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Reuse of Steel in the Construction Industry: Challenges and Opportunities

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Abstract

The construction industry plays a critical role in tackling the challenges of climate change, carbon emissions, and resource consumption. To achieve a low-emission built environment, urgent action is required to reduce the carbon emissions associated with steel production and construction processes. Reusing structural steel elements could make a significant impact in this direction, but there are five key challenges to overcome: limited material availability, maximizing different reusable materials from demolition, lack of adequate design rules and standards, high upfront costs and overlooked carbon impact of the demolition prior to construction, and the need to engage and coordinate the complete construction ecosystem. This article described these barriers and proposed solutions to them by leveraging the digital technologies and artificial intelligence. The proposed solutions aim to promote reuse practices, facilitate the development of certification and regulation for reuse, and minimize the environmental impact of steel construction. The solutions explored here can also be extended to other construction materials.

Keywords Steel reuse · Circular economy · Artificial intelligence · Resource efficiency · Digitalization · Construction industry

1 Introduction

The building construction drives current energy consumption and greenhouse gas (GHG) emissions, representing 36% of total energy use and 37% of the global GHG emissions, respectively (RICS Professional Standard, 2023; UNEP, 2021). Approximately, 10% of these emissions are related to the carbon emissions caused by the production of materials in buildings (le Den et al., 2022): the current amount of embodied carbon emissions in a new building is 600 $kgCO_2e/m^2$ on average, of that 70% of this embodied carbon is emitted upfront, during the building production and construction (A1–A5 life cycle) stages. Besides, construction activities consume a significant amount of natural resources and produce the highest amount of waste among all other sectors (BIO Intelligence Service, 2013). In order to comply with the EU Taxonomy requirements (Directorate-General for Financial Stability, 2023), new building construction must include a life-cycle Global Warming Potential (GWP) assessment for each stage in the life cycle, and disclose it to its investors and cliends on demand. Moreover, regarding the use of “metals”, at least 70% of the total material must come from secondary sources (reused and recycled). As a result, the construction industry is under more scrutiny than ever to reduce resource consumption, construction, and demolition-related waste (NBS, 2022; Askarizadeh et al., 2016; McFarland et al., 2021; Geissdoerfer et al., 2017). Building renovation of existing buildings and adaptive reuse of materials and components of a building can contribute to slowing down the resource consumption and the negative environmental impact due to material disposal, and new manufacturing.

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1.1 Why is Reuse of Materials So Important?

50% of the total material use in Europe is associated with buildings and other civil infrastructures (BIO Intelligence Service, 2013), and construction activities produce the highest amount of waste among all other sectors. The reduction in embodied carbon, resource consumption, and other environmental impacts, can be achieved by recovering building waste caused by demolition through material reuse, recycling or building repurposing through selective deconstruction and building system reuse (Assefa & Ambler, 2017). Furthermore, during the clean-up phases of construction, a substantial amount of the debris generated can be recycled or reused, reducing the volume of waste being sent to landfill sites and minimising the need for site remediation before new construction occurs.

At the heart of a circular economy, lies the fundamental principles of reducing waste generation and maximizing the value of products and materials by keeping them in use for as long as possible (Ellen Macarthur Foundation, 2022). The circular economy aims to preserve resources' functionality and value by recovering products, components and materials. Most value is preserved when the product or material remains close to its original state; preserving its integrity (Bakker et al., 2020). Thus, it is an opportunity to use waste materials in the construction industry by reuse of structurally functional parts (re-using) or the use of raw materials as components to produce new structural elements (recycling) (Assefa & Ambler, 2017). However, recycling is currently the common approach for construction materials at the end of their life. Recycling requires energy to process materials (e.g. material extraction, transportation, manufacturing etc.) and may result in a loss of quality. A more sustainable option is reuse, which implies only minimal physical transformation (Brütting et al., 2019; Blok & Teuffel, 2019). To upscale circularity, the reuse of building structural parts must become mainstream instead of demolition and recycling.

1.2 Load-Bearing Structures with Reused (Reclaimed) Elements

The reuse of load-bearing structures is critical due to the significant contribution of these elements to the environmental impact of buildings, considering their substantial material mass and energy-intensive fabrication process. According to the life cycle assessment of the case studies presented in (Brütting, Desruelle, et al., 2019a, 2019b), structures obtained using the reused elements showed a reduction in the environmental impact of up to 63%, compared to weight-optimized solutions made from new elements.

Despite the significant environmental impact reduction of designing with reused elements and the potential to avoid superfluous waste and sourcing new materials, designing a structure from a stock of reclaimed elements entails a change of design paradigm: in contrast to conventional design practice, the structural geometry and topology depend on element stock characteristics, e.g. material, available cross-sections and lengths. For example, there might not be enough elements of a certain length and cross-section available that fit within a required layout. In other cases, structures made from reused elements might be oversized with respect to structures made of newly produced elements (Brütting, Desruelle, et al., 2019a, 2019b). As a result, depending on the element stock, designing, and building a structure made only of reused elements brings its own challenges.

1.3 Among Other Materials, Why is Steel Reuse the Most Crucial for the Environment?

Steel can be manufactured entirely from recycled scrap (secondary steel) or from a mix of recycled scrap and new steel created from iron (primary steel). Ironmaking is part of the primary steelmaking process, and 1200M T of iron is produced annually in the blast furnace (BF) process using coke to reduce iron ore (World Steel Association, 2022). Another 100M T is made by reducing iron ore, often with natural gas (CH_4), in the direct reduced iron (DRI) process to produce solid 'sponge' iron. Depending on the method used to create primary steel from iron, either a basic oxygen furnace (BOF) or an electric arc furnace (EAF), the A1-A3 embodied carbon factor (ECF) for steel is nearly 2500 kgCO2e/t and 1000 kgCO2e/t from BF-BOF and DRI-EAF processes, respectively (W. Swann, 2021). Furthermore, even though most scrap steel arisings are captured and recycled or reused, the global demand for steel is such that it exceeds the availability of scrap by a factor of 3 and, without the dramatic decrease in material usage, the need for primary steelmaking to meet the demands of tomorrow is only going to increase (W. Swann, 2021).

The first available Environmental Product Declaration (EPD) on reused steel from EMR (EMR, 2023) reports Global Warming Potential (GWP) values of around 50 $kgCO_2e/t$ for the LCA stages A1-A3. This value shows that steel reuse can offer substantial environmental benefits, with potential reductions in GWPs of up to 95%, 90%, and 75%, respectively, in comparison to primary steel production, recycled steel, and renewable energy-based recycled steel as reported in several EPDs and databases (e.g. from reference steel producers such as Arcelor Mittal, (International EPD System, 2022). Therefore, with the pressure towards the implementation of a circular economy in the construction and various industries to achieve the ambitious goal of zero waste (EPA, 2022), the challenge to transition to carbon–neutral primary steelmaking and steel reuse is the most urgent one to face. In this article, an extensive review is made to discuss the methodologies to push the reuse practices of steel materials.

2 Examples of Reusing Steel Structural Elements

Five case studies are presented to demonstrate the practical application of reuse, and the lessons learned from these projects.

2.1 Holbein Gardens

A new floor extension was made on the top of an existing "Grosvenor Estate" building from the 1980s, creating a 25% upgrade in the available floor space. The aim of net zero was primarily achieved by relying on reclaimed steelwork and Cross Laminated Timber (CLT). In the building, 34% of the steel elements were reused from a previous demolition (Fig. 1).

Where reused steel was to be used, there was an engineering check as to the suitability of reused steel. However, warehouse reuse is permitted up to execution class 3 in EN1090 (CE marked) and only requires additional safety allowances in specific situations, as shown in the SCI Steel Reuse Protocol P427 (also P440) (D G Brown et al., 2019).

The reused steel was sourced from demolition on 2 existing Grosvenor projects and from reused stock from Cleveland Steel. The material was all re-tested using non-destructive and destructive laboratory techniques in accordance with P427 (also P440) of the SCI Steel Protocol (D G Brown et al., 2019). These tests allowed the grade, sub-grade, tensile strength and yield strength to be ascertained as well as the chemical composition. In turn, this allows for the CEV (weldability) to be calculated. The test results allowed the structural properties of the sections to be proven, and hence, the structure can be CE marked according to legislative requirements. Figure 1b shows the elements that were shot blasted and not yet painted, which shows how well the reused material can be cleaned before it is recoated.

This project involved approximately 67 T of steelwork involving reused elements. 25 T was reused material interconnected with new ones and not designated to specific areas. This allowed a carbon saving of approximately 60 T.

2.2 NTS Building

In this project, a second-hand portal frame (Fig. 2) was purchased to construct a warehouse.

All of the original drawings and details about the structure and steel were available at the time of purchase, which allowed to perform only a few laboratory tests to verify the available data. It was then possible to use that engineering data to calculate the new structure in its new location. A row of columns was stiffened, new base plates and drilling for new crane rails to allow for future expansion were required, and the structure had to be repainted. The job also used recovered road stones for the groundwork and kept all the soil on-site to save transport and disposal costs. The cost associated with the reuse vs. new construction is studied by Cleveland Steel & Tubes Limited, and the summary is reported in (Table 1).

2.3 East Arkengarthdale Bridge

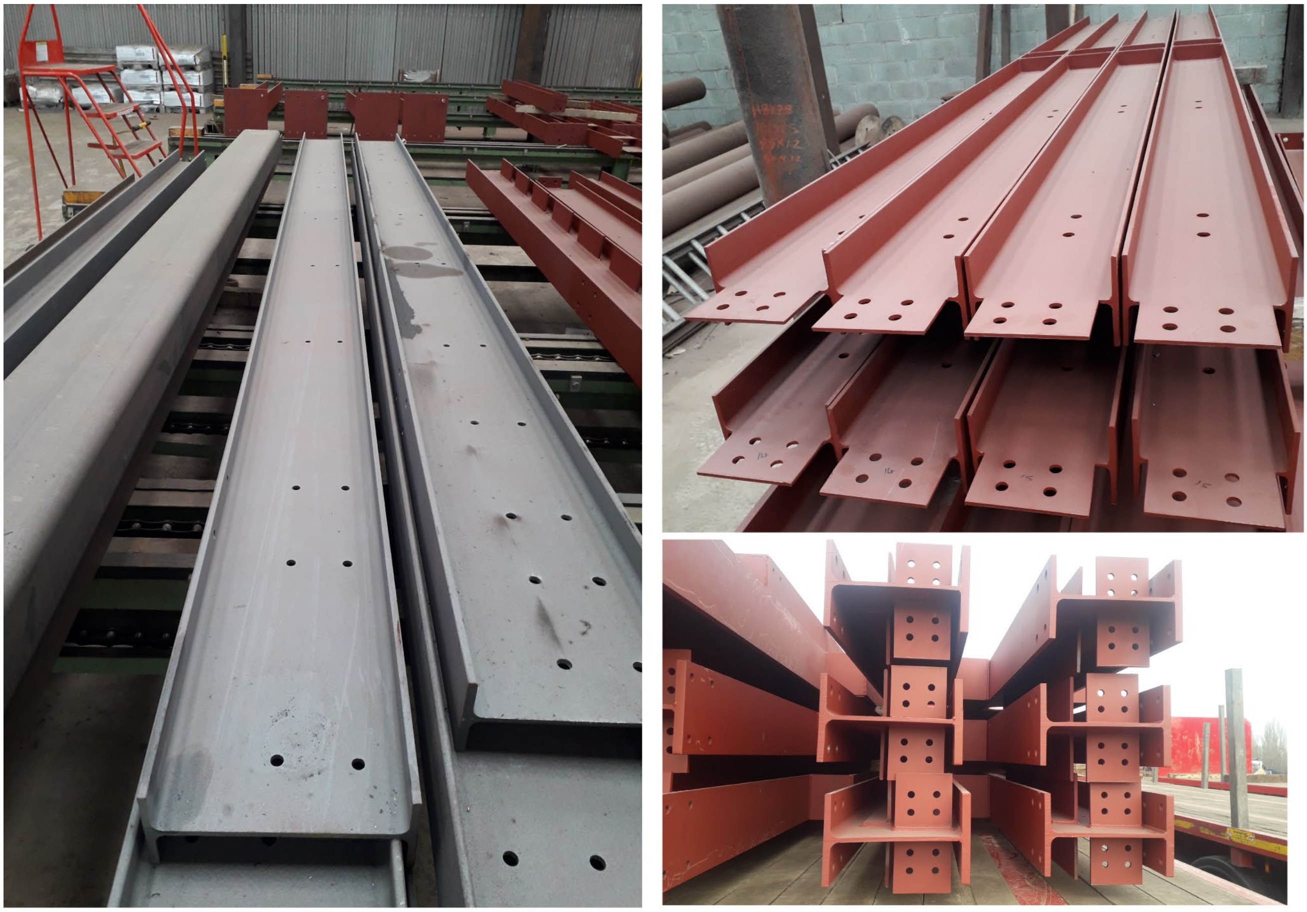
A hundreds of years old bridge in the Yorkshire Dales (Fig. 3a) was condemned, and Cleveland Steel could have a new deck designed and reused steel sections in a simple situation to save 8 T of carbon. This demonstrates the value of reuse without it having to be on major projects.

2.4 Sloane Square House

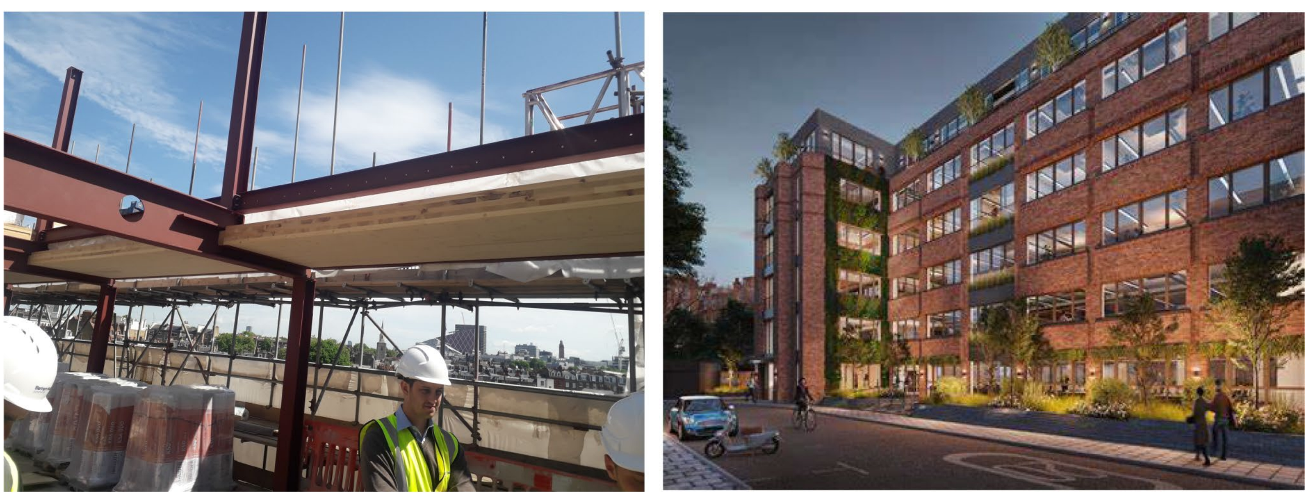
In this project, 100% reused steel sections are implemented. A storey extension was made on top of the existing structure as part of the wider office refurbishment (Fig. 3b). By using an in-house digital tool, sections from Cleveland Steel's stocklists have been matched with designed sections based on size and strength requirements. Furthermore, incorporating the parametric design criteria has enabled the architects, clients and design teams to assess the impact of different size steel member options. The tool's integration with structural analysis software and Revit has also enhanced the coordination process to achieve the current optimum steel reuse design. Through the collaboration, it was managed to achieve 100% reused steel sections at the end of Stage 3 ("Spatial coordination" from (The Royal Institute of British Architects, 2020)) The automated tool also enabled to easily work with a constantly changing stocklist during Stage 4 ("Technical design" from (The Royal Institute of British Architects, 2020)). Ultimately, 21T steel reuse led to an approximately 60% reduction in the upfront structural carbon impact. All reused steel was incorporated by adhering to the principles of P427 of the SCI Steel Reuse Protocol (D G Brown et al., 2019).

2.5 Port of Dundee East Redevelopment

The company was selected to supply and fabricate 1070 T of 911.8 mm diameter × 28 9 mm wall thickness, between 18.7 and 26.8 m for piling (Fig. 4). Initially, the requested size was 914 mm outer diameter × 25.4 mm wall thickness tubes.



a) Shot blasted steel before re-coating *b) Reclaimed steel ready for the new use*



c) The new structure made of the reclaimed steel

Fig. 1 Holbein Gardens Project (*Source*: Cleveland Steel & Tubes Limited)

However, the company had recently acquired a surplus gas pipeline measuring 911.8 mm outer diameter × 28.9 mm wall thickness, which closely matched the required specifications. This alternative solution proved cost-effective and sustainable, offering a significant carbon saving of 95% to 97% compared to new production. To adhere to the project's technical specifications outlined by BS EN 1090 EXC 2, the company removed the concrete coating from the pipes and

a) Steel from the demolished building *b) New building with reclaimed steel*

Fig. 2 NTS building project (*Source*: Cleveland Steel & Tubes Limited)

Table 1 Cost and carbon saving summary of NTS building project (*Source*: Cleveland Steel & Tubes Limited)

	Cost if new	Additional cost of reuse	Cost saving versus new	Net saving	Carbon saving (approx.)
Design/admin	£312,000	£26,000	£162,000	(£26,000)	n/a
Groundworks	£422,000	0	Planings = £130,000 Muck = £133,000	£260,000	Haulage—224 T CO_2 Stone—52 T CO_2
Steel	£1,020,000	£160,000	£566,000	£566,000	1000 T CO_2
Cladding	£740,000	n/a	n/a	n/a	n/a
Floor	£950,000	n/a	n/a	n/a	n/a
Landscaping	£150,000				
Foundations	£132,000		Muck—£4000	£4000	4 T CO_2
Erection	£239,000	n/a	n/a	n/a	n/a
Totals	£3,776,000		£995,000	£969,000	1480 T CO_2e

conducted 100% ultrasonic testing (UT) for all circumferential welds, as well as 300 mm of the long weld at each end of the finished piles underwent UT testing, with certification issued for all the tests. Project-specific carbon savings calculations revealed a carbon reduction of 2185 T compared to new production.

In conclusion, these real-world examples show that reuse of steel can significantly reduce embodied carbon emissions and costs, conserving material resources and reducing waste. The summary of the projects with the associated savings on CO_2 emissions and total reused steel is presented in Table 2.

In addition to the above, other highlights from the latest developments (Circular Steel, 2023) can be listed as the following: For the "Cambridge House" project in London, a 25T tower was disassembled from its original location, and the beams underwent testing to determine their suitability for reuse. After being shot blasted at the factory, the steel was refabricated to accommodate a new tower design, subsequently painted and assembled. The tower found application in the new project, leading to the saving of 2.5T of carbon emissions per tonne of steel compared to the conventional rolling production method. As part of a UK-funded project, a concrete-encased steel structure dating back to the 1950s underwent testing (following SCI P427 and P440 standards (D G Brown et al., 2019) with the supplement "reuse of pre-1970 steelwork") to determine its suitability for re-using the steel components in new structural applications. The test results revealed a yield strength of 248 N/mm2, a tensile strength of 388 N/mm2, and a minimum elongation of 25.8%. The evaluation showed that the primary damage occurred at the top flanges due to the removal of the concrete encasement, which was done using a hydraulic hammer. The construction of 100 Liverpool Street, completed in 2020, made use of reclaimed steelwork, which constituted approximately one-third (32%) of the building's steel frame, resulting in a carbon-saving of 3435 T. Where new steel was needed, the project prioritized the steel manufactured via Electric Arc Furnace. Scheduled for completion in 2025, the 1 Broadgate project, the pre-demolition audit and circular economy workshops helped formulating reuse strategies, including a 140t of structural steelwork that was carefully

a. East Arkengarthdale Bridge project (Source: Cleveland Steel & Tubes Limited)

b. Reused steel sections from Sloane Square House project

Fig. 3 Two examples from Cleveland Steel & Tubes Limited

removed, subjected to testing, and successfully repurposed in another development.

3 The Practice of Reuse in Other Disciplines

Through a literature analysis focusing on industries outside of steel construction, we have seen that the construction industry currently holds the greatest focus on the reuse of reclaimed parts. While other fields explore advanced methods like segmentation patterns for reuse, recycling tends to be the more common approach rather than reuse. This trend can be attributed to the construction industry's significant contribution to greenhouse emissions, where the potential impact on reducing global warming potential (GWP) is substantial through reuse. Nilakantan and Nutt (2015) proposed the production of numerous end-products, including medical devices, sporting goods, automotive and aerospace structures, construction materials, furniture, and shipping containers, all of which can be partially or entirely constructed from scrap thermoset prepreg. The efforts made in the aerospace industry to promote reusability can be relevant to the steel construction industry because the carbon fibre and resin found in scrap prepreg are valuable components that can be utilized without requiring destructive separation. To overcome the complexities associated with re-using large-sized, complex-shaped, and compositionally diverse composite products, Joustra et al. (2021) introduced a

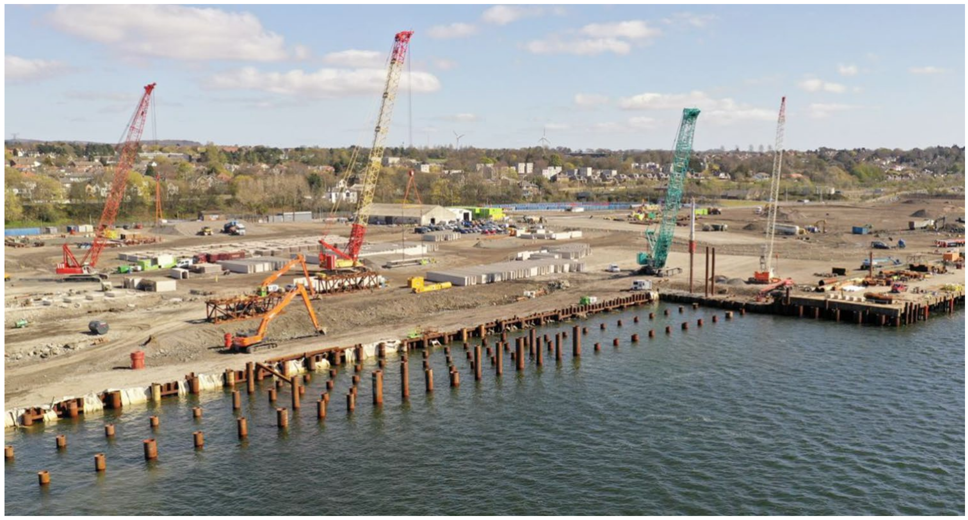


Fig. 4 Port of Dundee East Redevelopment (*Source*: Cleveland Steel & Tubes Limited)

Table 2 Summary of real-life steel reuse projects

Project	Type of structure	Purpose of reuse	CO_2 emission saved due to reuse (tonnes)	Primary steel material saved due to reuse (tonnes)	Project completion year
Holbein Gardens	Building	Elevation increase of the existing structure	50	25	2022
NTS Building	Warehouse	New warehouse construction	1000	500	2019
East Arkengarthdale Bridge	Bridge foundation	Simple deck construction	8	4	2021
Sloane Square House	Building	Elevation increase (new 2 storeys) of the existing structure	42	21	Underway
Port of Dundee East Redevelopment	Piling for Wharf	New piling	2185	1070	2021

systematic approach for defining segmentation patterns and assessing structural quality. This proposed method enables the structural reutilization of complex composite products through segmentation, structural analysis, and subsequent reuse applications. Although the properties and reclamation processes for steel and composite materials differ, the systematic approaches and segmentation patterns proposed for composite products can serve as valuable lessons for facilitating the structural reuse of reclaimed steel elements.

4 Barriers and Current Challenges in Reusing Structural Steel Elements

The environmental impact of re-using structural elements is evaluated by academic studies (Brütting, et al., 2019; Minunno et al., 2020; Hoxha & Fivet, 2018; de Wolf et al., 2018; Assefa & Ambler, 2017). Material reuse involves element sourcing and extra process for deconstruction, reconditioning (e.g. cleaning and sandblasting elements) and transport. Furthermore, re-using old buildings that were designed and constructed either when the seismic codes were not advanced or not enforced by law, lack of recorded information and other factors can also increase the financial risk and overall cost of the project (Rakhshan et al., 2021). Therefore, reuse/recycle break-even points are essential to calculate (Brütting et al., 2020). Level(s) Indicator 2.4 JRC Report states: “Steel: Construction technology was not seen to hinder the reuse of steel components, but rather the lack of established practices”. The overall reuse rate is not in streamline and needs a collective effort to realize it in the Architectural, Engineering and Construction (AEC) industry.

In this article, 5 major challenges are identified: Material availability, lack of adequate design rules and standards, high upfront costs and the overlooked carbon impact of demolition prior to construction, maximizing different re-usable materials from demolition, and the need to engage and coordinate the complete construction ecosystem.

4.1 Material Availability

The first, and most significant challenge is material availability for reuse. When cancelled projects, rejected components, and surplus materials can be found, they are generally available for reuse and allow for carbon savings by diverting waste. However, the vast majority of the material arises from demolition, posing very significant challenges. The demolition industry has invested heavily in equipment and methodology for the speedy demolition/destruction of buildings. To recover materials effectively, it is essential to develop new methods. The issue then comes down to cost and time. If the operation is slower and delays site project lead times, the demolition contractor may never be able to recover the material. If the time is available, then it comes down to finance, which depends on the demolition methodology and the reselling price of the recovered material. If the recovery of materials involves additional costs, there is a need for more incentives for the client or demolition contractor to absorb those costs.

The reduced availability of structural elements from demolishing building stocks can also limit the element's potential for reuse and make it even more difficult for builders and designers to find similar elements for their projects. The reasons could be the fact that the collection and storage of reused elements that have similar mechanical and geometrical characteristics can be expensive and complex, and some demolition contractors may not have the resources or expertise to do so effectively. This also highlights the need for more effective methods for collecting, storing, and distributing reused elements. The lack of appropriate incentives or regulations that mandate the recovery of materials for reuse from demolition is currently hindering the market for such materials. Such measures must be put in place before the consumption of these materials continues to be limited.

Materials Passports consist of comprehensive datasets outlining specific characteristics of materials present in the products, enhancing their value for potential recovery and facilitating their subsequent reuse (Smeets et al., 2019). Material Passports can effectively facilitate the reuse of structural steel by mitigating financial obstacles. The research demonstrates that relevant data has the potential to lead to substantial cost reductions in various aspects, such as sourcing, testing, reconditioning, and fabrication, with savings ranging from £150 to £1000 per ton, depending on the reuse approach undertaken (either remanufacture or direct reuse of elements/structures). The key stakeholders benefiting from this data are stockists and fabricators, who act as both suppliers and customers.

4.2 Design Rules, Regulations and Standards for Steel Reuse

Another significant factor affecting the reuse of building structural components is design-related issues, such as matching the design of the new building with the strength of the recovered elements (Rakhshan et al., 2021). The reuse practice is taking a slow pace as designers, contractors and property owners do not have enough information and rules for planning and executing reuse projects. This is also exasperated by a lack of legislation, standards, and widespread awareness (Hradil, 2014).

Despite there is no specific standard on reuse of steel components, the reuse of structural steel from existing buildings is currently possible due to clause 5.1 of EN 1090-2:

- Clause 5.1 of EN 1090-2 allows the use of constituent products not covered by harmonized standards.
- Clause 5.1 of EN 1090-2 requires the specification of material properties.

Although the practical challenges of certification and refabrication are adequately addressed in some countries (documents such as P427 (SCI) Structural Steel Reuse (D G Brown et al., 2019) provide the guidance needed for practical reuse and fabricators are coming on board in the UK), at the EU Level the following references are available:

- The Swedish guidance for structural steel reuse (MVR, 2021), an industry standard provides a practical methodology for specifying reclaimed material properties. The MVR (2021) scope includes steel produced before and after 1970 and defines different testing protocols depending on the availability of certificates and can be applied for EXC1 and EXC2.
- EU-RFCS PROGRESS Design Guide (Coelho et al., 2020) project outcomes provide a more conservative approach; only steels produced after 1970 are considered re-usable and the project scope is limited to single-storey buildings.

Both MVR and PROGRESS projects included efficient, practical and straightforward testing methodologies depending on the availability of certificates. Both methods provide guidelines for certifying constituent products when fatigue damages and plastic deformations can be discarded.

CEN TC 135 WG2 is currently producing a Technical Specification integrating elements from both the MVR and PROGRESS outcomes. The Technical Specification will likely be released during 2024. Despite the mandate from the EC, which includes EXC1 to EXC3 and constituent and manufactured product, in practice, the contents of the

Technical Specification will only provide a solid and robust methodology for EXC1 and EXC2 constituent products.

In parallel, different EU Member States; Denmark, Netherlands among others, are developing their own national standards on reuse, however whether these regulations will be aligned or not with the CEN TC 135 works is not clear, and there is a risk of creating a complex and non-consistent scenario in which some works are duplicated and other critical actions not addressed.

The material properties to be assessed, and the testing methodologies depend on the available certificates if the steel has been produced after 1970 and if the certificates are available, a simple checking of properties according to Annex A of EN ISO 18265 (2013) is allowed.

However, for steel produced before 1970 with unavailable certificates, destructive testing for all components is requested (EN ISO 6892-1, 2019; CEN/TR 10261, 2018). The characteristic values of yield and tensile strength shall be derived with the method in Annex D of EN 1990 (European Commission, 2002). In addition, the material shall also satisfy the ductility requirements (elongation at failure and ratio Rm/ReH) in part 5.2.2 of EN 1993-1-1 (European Commission, 2020). All destructive testing shall be performed by an independent and accredited party. The results shall be documented in a test certificate equivalent to a control certificate 3.1 according to (EN 10204, 2004). The test certificate shall be issued by the independent party that performed the tests.

In the EU, regulations must be also developed. The new version of the Construction Product Regulation (CPR) (that aims to harmonize the requirements on construction products at EU Level), according to its public draft (European Commision, 2022), will include reused components but it may not cover reused materials when these are repurposed for the same intended use, unless the responsibles for materials recovery voluntarily decide to produce a Declaration of Performance (CPR, Article 2). Therefore, national regulations must also be produced to cover materials being reused for the same intended use, including the necessary assessment to identify those elements that have been subjected to that preclude its reuse (e.g. fatigue loads).

Even under the CPR, the methodologies to demonstrate that components have not been subjected to stresses that preclude their reuse are to be defined by the EU Member States and implemented by the economic operators in charge of de-installation (CPR Article 12). However, the de-installation and recovery for reuse operations of construction products will be covered by the CPR and will make the economic operators in charge of de-installation operations responsible for materials specifications and also the definition of compatible uses (CPR Article 29).

The societal and political situations could be other contributing factors that retard the reuse practice in the construction industry. For instance, the lack of certifications and standards could discourage project planners, architects, and engineers from using reclaimed structural elements for their new projects, as it may be difficult to get building approval from local authorities if second-hand parts are used. Similarly, people generally have negative opinions toward second-hand materials, and it is believed that newly manufactured components are much more valuable than used ones. Furthermore, in general, the construction industry, being a highly fragmented sector, is conservative in adopting new practices.

4.3 Upfront Costs and Overlooked Carbon-Impact of Demolition Prior to Construction

The higher upfront cost of reuse originates from the quality checks, manual work during deconstruction, storage, and long transport distances. That said, Hradil et al. (2017) state that reuse can be more competitive with a further reduction of life cycle costs, by adopting cost-effective deconstruction, sorting, and inspection technologies that can significantly improve the economic benefit of reuse scenarios. Moreover, it is necessary to address the carbon impacts of demolition before construction. Such "upfront carbon impact" comes from the use of heavy equipment, transportation of waste, and the energy required for processing and disposal of the demolished materials in the site of a new construction. These carbon values are currently all attributed to the end-of-life of the building (module C). Very few research outputs are available on quantifying the upfront carbon impact of demolition (Broniewicz & Dec, 2022; Gonzalez et al., 2021). The latest RICS proposal on Whole Life Carbon Assessment (RICS Professional Standard, 2023) recommends that any demolition on a site intended for new development should take account of the carbon impact of demolition in the carbon assessment of the new building (considering the impacts of demolition, and site clearance as part of the carbon consequence of a new building on the same site is actually very natural). RICS propose a new "Module A5.1", titled "Pre-construction demolition" that would interact with the current Module C so that the demolition carbon is considered in the new building, and that can be reduced or offset by re-using materials, and hence reducing the carbon impact of demolition.

Currently, all reused materials enter a new building at much reduced carbon, up to 95% carbon saved for reused steel, thus reducing the "module A" of the new construction. Yet there have been carbon costs in reclaiming them, which are written off or absorbed by the demolished building in the current model. Reuse can have a positive carbon benefit by reducing Module C in demolition or Module A in new buildings. However, the upfront impact of demolition must not be ignored. It is essential to consider that although a product may have low carbon when introduced to a building or can be recovered with low carbon impact at the end of the building's life, the realization of these future benefits may be uncertain over 50 to 60 years. Thus, it is crucial to prioritize immediate carbon reduction measures and account for the true environmental implications of construction activities to combat the Climate Emergency effectively.

4.4 Maximizing Different Reusable Materials from Demolition

Current recycling practices are profitable, and the benefits increase for demolishers is reduced as the market demands scrap at attractive prices. Although the environmental benefits of reclaimed steel and the forecasted cost increase associated with the green steel transition will increase the margins between reused steel and scrap, it will be necessary to reuse other materials. If other components such as envelopes, cladding, slabs are also reclaimed and re-introduced in the market for their reuse, then the cost and complexity increase during the demolition stage will be offset by the valorization of other fractions that otherwise can only be backfilled or downcycled as low value fillers or aggregates. If steel is the only material to be reused, then reuse could be only cost-efficient in very specific buildings (industrial warehouses) or components (piles). Reusing construction products from existing buildings will be challenging in many cases and it will be necessary to identify what kind of buildings are optimal for the cost-efficient recovery (according to existing practices) and safe reuse of construction products. For new buildings, designed for reuse, the potential for reuse will be much higher, and reuse of components may become the preferred end-of-life option.

4.5 The Need to Engage and Coordinate the Complete Construction Ecosystem

To consolidate reuse as a common and safe practice, conducting a coordinated set of activities to interact across the whole supply chain will be necessary. While the steel construction community carries out the standardization efforts, the demolishers will be responsible for reclaiming construction products. Design offices and architects will be responsible for adopting design for reuse constructive techniques with associated reclaiming methodologies that the demolition industry must validate. The process must be implemented for every construction product in foundations, superstructures and envelopes. The regulations that foster reuse but allocate legal and economic liabilities are also to be defined fairly and rationally. Therefore, synergies are to be identified, agreements are to be set, and a roadmap is to be determined integrating all the ecosystem stakeholders.

5 Opportunities to Enable Higher Reuse of Steel in the Construction Industry

The challenges mentioned above in the construction industry can be addressed with new frameworks for identifying re-usable elements, digital technologies that facilitate reuse, and well-established certification and regulations that push further the material reuse practices in the industry.

5.1 Certification and Legislation to Reclaim Structural Steel Elements

To achieve the significant environmental benefits from steel reuse, reuse practices must increase to at least the same level of recycling for end-of-life steel stocks. Reuse certification protocols will strongly impact the consolidation of steel reuse as a common practice. Therefore, safe and cost-effective re-certification protocols are indispensable to accelerate the shift from recycling to reuse.

Steel undergoes no major changes due to ageing, except for corrosion and plastic deformation that earthquakes may cause. Nevertheless, the material must comply with specific performance and quality requirements to ensure the adequacy of reclaimed members for reuse. A protocol has been suggested by SCI (D G Brown et al., 2019) (D G Brown, 2013) and ECCS (Coelho et al., 2020), which recommend that several material properties have to be declared to guarantee the material's reusability. In particular, the following mechanical properties must be determined according to EN 1090-2 clause 5.1 (Coelho et al., 2020).

- Strength, i.e., yield strength and tensile strength.
- Ductility.
- Heat treatment delivery condition.
- If the steel is to be welded, its weldability shall be declared by identifying its chemical composition. The chemical composition is also required if the reclaimed material needs re-certification due to the absence of original certificates.

Reclaimed structural steel components must obtain a CE marked Type 3.1 or Type 2.2 Inspection Certificate (EN 1090-2) to be admissible for reuse. These certifications contain the chemical and mechanical properties of steel, assuring that the material meets the required standards. Despite these requirements, no standardization of the testing protocols is currently available. Efficient and cost-effective protocols for requalifying reclaimed steel members would highly incentivise reuse practices.

Currently, decisions regarding the testing method to be implemented, the number of tests to be performed, or the selection of specimens are ultimately made by the responsible engineers.

5.1.1 Testing of Reused Steel Elements

Material evaluation usually involves on-site/off-site non-destructive testing (NDT) and destructive testing (DT). Dimensional inspection, indentation test, chemical composition test, and degradation inspection are among many of the NDT that can be deployed to evaluate the structural performance of steel. NDT and DT processes are time-consuming, significantly increasing costs, hence making reused steel less appealing. Despite its evident limitation, NDT does not damage the elements, and eliminates the time-consuming process of laboratory testing, while accurately identifying, locating, and measuring the size of defects. The reclaimed structural steel elements must be damage-free when retrieved from their previous use to be suitable for reuse. These members must not have significant imperfections, permanent deformation, or sectional losses due to corrosion (Coelho et al., 2020; TITUS Steel, 2022a, 2022b).

The characteristics commonly recorded against each beam/piece of reclaimed steel are shown in the Table 3. It is important to consider and evaluate deterioration and damage separately. Deterioration is the reduction in material characteristics and/or size due to exposure conditions. The most typical deterioration observed in steel is corrosion, a process that is "fed" by environmental conditions. The progress of corrosion depends on the amount of oxygen and water in contact with the steel. A coating layer is usually applied to act as a barrier between the environment and the metal to prevent such degradation. Nevertheless, corrosion might also develop beneath the coating layer, and its detection poses a challenge due to its hidden location.

A common technique used to detect corrosion is Ultrasonic Testing (UT). UT is based on generating ultrasonic waves by a transmitting transducer coupled to the metal surface through a suitable medium and receiving back these signals by a similar receiving transducer positioned at a known distance from the transmitter (Sause & Jasiūnienė, 2022). Such a technique can be adequate for measuring corrosion thickness, consequently accurately indicating the sectional loss. The latter is essential for determining reuse adequacy. Ultrasonic methods can be adapted to determine mechanical properties (Sano et al., 2014) and detect surface and internal defects such as cracks (Brockhaus et al., 2014). Nevertheless, strength results obtained from ultrasonic tests are susceptible to errors; thus, calibration using destructive tests performed on elements of the same series is suggested. The most accurate methods for assessing surface and internal defects are radiographic methods: X-ray and gamma defectoscopy (Jaskowska-Lemańska & Sagan, 2019). These tests can be performed only when both sides of the specimen can be accessed. Radiation is transmitted on one side, while the detector film records the differences in absorption on the other side. The contrasting images are then inspected by skilled technicians to detect hidden flaws within the metal such as cracks, voids, and corrosion (ATS Lab, 2022). Although such a method can correctly determine defects' location, dimensions, and sizes, the interpretation of the output imagery is relatively time-consuming and often challenging. Damage, on the other hand, is the result of extreme loads not considered during design, such as seismic loading, blast, or explosion. Damage can also be induced by several other factors, such as the fragility of elements and improper connectivity among the members. Furthermore, dismantling often introduces damage (de Wolf et al., 2020).

The ultimate tensile strength of steel can be measured by non-destructive hardness testing. In this test, a steel ball is pressed against a smooth surface with a known force, and the resulting indent is measured. As a result, a hardness

Table 3 The commonly recorded characteristics reclaimed steel

Piece number	Generated by the system and every piece is allocated a unique number which is kept throughout its life and is retained forever even after it is sold
Purchase	Purchase order number
Section	Size of the section
Length	Usable length of the material in mm
Quality	Whether it is prime, second hand, surplus etc
Condition	Describes the surface condition of the material (how heavy is the rust, painted or galvanised)
Ends	End condition (e.g. gas cut, saw cut, end plates etc.)
Coating	If it is painted then what sort of paint or coating
Defects	Bends, dents, holes etc.(these defects can be graded between 1 and 10 according to severity)
Grade	Grade of steel
Location	Location of steel
Source	Where the material came from (e.g. building name or steel mil if known)

number is provided, e.g. Vickers number according to ISO 6507, which is empirically correlated to the yield and ultimate strength of the material. Such correlation is considered accurate enough to determine the material grade. Hardness testing should be performed on the flanges of the reclaimed elements. Any surface treatment shall be removed before the test is performed. The protocol suggests that the hardness should be calculated as the average of three measurements taken in the same location (Coelho et al., 2020).

5.1.2 Technological Implementation in Non-destructive Testing

Generally, the experimental tests are time-consuming and often challenging to interpret, hence making reused steel less appealing. Implementing artificial intelligence (AI) techniques would contribute to reducing current human operators' efforts, leading to a facilitated re-certification process. For example, Penetrant Testing (NDT), used to indicate surface cracks as suggested in the inspection protocol for welds, has been automated through deep learning to facilitate decision-making, reducing the inspection time. Such an approach was introduced by Niccolai et al. (2021) in the context of an automated fluorescent penetrant inspection project, a research program funded by the MANUNET initiative, in the framework of EU's Horizon 2020 research initiative, aiming at automatically detecting failures of industrial components. The main architecture is based on spot/crack identification. Each crack identified in the original image is directly processed using a neural network. In this architecture, both deep neural networks and multi-layer perceptron are exploited. The system's output is the classification of the spots among three possible classes, relevant to the aerospace manufacturing field. A similar approach could also be implemented in the context of reused steel damage assessment.

5.1.3 Structural Digital Twin for Reusability Assessment

A structural digital twin (DT) is a virtual replica of a structure that can be exploited to provide real-time health monitoring and predictive maintenance, thereby saving the cost of simulation, testing, and analysis (Sasmal & Voggu, 2021). The DT can effectively reflect structural degradation based on material properties, loading, and environmental conditions. For an accurate prediction, it is essential to integrate into the model the time-dependent multi-scale response of the materials. With an effective combination of historical data and maintenance history, the digital twin has the potential to forecast the health of the structure and even predict the failure probability. The most fundamental capability of the DT technology is the capacity to accurately determine the time and location where structural damage or/and failure is likely to occur. Decisions must be made regarding the locations that must be monitored, the sensors to be installed, the frequency of data retrieval, as well as the interpretation of the acquired data (Errandonea et al., 2020). Despite its prominent potential, digital twin technology can be costly to implement, and such an upfront cost makes it a less attractive solution to the industry.

5.1.4 Time Dependent Reliability Index

Using the reliability index, one possibility to evaluate the remaining capacity of structural elements and the reuse potential for a second life. Reliability is defined as the probability of a structural component performing its purpose adequately for the period intended under the operating conditions encountered (De Carlo, 2013). This concept is broadly accounted for by introducing the safety factor in the design process. Structural reliability analysis calculates the time-varying reliability index of structural components by combining deterministic stress/fatigue analysis results with degradation mechanisms (Paik & Melchers, 2008). It includes the stochastic variability of loads, soil properties, geometry, and corrosion processes. This index can be exploited to evaluate the appropriate inspection frequency, considering that the structure is under continuous degradation (i.e., strength loss due to corrosion of steel) (Nie et al., 2020).

A target level of the reliability index indicates the acceptable range of failure probability. That being said, if the reliability index falls under the target level, this does not mean that the structure is deemed to fail, but rather that a higher probability of failure is present. The chosen target is rather complex, accounting mainly for the component's criticality to the structure's integrity. For example, different curves of the reliability index of steel members can be constructed based on the corrosion rate. These descending curves will intersect the target level at different times (Paik & Melchers, 2008). The component must be inspected before the threshold is crossed; hence, a proper estimation of the corrosion rate is essential for the accuracy of such a method.

While fatigue reliability assessment can help to estimate the remaining life of steel structures and adjust inspection intervals, the reuse of steel components in new structures requires careful evaluation of their fatigue life and inspection history to ensure their reliability and avoid using components that have been subject to fatigue damage or have not been inspected properly.

Many deterministic approaches have been proposed to determine the residual bearing capacity of steel corroded structures. However, the importance of accounting for uncertainties has led to an increased interest in assessing the deterioration of steel over time with reliability analysis. Only a few studies have been devoted to the reliability analysis of steel structures. (Nie et al., 2020) conducted a study to investigate the time-dependent reliability of corroded steel beams.

The time-dependent reliability of steel structures depends mainly on the variability of loads and structural resistance. The structural resistance is dependent upon some random variables that deteriorate with time, such as geometric size and strength decrease due to corrosion; hence, it is a stochastic process that can be represented by a probability density function. In the context of evaluating the reliability of reused steel components, structural reliability analysis can provide a measure of safety against failure by assessing the failure probability and reliability index. However, the complex nature of the limit state functions and the need for numerical integration or approximation methods must be considered. The time variation of loads should also be taken into account.

5.2 Digital Methods to Enable Reuse of Steel

The risk and uncertainties associated with re-using structural elements from end-of-life building stocks can be alleviated by adopting advanced digital technologies (Çetin et al., 2021). However, the level of digitalization in the industry is now a bottleneck as the construction industry is the least digitalized sector among others (McKinsey & Company, 2016). Some of the barriers mentioned above require a multi-criteria decision-making framework that evaluates the reuse potential of structural elements considering the associated factors in logistic feasibility, structural performance, life cycle and economic assessment, and safety. Secondly, incorporating advanced digital technologies can help facilitate reuse by automating part of pre-demolition audit and reuse assessment procedures while reducing cost, and increasing reliability. A deep custom CNN model architecture for reuse developed by (Birhane & Kanyilmaz., 2022) is shown in Fig. 5. Thanks to their wide range of applications in different industries, such solutions can facilitate the development of well-established certifications and regulations for reuse of materials in the built environment.

5.2.1 Multi-criteria Decision-Making Criteria for Reuse

The decision on what should happen to the existing buildings is complex and involves a range of stakeholders and decision-makers (Baker et al., 2017). Engineers, architects, planners, project developers, urban designers and environmental managers often have different priorities in the decision-making process. Decision-making criteria tools are often designed to balance these multiple requirements/priorities and find the most optimized solution in a given possible outcome domain. These tools are even more promising in getting the global optima solution in a significant and often tedious solution-searching process that involves various complex and non-fully overlapping multi-dimensional domains; a currently developed tool by (Kanyilmaz et al., 2022) compared reused steel with other materials quantifying the cost and embodied carbon benefits with the non-dominated sorted genetic algorithm method (Kanyilmaz et al., 2023).

A range of academics has researched criteria used to assess the adaptation potential of existing buildings. For example, Kutut et al., (2014) used an analytical hierarchy process and pairwise comparison to weight criteria, including whether the building requires investment or not, its heritage value and the state of the building. Other academics have expanded on the provision of the criteria and created tools that aid decision-makers (Baker et al., 2017).

The transformation meter and the IconCUR have been designed for asset managers to assess buildings for appropriate intervention. The transformation meter (Rob Geraedts & Van der Voordt, 2007) was designed in the Netherlands for rapid adaptation assessment of residential buildings. The tool comprises five stages, each requiring a binary yes/no answer. The main stages are the quick scan, the overall feasibility of adaptation using building and location criteria,

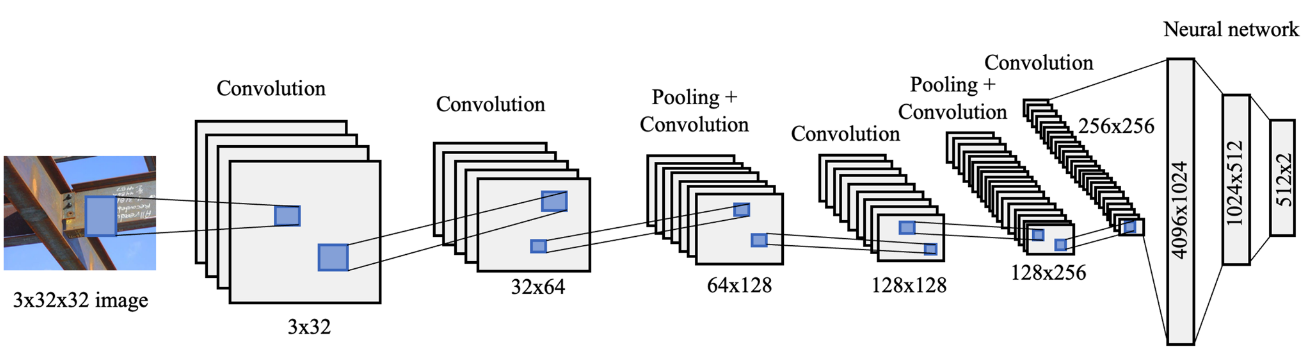


Fig. 5 A deep custom CNN model architecture comprising six convolution layers, three pooling layers and a three-layer fully connected neural network (NN) model for binary classification (Birhane & Kanyilmaz, 2022) (image source: https://www.pinterest.com)

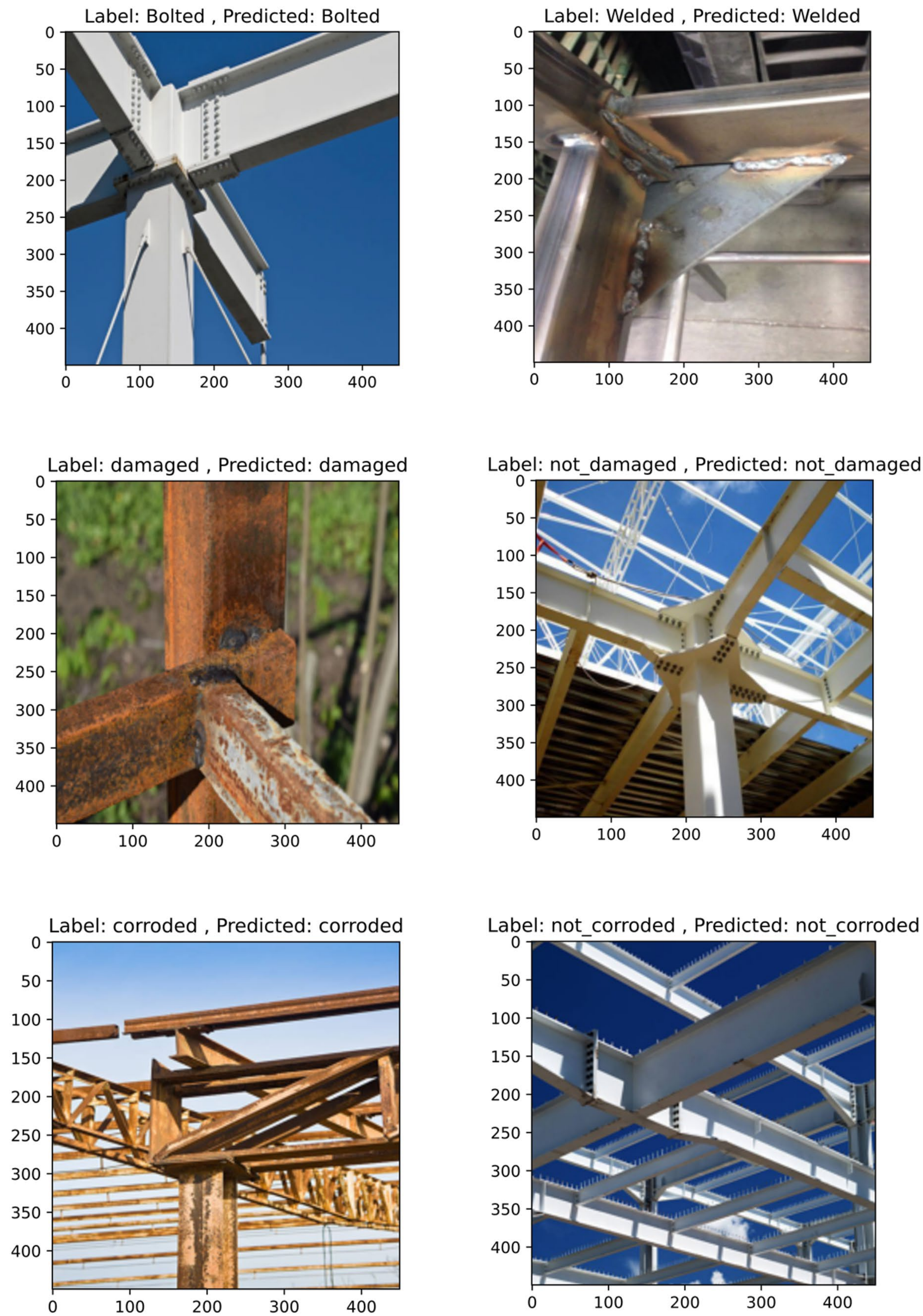

Label: Bolted , Predicted: Bolted
Label: Welded , Predicted: Welded
Label: damaged , Predicted: damaged
Label: not_damaged , Predicted: not_damaged
Label: corroded , Predicted: corroded
Label: not_corroded , Predicted: not_corroded
0 50 100 150 200 250 300 350 400
0 100 200 300 400

Fig. 6 Validation of the CNN connection, damage and corrosion models with random images (Birhane & Kanyilmaz, 2022) (image source: https://www.unsplash.com)

transformation class identification, financial feasibility, and risk identification. For each stage, different criteria are set to determine if each stage is met.

Langston and Smith (2012) have created a three-dimensional (3D) spatial tool, called IconCUR, that uses multiple criteria to assess the performance of an asset during its life cycle in the early stage of decision-making and has been integrated into commercial asset management software. This tool, in addition to the adaptation potential of the building, identifies the possible alternatives to adaptation, such as renovate/preserve, retain/extend, reuse/adapt or reconstruct/dispose, depending on a range of weighted criteria.

Similarly, Hradil et al. (2017) introduced a new method for the reusability assessment of components and structures of steel-framed buildings. It evaluates the reuse potential of end-of-life steel frames based on eight categories, i.e., deconstruction and disassembly, handling manipulation, separation cleaning, redesigning, adopting for another purpose, modification, and quality check. Furthermore, the method is applied to an existing typical industrial hall structure to evaluate the reusability factor of the building and compute the environmental impact of reuse for a second life. The result shows that approximately 60% of the steel structural elements are suited for reuse, and up to 70% of the environmental impact can be reduced if only the rafters of the structure are reused 1.46 times on average compared to the scenario without reuse.

On the other hand, although the existing state of the art regarding the current state of steel reuse is broad-ranging, (Yeung et al., 2015) identified that several supply chain models have been presented in the field of steel reuse, but these models do not incorporate engineering decision-making processes. As a result, the authors proposed a decision-making framework that refers to decisions around the feasibility of effectively reusing structural steel for reuse. A recycle/reuse decision making framework has been recently developed by (Birhane & Kanyilmaz, 2022).

5.2.2 Artificial Intelligence for Reuse

Artificial Intelligence (AI) has a huge potential to facilitate and achieve the goals of the circular economy (Noman et al., 2022). According to (Ellen Macarthur Foundation, 2021), there are many opportunities for AI to help streamline the infrastructure needed to circulate materials in the economy—many of them focusing on the ability of AI algorithms to recognise and identify objects using cameras and other sensors. Three ways AI can impact the circular economy are:

a. *Automated assessment*: automated condition assessment of used products, and recommendations for whether they can be reused, resold, repaired or recycled to maximize value preservation.
b. *Automated disassembly*: automated disassembly of used products employing AI to assess and adjust the disassembly equipment settings based on the condition and position of a product.
c. *Sorting*: sorting of post-consumer mixed material streams using AI visual recognition techniques combined with robotics.

Given the vast potential of AI in promoting the circular economy, its application can also be extended to reuse materials in the built environment. Machine learning models can be trained and validated to automate the preliminary condition assessment of re-usable elements from structural image data. For example, a recently developed tool can predict corrosion, connection type, and damage with an accuracy of 83%, 89% and 83%, respectively (Birhane & Kanyilmaz, 2022) (Fig. 6).

Adopting this technique can overcome the high identification and analysis cost and increase reliability. Furthermore, as the number of images that can be collected increases with the advent of technologies and the ever-increasing use of camera-equipped devices such as drones (UAVs), ground robots, smartphones, or tablets, these AI-based tools in the computer vision subdomain, such as convolutional neural network (CNN), becomes vital to extract meaningful information by detecting, identifying, and classifying various reusable elements present in an image. To that end, automating these tasks would also make it easier for building owners and reuse experts to evaluate their end-of-life building assets for reuse.

6 Conclusions and Outlook

This article discussed the challenges and opportunities to push further reuse practices in the construction industry, on its road to a circular economy. The pressures on industry to achieve low-carbon construction are huge. There are legislative targets for Net Zero, and the industry is being held to account over the climate emergency by consumers; hence the awareness of the issue of embedded carbon is rising. This awareness and activity in the area of sustainability and steel reuse have exponentially increased in the last two years in the UK. Furthermore, the focus on sustainability and reducing waste has led to increased regulations and initiatives in EU to promote resource efficiency, including the steel industry (EU Technical Expert, 2020). For instance, Circular economy is now being written into the contractual requirements of many large construction projects in the UK

(Cleveland Steel & Tubes Ltd is currently active in over 20 projects, and it is believed more than that are being carried out by other companies).

On the demand side, there is huge interest and impetus currently as the carbon savings of reused steel are very high. The short-term goal must be to facilitate as many reuse projects as possible to ensure it become accepted in mainstream construction. More specialized seminars and courses should be given to engineering community professionals. The proper usage of media outlets (internet, journals, and documentaries) can also contribute to widespread the benefit of reuse and help realize more reuse projects. The willingness is there but it must be matched with the supply side.

Since the material arising from demolished building stock (Verhagen et al., 2021) only offers a reduced yield (maybe 30% of material is lost as it is unsuited to reuse or damaged), the reuse market will permanently be restricted to the available materials. That being said, by using material efficiently, updating the standards and regulations, and increasing lifecycle thinking, the construction industry can and will save huge tonnages of carbon through steel reuse.

In general, the reuse practice may be less common due to problems related to traceability, quality certifications, regulations, availability, and lack of expertise. However, in the near future, these challenges can be overcome with non-destructive testing, remote and drone surveys, better supply chain integration, provision of regulation, and fiscal incentives. Furthermore, with the advent of digital technologies that facilitate digital transformation, design for deconstruction and reuse, and standardization, the reuse practice has a bright future. However, the current situation in reusing the structural elements of buildings shows the need to develop robust interdisciplinary reusability evaluation tools to improve the reuse rates.

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