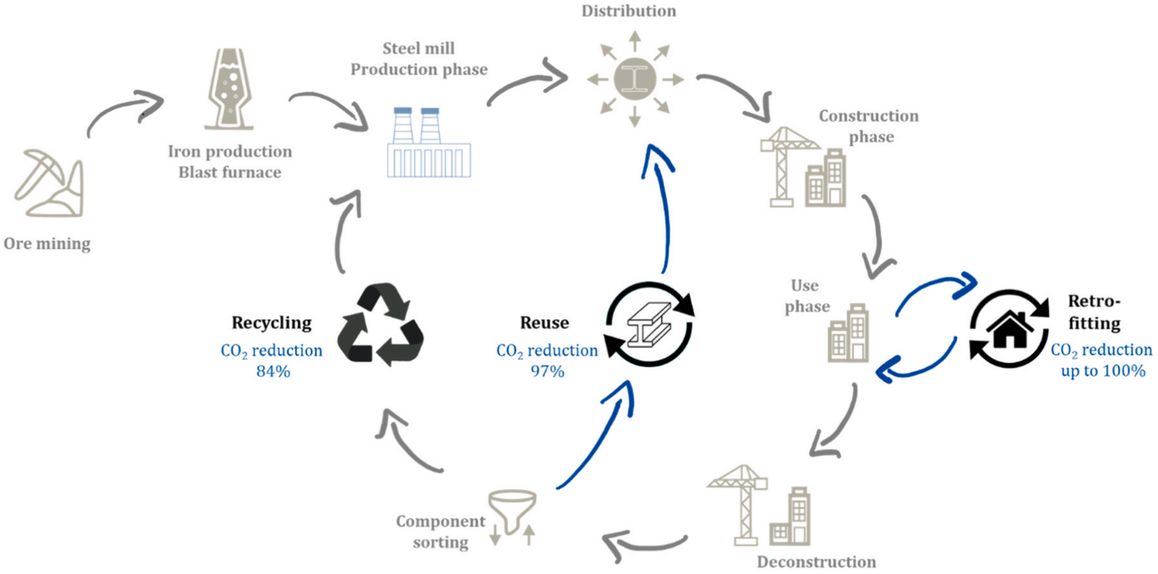


Fig. 4. Circular economy of steel products.

effective implementation of the circular economy, particularly the reuse of steel components, necessitates the establishment of uniform standards at the international level, most notably at the EU level [20]. Specifically, the design of reused steel components is missing from the European regulations [21]. In CEN/TC 250/SC 3 a working group "WG24 – Design of reclaimed steel components for Reuse" has been founded, working on the establishment of design rules for the reuse of reclaimed steel components in the context of EN 1993. For first information see [22–24].

4. Reuse, recycling and retrofitting

In the context of the circular economy in the construction industry, it is essential to differentiate between the three key terms: *reuse*, *recycling*, and *retrofitting*.

The term **reuse** is defined as a process in which steel components from existing structures are used again for a new purpose without the need to melt down the steel elements [25,26]. According to the EU Waste Directive (2008), the preparing of reuse is the preferred method of waste management after waste prevention [27].

Steel **recycling** is the process of converting scrap steel into new steel products by melting down the old steel, commonly in an electric arc furnace (EAF). The recycling process ensures that the inherent properties of the steel are retained so that it can be reused for the same or similar applications without loss of quality [12]. Steel is 100 % recyclable and structural steel usually contains around 70 % recycled content. The German Steel Federation has set a goal of becoming climate-neutral by 2045. This is to be achieved by saving resources and using hydrogen and green electricity in steel production [28].

The term **retrofitting** refers to the reuse and adaptation of steel structures in existing buildings. Various techniques are employed to maintain or enhance the structural integrity, safety, and energy efficiency of the steel components. Retrofitting may encompass measures for maintenance, reinforcement, adaptation to new standards or changes of use, as well as the integration of modern technologies [22].

These three concepts should not be seen as competing approaches, but as complementary functions that serve different purposes throughout the life cycle of buildings and infrastructures. The essence is to choose the most effective method for each specific case: **Reuse** is optimal when the components are accessible, certifiable and undamaged in their current form. **Recycling** is used when the steel component is damaged and non-compliant, so material recovery is the only viable route. **Retrofitting** is recommended when the existing structure can be maintained and improved, thereby extending the life of the structure.

5. Potential, benefits and barriers of reuse in steel construction

5.1. Different reuse approaches in steel construction

In the circular economy, four different types of reuse can be distinguished:

- adaptive reuse,
- architectural reuse,
- material reuse and
- reuse of structural elements.

Adaptive reuse describes the repurposing and conversion of a building or steel structure on the same site, where at least 50 % of the building stays intact. **Architectural reuse** refers to the integration of non-load-bearing structural elements such as windows, doors and facade panels from existing buildings into new construction projects. **Material reuse** focuses on reprocessing steel, upcycling or downcycling it for new applications, without retaining complete components. In the context of this work, the focus is on **the reuse of structural elements**, whereby the term "structural components" encompasses beams, columns, piles, foundations, and cladding [29]. Alternative distinctions can be made between different types of reuse.

5.2. Opportunities and benefits of reuse

Steel is an especially suitable construction material for reuse, as it meets the requirements regarding technology, reusable connections, modularity, and durability [30]. The principal advantages include the reduction of CO_2-emissions (Section 5.2.1), the minimization of costs (Section 5.2.2), functional modular construction (Section 5.2.3) and emerging technologies (Section 5.2.4).

5.2.1. Carbon savings

The reuse of steel components makes a significant contribution to reducing waste and lowering the energy and emissions associated with the production of new steel parts [31]. A detailed examination of the environmental consequences reveals that the reuse of steel results in a 96 % reduction of carbon emissions compared to the production of new steel [32]. In a study conducted by Berglund-Brown [29], the carbon dioxide content of reused steel was compared with that of recycled steel. In order to gain a comprehensive understanding of the subject matter, the study made use of a range of sources, including values from the existing literature, EPDs (Environmental Product Declarations), and data from the authors' own LCAs (Life Cycle Assessments). These were then subjected to a comparative analysis. The findings of the study demonstrate that, comparing reuse with recycling, an average reduction in carbon dioxide emissions of 87 % result when steel is reused in comparison to recycling [29]. Even if green, CO_2-free steel production is possible across the entire production range at some point, reuse will play a central role as a sustainable variant of material provision, at least as a transitional solution.

5.2.2. Costs

The primary motivation for engineers engaged in the development and integration of steel reuse is to reduce the environmental impact and thereby fulfil climate protection objectives. Nevertheless, these measures are not enough to overcome the barriers (see Section 5.3), including the additional costs for many stakeholders [33]. The reuse of structural steel components can also generate economic benefits:

- On the one hand, production costs can be reduced as significantly less new steel is required, despite expensive on-site modifications.
- On the other hand, the business volume of fabricators can be increased, if modification of reused components is necessary [31].
- Furthermore, it is possible to generate income by selling of reclaimed components for reuse [34].
- An additional method for reducing costs is the reuse of building elements during demolition for subsequent use on the same construction site for a new building [31].
- Another promising way for enhancing economic benefit is the reduction of life cycle costs. This necessitates the implementation of cost-effective technologies for dismantling, sorting, and inspection, which serves to enhance competitiveness [35].

5.2.3. Modular construction

Reuse can also be realized through modular construction, as individual modules or components can be repurposed in new building projects using components of the past in the present stock or future components designed for reuse. The use of modular construction methods offers significant advantages in practice, allowing for the efficient and cost-effective execution of building projects [36].

The main benefits are:

1. Time savings: Modules can be prefabricated in parallel with site preparation, reducing overall construction time.
2. Flexibility and adaptability: Existing buildings can be more easily converted or dismantled, as modules can be adjusted or reused.
3. Cost reduction: Standardized prefabrication and optimized logistics lower material and labour costs.

5.2.4. Technologies

A range of innovative technologies has been developed with the purpose of facilitating the efficient reuse of steel components. Risks and uncertainties can be reduced through the use of innovative digital technologies by automating reuse assessment processes. Such an approach may result in cost savings and an enhanced level of reliability. For example, a digital twin (DT) is capable of predicting the condition of a structure and, most importantly, determining the time and location of damage and failure. Potentially in the future, the digital twin can predict the lifetime for reuse, provided that the DT is already used in the design phase [37].

In addition, apart from common non-destructive-testing (NDT) methods, innovative approaches such as radiographic techniques, e.g. radiography and gamma ray defectoscopy can be used to evaluate surface and internal defects, for example. Such methods can be used to determine the location and size of defects such as cracks and corrosion in the metal, however, they are quite time consuming and, in some cases, difficult to perform [38]. To complement NDT techniques in the assessment of structural integrity, tools for managing and evaluating building assets are essential. Langston and Smith [39] have developed a tool, designated "IconCur", which is utilized for the administration and assessment of building assets with the intension of facilitating modifications during the initial phases of decision-making processes.

Also, in the context of reuse, the application of artificial intelligence (AI) is emerging. There are a lot of ways in which artificial intelligence can be used to improve the efficiency of infrastructure to support the circular economy [40]. The first option includes assistance in the automatic assessment, the second option is the development of automatic dismantling and the third option an enhanced method for sorting of mixed materials. The growing number of images from new technologies and devices like drones, robots, and smartphones shows the potential for AI tools, e.g. for neural networks, in finding and classifying reusable elements by using images [5].

These innovative technologies also open up new markets for reuse, which is advantageous, and can additionally help reduce extra costs associated with reuse.

5.3. Barriers of reuse and their potential solutions

5.3.1. General

Despite its potential, steel reuse faces several barriers, including regulatory challenges, economic constraints, technical and logistical difficulties, market perception and knowledge gaps [41,42]. Addressing these barriers is critical to promoting a circular economy in the construction sector.

5.3.2. Availability and effort of carefully demolished steel components

One of the most significant obstacles to the reuse of structural steel in the construction industry is the availability of suitable material. In contrast to new steel, the supply of reusable steel depends on the damage-free demolition and dismantling of existing structures. The majority of available reusable steel is derived from demolition work [5], Fig. 5. Although reusable steel can also be obtained from cancelled projects, rejected components and surplus materials, these sources play a minor role due to their limited volume.

Nevertheless, this presents a potential issue, as the demolition industry has thus far prioritized rapid and effective demolition, despite the necessity for careful dismantling to guarantee the integrity of the steel components [43]. So far, demolition companies have also concentrated their efforts primarily on material recycling, with comparatively less emphasis placed on demolition follow-up plans and reuse [44]. In conclusion, it can be stated that both financial and temporal incentives are lacking. As an example, the total cost of dismantling for reuse of the components was estimated to be between 17 % and 25 % higher than that of demolition for residential buildings in Massachusetts [45].

Existing structures were not planned for careful dismantling in the past, which is why connections between different components were often made monolithically (e.g. welded connections), which often makes non-destructive dismantling impossible. Already existing bolted joints are considered demountable and should be used as standard connections in new planning. To avoid the issue of monolithic connections furthermore, dismantling of the system should already be planned for reuse in the planning phase and new demountable interlocking connections could also be used. These detachable connections are currently being developed in various research projects for beam-to-beam [46] or beam-to-column [47,48] connections.

5.3.3. Design rules, regulations and standards for steel reuse

In general, there are no standardized design rules that are specifically applicable to the reuse of reclaimed steel components in Europe. Regarding the assessment of existing structures, which depicts a closely related topic to the assessment of reclaimed components for reuse, proposals for standards already exist with CEN/TS 17440 [49] and prEN 1990-2 [50]. Some rules of these documents might also be relevant for reuse, in other areas existing structures and reused components differ. It is essential that the reliability of reclaimed components for reuse offers the same level of reliability as new components.

Regarding execution, CEN/TS 1090-201 [51] contains provisions for the use of reclaimed components in the execution of steel structures in accordance with EN 1090-2 [52]. For the design of reclaimed components for reuse, a new document is currently being developed as CEN/TS in CEN/TC 250/SC 3/WG 24, which contains rules for the design of reused steel members [22].

Today, the professional use of construction products requires CE marking on construction products. If the properties of the components have changed, a new declaration of performance might be required, as well as CE marking, in order to be able to use them again. Despite these requirements, no standardization of the testing protocols is currently available for CE marking. This results in increased costs and time effort. Without CE marking, use as construction materials or sale as construction products by professionals is prohibited at the moment [53], as the exceptions to the CE marking, which only apply to individually manufactured or custom-made products for a given use or where the manufacturing of the product has to maintain traditional processes to guarantee the conservation of officially protected works, cannot be applied to reclaimed steel structures [54]. A new certification system or a further specification of the CE marking system regarding reclaimed components could be developed to ensure a uniform system within the European market.

5.3.4. Composite structures

The implementation of reclaimed composite components in existing buildings presents certain challenges. Conventionally, e.g. shear pins are

Fig. 5. Careful deconstruction of steel beams: Loosening bolted connections (left) and thermally cutting through beams (right).

utilized for the connection of steel and reinforced concrete, which makes it difficult to dismantle the structure without causing damage. It is anticipated that the use of bolted connections in composite structures could facilitate the dismantling process, but the usability of these steel components freed from concrete would still be limited due to the high number of holes in the top flange. The process of separating concrete from steel beams is also a costly addition to the overall project [55]. On the other hand, a recent study by Chen et al. found that wall sawing is a promising method for the reclamation of steel components from composite structures. This method permits clean separation with minimal surface damage and no significant impact on the mechanical properties of the steel [56].

As a further alternative, steel-reinforced-concrete-composite components could be reused without separating the two materials – the exact way in which this can be done remains to be investigated.

5.3.5. *Lack of customer interest and demand*

A study by Anastasiades et al. has indicated that demolition contractors notice a lack of demand for cautious dismantling from clients [44]. Furthermore, the image of reuse needs to be improved through green marketing, for example, as the general public's perception of demolition work has been very negative to date. Another contractor experienced the storage of reusable components that were not subsequently reused and therefore ultimately sold as scrap [44]. A further study emphasizes that increased customer demand for reusable steel would drive the market forward [57]. Successfully implemented pilot projects could improve acceptance in society. Financial incentives increase the willingness to reuse steel components.

5.3.6. *Logistical challenges*

One of the most significant challenges in the transition to a circular economy is the establishment of an entirely new infrastructure [34]. Effective coordination throughout the process chain is essential to facilitate the reuse of steel components, see Section 6. Furthermore, it is important that planners conduct an early review of the range of reusable steel components available in order to identify the optimal components for a project in a timely manner [57]. A lack of suppliers of reusable products combined with a lack of information on the availability of components for reuse in new construction projects poses a major challenge [25].

The issue of storage is not the only challenge associated with the transportation of components. It is not uncommon for components to be transported over considerable distances from construction sites to warehouses and new construction projects, with no guarantee that they will be reused. This results in significant financial expenditure and adverse environmental impacts [25]. To overcome the issue of stockpiling reclaimed steel without a guaranteed reuse path, a digital reuse marketplace should be created. This marketplace allows suppliers to list reclaimed steel with the needed information and allows engineers to search for materials during the design phase and the structure can be adapted to the existing reclaimed steel.

5.3.7. *Uncertainties regarding component condition*

Another obstacle is the lack of clarity regarding the properties and quality of the steel components. For instance, corrosion and mechanical stress can alter the structural properties, thereby leading to a difficult assessment of the material properties [34]. Additionally, there is a prevalent perception that newly manufactured components are of superior quality to those that have been previously used [5]. The lack of certainty regarding the material properties of a given component might lead to additional costs and risks, which are often perceived as significant barriers to reuse.

To overcome these barriers, it is essential to establish standardized assessment procedures and transparent guidelines to ensure the reliability and safety of reused steel components [58]. Moreover, increased efforts should be made to highlight and promote existing structures that effectively demonstrate the use and reliability of reclaimed components. Several examples of such projects are presented in Chapter 7.

5.3.8. *Summary*

Table 3 provides a clear overview of the barriers and possible solutions discussed in the previous chapters.

5.4. *Reuse potential rates*

The potential for reusing a building component is evaluated based on the extent to which its functionality is preserved even after the end of its first life. As stated by Iacovidou and Purnell [1], the potential for global reuse of steel components exceeds 50 %, thus classifying it as a material with "high potential" in comparison to other materials. In a study conducted by Cooper [59] it was found that up to 80 % of hot-rolled steel from existing buildings could be reused. Steel components have considerable potential for reuse, primarily due to their flexibility and durability [43]. In the event of corrosion or the formation of rust on steel components, reconditioning through maintenance is a viable solution [1]. In most cases, damage caused by fire is considered to be permanent [59].

Also, steel components that have been subjected to fatigue loading may not be suitable for reuse, as they could be affected by microcracks [60,61]. The reuse of components that exhibit fatigue damage or have not been extensively inspected should generally be avoided [5].

Table 3

Comparison of barriers and possible solutions as well as future directions regarding the reuse of steel components.

Barrier	Potential solution
Availability of suitable material	Storage of reused and new material; digital market platform; just in time “harvesting” of steel material; modular construction; mechanical adaptation **Future Direction:** Develop “Design for Reuse” strategies
Composite construction	Apply modular construction when designing new constructions
Corrosion	Regular maintenance; reconditioning
Integration into new design	BIM-based early design integration **Future Direction:** Automated component-project matching tools
Joining of steel components	Standardising bolted joints and plug connections more as done already today
High costs	Financial incentives; support by the government; compensation by carbon pricing; less life cycle costs; cost-effective technologies
Lack of costumer interest and demand	Marketing by successfully completed pilot projects
Lack of suppliers	Regional reuse hubs; job creation
Liability concerns	Define responsibility across lifecycle stages **Future Direction:** Legal frameworks
Properties and quality of the material	Standardized assessment procedures; transparent guidelines to ensure reliability and safety; non-destructive testing; digital twins (predict life-time of reuse); classification schemes; **Future Direction:** Digital passports
Regulation	EU-wide standardization; Orientation on other EU-guidelines; testing protocols; develop CE-marking system **Future Direction:** CEN/TC 250/SC 3/WG 24 “Design of reclaimed steel components for reuse”, EN 1990
Technically challenging dismantling	Design for Deconstruction; automatic dismantling; identification of usable steel components before dismantling
Storage and transportation	Regional reuse hubs **Future Direction:** Real-time digital platforms for reused steel components

However, if it is known that a component has been exposed to fatigue loads and load history is clear, a fatigue assessment can be performed to verify the remaining fatigue life of the component. Furthermore, fatigue loaded components without damage may still be used in applications involving purely static loading.

Non-destructive testing (NDT) identifying damage and microcracks due to fatigue is crucial with regard to the reuse potential of steel components. For example, Szymanik et al. [62] use two types of measurements including three non-destructive testing methods to monitor different aspects of the structural changes of the material during the fatigue process. The non-destructive testing methods here include infrared thermography (IRT), an electromagnetic method and an IRT method assisted by microwaves (MW). In another study, a non-destructive testing method for predicting the remaining fatigue life (RFL) of metals with fatigue predamage subjected to tensile-compression fatigue loading is presented [60].

In addition to the factors already discussed, several structural or historical features can significantly limit the potential for reuse. According to established protocols such as SCI P427, steel components that show signs of plastic deformation or that have been subjected to high loads, fire exposure or significant section loss due to corrosion are considered unsuitable for reuse. The material standards and traceability of structures built before 1970 are often unclear, which makes reuse difficult. However, these criteria are not always definite. For example, reused welds may be permitted if they are subject to thorough inspection and testing. In cases where there is only limited corrosion or deformation, components can be reused under conservative design assumptions, such as increased safety factors. Therefore, a structured assessment combining visual inspection, standardised testing and classification is essential to make informed decisions about the suitability of components [63]. If after evaluation steel components cannot be reused, recycling may be applied instead.

6. Processes of reusing reclaimed steel components and its integration plan

6.1. Process chain

In order to facilitate the practical reuse of components, it is essential that a comprehensive system is developed by industry and authorities. Such a system must encompass an end-to-end process chain, Fig. 6.

During recent investigations, 8 process steps have been proposed [22,24]. The important steps towards designing reclaimed components for reuse are the following:

- Component Survey: Inspection and/or Testing
- Component Assessment of Design Properties and Classification
- Design of reclaimed components for reuse

Overall, there is a lack of studies on the entire building supply chain to investigate the marketability and standardization of reusable steel building components [64]. Furthermore, the liability for the reused structural steel components has not yet been clarified. It can be argued that mutual trust between the players is an essential factor in the establishment of reuse and, consequently, the development of the process chain [65]. The most important aspects of the literature in relation to the 8 Steps are briefly reviewed below.

The first phase **Reclaim** involves reclaiming steel components from an existing building. Due to the need for a more careful approach to disassembly, additional time is required, resulting in an extension of the overall process. Planners and designers have a major influence on the cost and time efficiency of dismantling. It is recommended that solutions be developed to cover the cost of dismantling [66]. Sanchez et al. [67] present an approach to deconstruction programming that creates the disassembly plans for each target component to address inefficiencies in the deconstruction planning phase. The decisions made by planners and designers affect the design of the entire building and thus the subsequent disassembly and reuse of components [68]. It is essential that the design of a new building considers the fact that it can be easily dismantled at the end of its life [43]. Using components designed from the outset to be disassembled increases the possibility of reuse at the end of their life cycle. This can reduce the amount of waste at disassembly [69]. In a comparative analysis of construction and demolition waste (C&DW) production across European countries, Germany is identified as one of the three largest producers, with an estimated volume of 85 million tons in 2014 [70]. However, this is offset by a recycling rate of 80–90 % [71].

The "Design for Deconstruction" (DfD) concept is an investigative approach that aims to identify the most efficient method for deconstructing a building at the end of its useful life, even before its construction [72], see Fig. 9. Specifically, the use of modular systems and standard dimensions for beams and columns can increase the reuse rate. Furthermore, bolted connections are especially conducive to straightforward disassembly, thus facilitating subsequent reuse [73]. For example, in a publication by Selvaraj et al. [74] they present the extended design concept "Design for Deconstruction and Reuse" (DfDR). The design includes the use of dismountable, interlocking connections to facilitate the reuse of steel components.

Once the building has been dismantled and the reusable steel components have been removed, they must be subjected to an examination and testing process in the second step **Component Survey**. The inspection of the steel components that are to be reused can also take place before dismantling if necessary, as Fig. 7 shows. In certain cases, this is even more reasonable. Several research investigations address this step. In a study by Yeung et al. [75] an algorithm for the automatic geometric characterization of structural steel is presented. The automatic identification of cross-sections and the associated calculation of resistance factors aims to increase the reuse rate in the construction industry.

As part of the project "Provides for a Greater Reuse of Steel Structures" (Progress), a classification for steel components is presented [76]. The classification differentiates with regard to the recommendations for action for testing and approval procedures, whereby the presence of documentation is used as a criterion. A distinction is made between three material classes. For class A, the original test certificates are available and represent proof of conformity. For components assigned to class B, however, the original documents are missing, and recertification is required. This is done by means of a comprehensive test that examines the mechanical properties and chemical composition with quality tests. Class C includes structural steels whose material properties and composition cannot be identified. It is therefore necessary to assume the most conservative steel grade.

The shortly developed CEN/TS 1090–201 [51] also contains proposals for test protocols of reclaimed steel, depending on the level of

Fig. 6. Processes during reuse of reclaimed steel components – Variant 1.

Fig. 7. Processes during reuse of reclaimed steel components – Variant 2.

information of components. The application of these rules for the design of reclaimed components for reuse still has to be investigated.

After survey of the components, they need to be **assessed and classified** in the third step.

In one of their studies, Hradil et al. present a method for assessing the reusability of steel components [77]. In order to achieve this, a reusability indicator $r = w \bullet p$ is introduced, which provides a weighted average value for the assessment of reusability for eight different operations. Each of the processes mentioned, i.e. dismantling and disassembly, handling, cutting and separation, new design situation, cleaning, redesign, quality and geometry testing, is assigned its own weighting w [%] which reflects the relevance of the process for reuse. Moreover, p [%] indicates how difficult or easy it is to achieve the individual categories. Furthermore, the Progress project presents a proposal for a decision-making process regarding the reusability of individual structures and an associated classification [76]. Certain criteria must be met for the structures to be considered for reuse. For example, the building should have been built after 1970 and should not have been subjected to heavy dynamic loads.

In the fourth step, the collection and **stockage** of steel components for subsequent reuse is in focus. Following dismantling, testing, and classification, the components are possibly stored in designated production warehouses prior to being transported to processors and constructors via large-scale plants or directly. A greater number of storage locations results in increased storage costs, whereas transportation costs are reduced due to the probable shorter transport routes. Moreover, a larger number of warehouse locations permits the storage of a greater number of components, thus ensuring optimized customer supply [78]. Also, just-in-time harvesting and reuse of steel components is possible, reducing stockage efforts.

The fifth step comprises the **market placing** of the components. Here, it is essential that competent authorities develop and implement appropriate rules and regulations. A sample specification already exists in the UK that is relevant for suppliers of steel products that are offered as reused steel profiles for use in steel structures. This specification is relevant to the contract between the stockholder (the supplier) and the steel construction company (the customer) [79].

The next step is the **design of reclaimed steel components for reuse**. Here, a new part of EN 1993 or an addition of the code is necessary for the design process. The Working Group “WG 24: Design of reclaimed Steel Components for Reuse” was established within CEN/TC 250/SC 3 to develop according regulations regarding design.

Regarding existing first attempts on establishing regulations for the design of reused components, requirements for the load-bearing capacity and serviceability of steel components intended for reuse were defined in a leaflet published by the state of Brandenburg in Germany [80]. This document is intended to supplement EN 1993-1-1 [81] and can thus facilitate the reuse of components by providing a proof of usability and approval in individual cases in this state.

In Switzerland, the central standard for the maintenance of steel structures, which is related partly to the design of reusable steel components is SIA 269/3 [82]. It contains general requirements and guidelines for the implementation of assessments and tests [83,84]. Furthermore, the SIA 430 standard, entitled "Avoidance and disposal of construction waste," [85] introduces the terms "reuse" and "deconstruction". This standard places particular emphasis on the circular economy of building materials and incorporates a planning process aligned with the SIA phases [86].

In the Netherlands, NTA 8713 (Netherlands Technical Agreement) [74] has been developed for the reuse of steel components. The Construction Regulation and EN 1993 form the basis of the NTA, so that reused steel meets the same safety requirements as new steel. The document also contains guidelines for the preparation of an inspection document with suggestions for determining the geometric and material properties of the steel elements.

Also, there are numerous guidelines for the reuse of steel in the UK. The most important guideline is the publication P427 Structural Steel Reuse Protocol [63] which proposes a system for testing the material properties and thus a way to recertify reused steel elements. In general, advice is given for the recovery and reuse of steel structures.

At international level, some countries have already developed standards that could serve as a valuable reference for European regulations. In the United States, for example, the LEED rating system awards points for the reuse of structural steel in construction. To fulfil the requirements, reused steel must undergo mechanical testing (ASTM A370) and chemical analysis (ASTM A751). In addition, Appendix 5 of the AISC specification provides guidelines for the assessment of existing steel structures [87]. These frameworks could be helpful in the development of standardised and practical rules in the European context. The certification system also actively creates an incentive for the reuse of steel components.

Although there are already important guidelines, there is still research to be done on the application requirements of reused steel components. When designing reused steel, not only the steel beams themselves, but also any existing welded joints must be considered. These can contain imperfections, especially in old steel structures – larger weld imperfections than we require today. Recent research results have shown that weld imperfections do not always have to have a major influence on the load-bearing capacity - in the case of fatigue loading [88,89] or especially static loading [90,91], which is the focus when regarding the design of reclaimed components for reuse. Larger component imperfections must of course also be considered if stability failure plays a role in the design of a reclaimed component.

After the design of the reclaimed components, the **structural modification** of the component takes place in the seventh step. This is only necessary if modifications, repairs, extensions, or reinforcements are required. Finally, in the last eighth step, the reclaimed components are **installed** in a new building, completing the process of reuse.

In addition to the two first reuse sequences mentioned, the storage and market-placement phases may be omitted when reclaimed components are to be reused by the same client in a new project, Fig. 8. Under these circumstances, a direct reuse pathway can be implemented, substantially reducing administrative burden. This variant would involve fewer stakeholders, thereby simplifying coordination efforts. Moreover, since no storage is needed for dismantled steel components, associated costs for warehousing and transportation are eliminated. As a result, the overall infrastructure requirements are significantly reduced.

6.2. Integration plan across the 8 steps of the proposed model and key action fields

The transition towards a circular economy in the construction sector

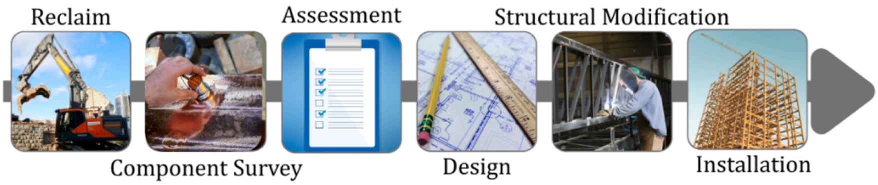


Fig. 8. Processes during reuse of reclaimed steel components – Variant 3.

Fig. 9. Deconstruction for Reuse.

requires a coordinated integration plan between industry, government and research institutes.

The following plan addresses the technical and management aspects across the previously proposed eight key process steps.

1. The first step involving dismantling of the existing building demands a selective and careful deconstruction, guided by the DfD principles. Early-stage building planning must incorporate disassembly potential, promoting modular systems, bolted connections, and standard dimensions to increase reusability. Planning tools like BIM-assisted deconstruction schedules can enhance efficiency.
2. After the reclaim of the components, or sometimes depending on the structure even prior to dismantling, these components must undergo a survey phase. To standardize this step, technical protocols should be adopted. Management integration requires standardized testing protocols and classification schemes (e.g., Class A/B/C).
3. After this survey, the components are classified and assessed for their reusability. Tools such as the reusability indicator offer a structured approach for decision-making. Additionally, eligibility criteria (e.g., construction year, load history) must be codified. Stakeholders should collaborate on certification models that assign responsibility and reduce the perceived risk of using second-hand materials.
4. Steel components may be stored at designated facilities before reuse. Efficient logistics planning, especially balancing storage and transport costs, is essential. Just-in-time solutions are to be preferred. Also, a digital inventory with material passports should be implemented. Governments could co-finance regional reuse hubs to maintain adequate storage infrastructure while managing stock levels.
5. To facilitate market uptake, steel components must be placed in transparent marketplaces featuring standardized descriptions and certifications.
6. Reused components must be designed into new structures using codes. Current developments such as additions to EN 1993 within CEN/TC 250/SC 3/WG 24 as well as Technical Specifications provide initial guidance.
7. Final installation involves integrating reused components into new construction. Building authorities should simplify permitting for reuse projects and offer benefits for meeting circularity targets. Integration with BIM and digital twin platforms will support lifecycle monitoring and future reuse.

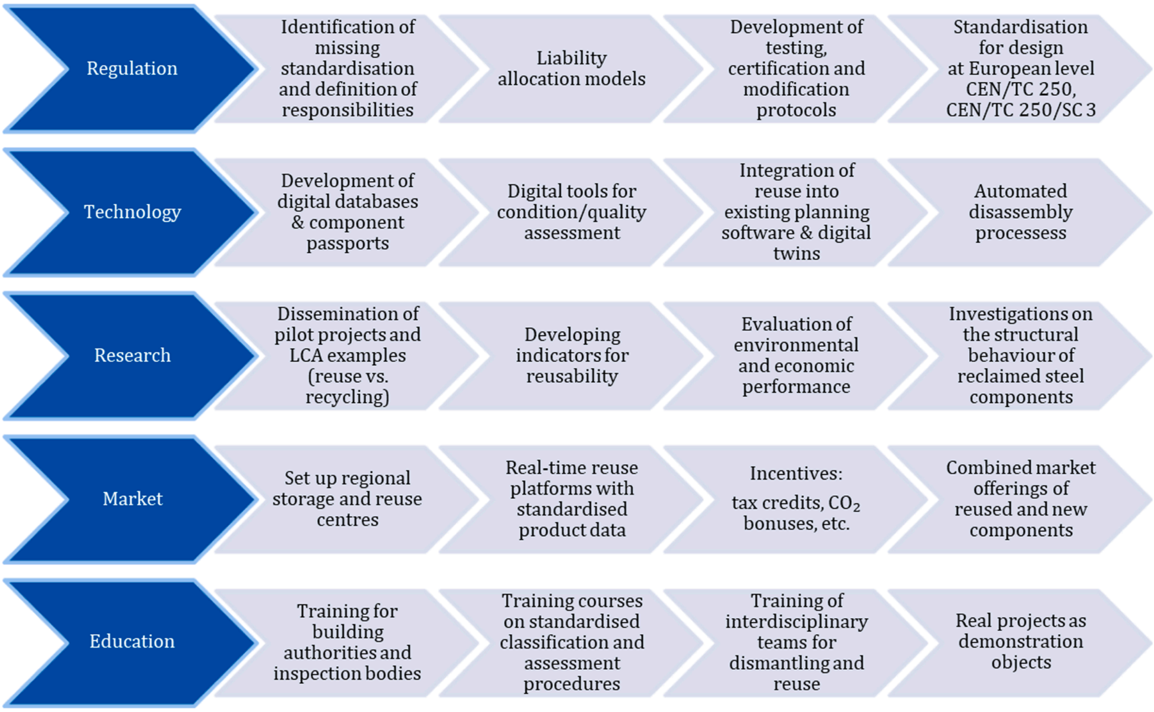
Fig. 10 schematically shows which steps must be taken in regulation, technology, research, market and education to enable the reuse of steel components.

7. Case studies

There are already numerous applications of reuse, although there still are few standardized regulations and the challenges already mentioned in Section 5 exist. The following section presents case studies that show how the reuse of components is being implemented in real projects around the world. Fig. 11 gives an overview over the presented studies.

In 1994, the steel structure of an old school building in northern British Columbia was reused to rebuild the Roy Stibbs School after a fire, maximizing reuse by incorporating over 75 % of the original steel components. The primary challenges in adapting this steel for a new seismic zone and coordinating its transport and structural adjustments highlight the adaptability and logistical complexities of reusing steel in construction. Higher seismic requirements were addressed through targeted strengthening and adjusted bracing [92].

Another example of sustainable construction is the BedZED project, completed in 2002, which used reclaimed steel to reduce costs and environmental impact, demonstrating the economic viability of recycled materials in eco-friendly housing. This case shows how reclaimed steel can effectively support sustainable development by conserving resources and reducing waste [105,106].



Regulation	Identification of missing standardisation and definition of responsibilities	Liability allocation models	Development of testing, certification and modification protocols	Standardisation for design at European level CEN/TC 250, CEN/TC 250/SC 3
Technology	Development of digital databases & component passports	Digital tools for condition/quality assessment	Integration of reuse into existing planning software & digital twins	Automated disassembly processess
Research	Dissemination of pilot projects and LCA examples (reuse vs. recycling)	Developing indicators for reusability	Evaluation of environmental and economic performance	Investigations on the structural behaviour of reclaimed steel components
Market	Set up regional storage and reuse centres	Real-time reuse platforms with standardised product data	Incentives: tax credits, CO_2 bonuses, etc.	Combined market offerings of reused and new components
Education	Training for building authorities and inspection bodies	Training courses on standardised classification and assessment procedures	Training of interdisciplinary teams for dismantling and reuse	Real projects as demonstration objects

Fig. 10. Essential action fields for enabling the steel component reuse in construction.

The Mountain Equipment Co-op (MEC) Winnipeg building, completed in 2002, shows sustainable construction by incorporating reclaimed timber and steel components sourced from on-site deconstructed buildings. This project demonstrates the effectiveness of designing for future disassembly and integrated systems that enhance resource conservation and facilitate further material reuse at the end of its life cycle. Early team coordination and flexible, modular design enabled over 96 % reuse of timber and steel [107,108].

Similarly, the MEC Ottawa building, first completed in 2000 and expanded in 2012, showcases sustainable construction through the reuse of reclaimed steel and other materials from on-site deconstruction [109].

The UTSC Student Centre, opened in 2004, highlights sustainable construction by reusing 18 tons of steel from the demolition of the Royal Ontario Museum. This student-centred facility, developed with significant student involvement in the design and planning process, is supposed to demonstrate how recycled materials can be integrated into new constructions to promote environmental sustainability while serving the diverse needs of the university community [110].

The Blue Steel building in East Leeds underwent refurbishment in 2005, transforming an existing 14,500 m^2 steel portal frame warehouse into a modern facility for Carlsberg UK. By extending the steel frame and incorporating reused materials, the project enhanced storage capacity and energy efficiency while preserving the original structure. Through a straightforward process, the refurbishment was achieved quickly [111,112].

The Rue Bel-Air 740 project involved deconstructing an existing building on the same site to reuse materials in a new government facility. Roof beams from the former industrial building were reused here [113].

During the Carrwood Park project the refurbishment of an 1800 m^2 portal-framed building has been performed using 82 tonnes of reclaimed structural steel from an old warehouse [31,111].

A relocation of the building at 9 Cambridge Avenue in Slough in 2015 exemplifies steel's role in the circular economy, as it reused a significant portion of the original structure. The project involved relocating and flipping the 3320 m^2 warehouse while reusing the steel frame, glazing, staircases, and other elements, resulting in 56 % less embodied carbon and 25 % cost savings compared to constructing a new building. A new roof was installed on the relocated building in order to mitigate the risks associated with reusing the old roof, particularly the roof lights. [114,115].

Stadium 974 in Doha is a fully modular structure designed for complete dismantling and reuse, featuring 974 standard shipping containers integrated into a steel framework. Its design allows for various configurations, enabling sections to be repurposed as standalone stands or circular arenas, showcasing the potential for sustainable stadium construction. The site's transport links enable future reuse, and Design for Disassembly makes the stadium adaptable for circular use [116].

The Primeo Energy Cosmos project, completed in late 2022 in Münchenstein, features a unique building made of wood and surrounded by a steel structure crafted from reused electricity pylons. The design incorporates various reused materials, including steel bars, HPL panels, and PV panels, resulting in a total material intensity of 641 kg/m^2, with 11 % of materials being reused [117].

In 2022, the redevelopment of the original 1980s building at 7 Holbein Place, London, highlights the use of reclaimed steel. The project aimed to retain existing structures and materials while implementing low-carbon alternatives to create a modern office space [93].

There are plenty of further examples of similar initiatives, unfortunately not all of which can be described in detail here. See [118–124] for further design examples.

8. Conclusions and outlook

This review paper describes the state-of-the-art of potential and challenges of the reuse of reclaimed steel components in construction and proposes future directions. The following main conclusions can be drawn:

1. A structured literature review has been conducted, taking into account research articles comprising the keywords *reuse*, *steel*, *components*, *circular economy* and *construction*. The review resulted in a

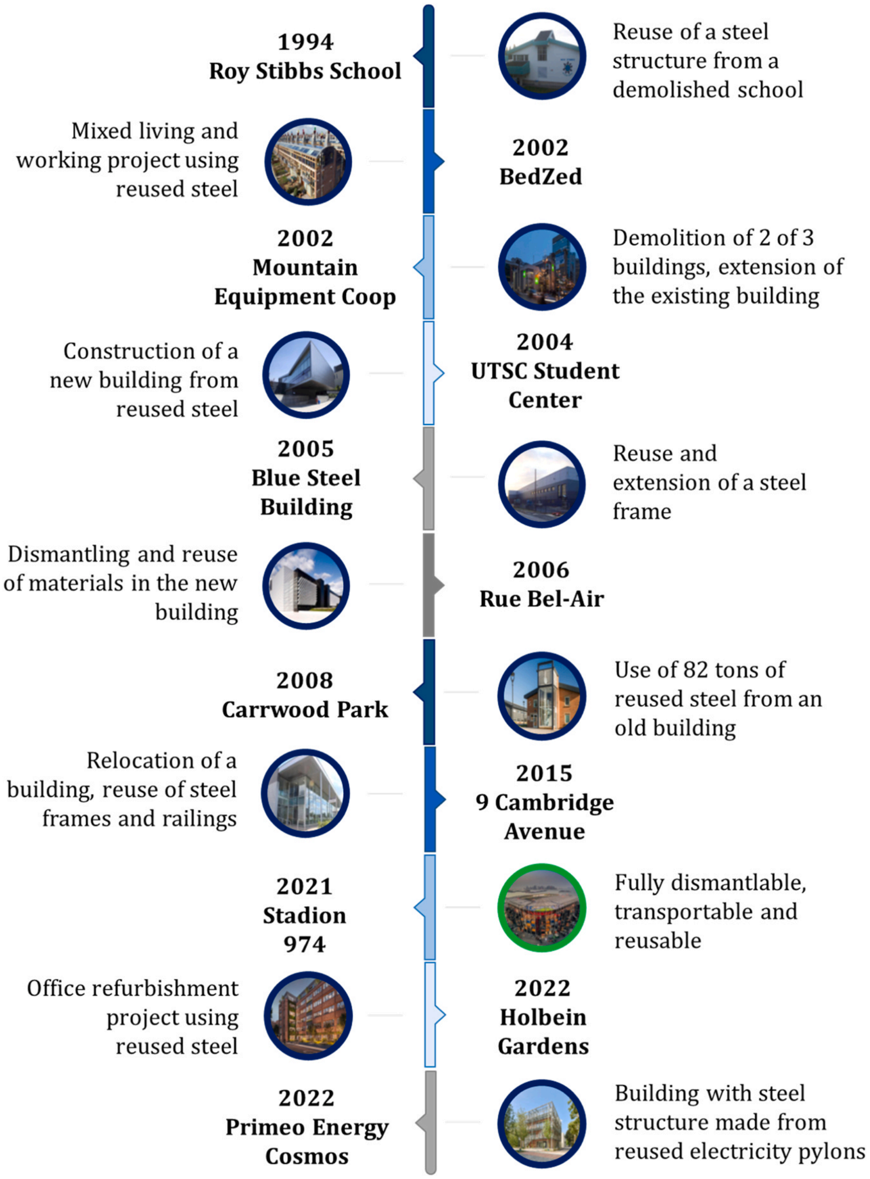


Fig. 11. Overview of important design examples regarding reused steel (blue frame) and design for future reuse (green frame); Content: [92,93]; Photos: [94–104].

number of 137 publications, while about 80 % have been actually utilised for the review.

2. The analysis of potential and benefit showed that the environmental potential is an important driver for reuse. At the same time, the review reveals different barriers of reuse, such as the expensive effort of reclaiming steel components for reuse, missing design regulations in Europe or logistical challenges. Potential Solutions have been worked out and are presented.
3. The processes during reuse of reclaimed steel components are analysed in detail, presenting current challenges of the single steps. Although many of the prerequisites for reuse of steel are already in place, some essential topics – such as component classification, legal liability and digital documentation – still need to be addressed. An integration plan across the process chain as well as action fields are presented.
4. Case studies from 1990 to the present show that reuse is technically and practically feasible when supported by careful planning strategies, good co-ordination, quality assurance and marketing.

In the future, the reuse of structural steel will play an increasingly important role. To realise its full potential, targeted efforts are needed in the areas of regulation, technology, market infrastructure and education. Reuse should be established as one important strategy for extending the life cycle of steel structures. Whenever conditions allow, it should be prioritised over recycling as part of an integrated circular economy in construction.

CRediT authorship contribution statement

Helen Bartsch: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization.

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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