Chapter 5
Recovery and Reuse of Salvaged Products and Building Materials from Existing Structures

Viorel Ungureanu, François Fohl, Jie Yang, Oliver Hechler, Vlatka Rajčić, and Raluca Buzatu

Abstract The recovery and reuse of salvaged products and building materials from existing structures is an essential practice in sustainable construction and environmental conservation. This process, often referred to as building deconstruction or architectural salvage, involves carefully dismantling buildings to preserve reusable materials. It offers numerous benefits, including significant environmental impact reduction, economic advantages, and historical preservation. Environmentally, it reduces the amount of construction and demolition debris in landfills, conserves natural resources by reusing existing materials, and reduces the carbon footprint by decreasing the need for new materials, thus reducing emissions from manufacturing and transportation. Recovery and reuse involve several steps. It begins with assessment and planning, where a detailed site assessment is performed to identify salvageable materials. A deconstruction plan is then developed that details the steps

V. Ungureanu (✉) · R. Buzatu
CMMC Department, Politehnica University of Timisoara, Timisoara, Romania
e-mail: viorel.ungureanu@upt.ro

R. Buzatu
e-mail: raluca.buzatu@upt.ro

V. Ungureanu
Laboratory of Steel Structures, Romanian Academy, Timisoara Branch, Timisoara, Romania

F. Fohl · O. Hechler
ArcelorMittal Commercial RPS, Esch-sur-Alzette, Luxembourg
e-mail: francois.fohl@arcelormittal.com

O. Hechler
e-mail: oliver.hechler@arcelormittal.com

J. Yang
ArcelorMittal Global R&D, Esch-sur-Alzette, Luxembourg
e-mail: jie.yang@arcelormittal.com

V. Rajčić
Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia
e-mail: vlatka.rajcic@grad.unizg.hr

L. Bragança et al. (eds.), *Circular Economy Design and Management in the Built Environment*, Springer Tracts in Civil Engineering,
https://doi.org/10.1007/978-3-031-73490-8_5

and methods to safely dismantle the structure. During the deconstruction phase, the building is carefully dismantled, starting from the top down, using manual labour and specialised tools to preserve the materials in good condition. These materials are then separated into categories such as steel, timber, concrete, bricks, etc. Next, the salvaged materials undergo cleaning and processing, making them ready for reuse. Proper storage and distribution are crucial to preserve the integrity of materials. However, practice faces challenges such as labour intensity, risks of contamination from hazardous materials such as asbestos and lead paint, fluctuating market demand, and ensuring the quality and safety of reused materials, which may require certification and compliance with building codes. The present chapter starts with aspects of pre-demolition/deconstruction audit that involves the collection of information about the materials and elements that will be recovered and continues with the evaluation of reusability of materials, mainly with steel, timber and concrete, structural components, entire primary and secondary structure.

Keywords Recovery · Reuse · Upcycling · Salvaged products · Building materials · Existing structures · Pre-demolition/deconstruction audit

5.1 Introduction

Salvaging and reusing materials from existing structures is a cornerstone of the use of circular materials in construction, minimising waste and conserving resources. Instead of demolishing buildings and sending the debris to landfills, salvaging materials by disassembly allows for their reuse in new construction projects, reducing waste and conserving resources.

Crowther [1] highlights the principles of disassembly as an alternative to demolition. These include the following:

- offer unimpeded access to all building elements slated for disassembly;
- enable disassembly at any scale, from individual materials to entire structures;
- arrange components based on a hierarchy of access that correlates with their respective life expectancies;
- facilitate simultaneous disassembly of multiple elements instead of linear sequences;
- clear label of components and document their assembly/disassembly procedures;
- separate building structure, envelope, and internal walls using distinct systems;
- standardise and limit the number of material types, components, connections, and systems while ensuring compatibility with existing standards;
- embrace open construction systems that accommodate various structural alternatives;
- minimise the number of components and connections for straightforward disassembly;
- prioritise mechanical connections over chemical ones for easier separation;

- favour readily available tools and practices for widespread adoption;
- design component sizes compatible with intended disassembly methods;
- utilise lightweight materials to simplify handling;
- prevent component deformation caused by repeated assembly/disassembly.

Here are some key aspects related to the recovery and reuse of salvaged building materials:

1. Salvage Operations: Salvage operations involve carefully deconstructing or dismantling existing buildings to recover reusable materials. This process requires skilled labour, the right tools and techniques to ensure the safe removal and preservation of salvaged items;
2. Materials Identification and Sorting: During the salvage process, the materials are identified, categorised and sorted to determine their reusability and potential applications. This includes assessing the condition, quality and compatibility of salvaged materials for future reuse;
3. Preservation and Storage: Salvaged materials may require proper preservation and storage to maintain their quality and usability. This may involve cleaning, repairing, treating, or storing materials under the appropriate conditions to prevent deterioration or damage;
4. Material Assessment and Testing: Salvaged materials should be evaluated and tested to ensure that they meet safety and quality standards for reuse. This includes evaluating their structural integrity, durability, and performance characteristics to determine their suitability for future applications;
5. Inventory and Cataloguing: Establishing an inventory and cataloguing system for salvaged materials helps streamline the reuse process. It enables architects, builders, and designers to easily access information about available salvaged materials, facilitating their integration into new construction projects;
6. Design Considerations: Incorporating salvaged materials into new designs requires careful consideration of their characteristics, limitations, and aesthetic appeal. Designers and architects need to explore innovative ways to integrate these materials while ensuring structural integrity and meeting regulatory requirements;
7. Local Networks and Partnerships: Building networks and partnerships among salvage yards, contractors, architects, and other stakeholders can improve the reuse of salvaged materials. Collaboration allows for the exchange of information, expertise, and the creation of marketplaces for salvaged materials;
8. Education and Awareness: Increasing awareness among industry professionals and the general public about the benefits and opportunities associated with salvaging and reusing building materials is crucial. The implementation of educational programs, workshops, and public awareness campaigns aimed at various stakeholders can significantly contribute to the promotion of disassembly design principles and the creation of a robust market for salvaged materials.

The recovery, de-characterisation and reuse of salvaged building materials offer multiple benefits, including waste reduction, resource conservation, cost savings, preservation of architectural heritage and environmental impact reduction. By incorporating salvaged materials into new construction projects, the construction industry can significantly contribute to circular material usage and sustainable building practices, even reduce costs due to the significant rising costs of some raw materials. The following subchapters deal mainly with steel, timber and concrete.

5.2 Pre-demolition/Deconstruction Audit

Selection of demolition methods depends on the construction materials and site conditions and is subject to regulatory requirements. Top-down demolition method is commonly used for multi-storey buildings meaning that demolition starts from the top floor level. Temporary propping and shoring are usually needed to ensure stability of the structure. Excavators are generally used to demolish the structure; structural steel members sheared, or flame cut into short lengths for ease of handling, transportation, and recycling; and concrete demolished for down-cycling or landfill.

Pre-deconstruction audit involves the collection of information about the materials and elements that will be recovered, the waste streams, and recommendations for further handling and reuse. Recommended waste audit includes field survey, documentation research, condition evaluation, and management recommendations [2, 3]. Guidance for the deconstruction process using the top-down method is available, offering recommendations from project planning to deconstruction stages, along with compliance legislation [4].

A *Pre-demolition audit–overall guidance document* has been prepared as an extension to the Waste Audit Guideline released by the European Commission in 2017 [5]. The pre-demolition audit guidance package has been prepared within the project "*Best practices for Pre-demolition Audits ensuring high quality RAw materials–PARADE*" funded by EIT RawMaterials. The Guideline helps maximize the recovery and reuse of valuable materials and components from buildings and infrastructure, prioritizing sustainability while upholding the safety standards outlined in the EU Construction and Demolition Waste Management Protocol [2].

A document offering guidelines on conducting a reclamation audit was developed through a collaborative effort within the project Interreg NWE 739: Facilitating the Circulation of Reclaimed Building Elements (FCRBE), October 2018–January 2022–*A guide for identifying the reuse potential of construction products* [6]. This manual guides you through the process of conducting these audits. It's designed for building professionals, and anyone involved in (de)construction, including architects, engineers, contractors, and owners.

According to Building and Construction Authority [7], the Pre-demolition Audit is a continuous process, spanning across three key phases: (a) pre-demolition planning, (b) active demolition, and (c) post-demolition assessment. This multi-stage approach ensures the optimal recovery of demolished materials for beneficial reuse and recycling, while always prioritizing safety practices and measures.

Steel. The practice of deconstruction with the intension of reclaiming and reusing structural components is not yet commonplace due to a lack of demand for salvaged materials and the associated time and labour costs. Many existing buildings present challenges for deconstruction and material reuse due to their original design. The findings of the PROGRESS project [8] indicate that deconstruction of existing single-storey steel-framed building is relatively straight-forward when following a reversed construction sequence. Deconstruction begins with the removal of non-structural elements and equipment, followed by the methodical disassembly of flashing elements, cladding, and secondary structures before tackling the primary structure. This deconstruction is recommended to be carried out on a bay-to-bay basis rather than by the entire building layer. Optical Emission Spectroscopy analysis can easily and quickly analyse chemical composition of steel which can serve as a non-destructive method to sort steel from waste stream. In general, steel is the perfect material to reuse, as the integrity of a steel element after deconstruction can be easily tested, compared to other construction materials. Steel is predestined for deconstruction after service life as there is a wide variety of mechanical connections.

At the European level, a technical specification for reuse of structural steel is under development, which is complementary to the provisions in EN 1090-2 [9] for the execution of steel structures. It specifies requirements for both reusability assessment and quality assessment. A testing protocol is proposed for determining the following properties: yield and tensile strength, elongation, tolerances on dimensions and shape, heat treatment delivery condition, and weldability [10, 11]. Non-destructive or destructive techniques may be used depending on the provenance of steel and availability of original inspection documents.

Precast Concrete. The widespread use of pre-cast elements throughout Europe creates a readily available pool of materials for large-scale reuse, making this approach particularly attractive. Evaluating the potential for concrete reuse demands a two-step process: delving into historical records like design drawings and calculations, followed by on-site inspections involving visual and non-destructive assessments. Complete original manufacturing drawings and certificates, if available, can provide invaluable information to assess concrete reuse potential, further validated through suitable testing. Information availability, historical exposure level, and intended new application will determine the 'pre-classification' categories for concrete elements, which will guide further evaluation.

The European research project *ReCreate–Reusing precast concrete for a circular economy* [12], aims to address the challenge of damaging demolitions. This European research project explores methods for deconstructing precast concrete elements for their safe reuse in new buildings, with the objective of transforming waste into resources and creating a profitable circular economy model for construction. This project explores innovative approaches to deconstructing precast concrete, even for structures built without disassembly in mind, aiming to improve both the technical feasibility and economic attractiveness of this sustainable approach. Deliverable D2.1 of the projects discussed in detail the process of information collection as a BIM-aided pre-deconstruction audit process [13]. A central goal of the pre-deconstruction audit is to create a comprehensive inventory of recoverable materials and components within the donor building, maximising potential for reuse and minimising waste. Buildings incorporate a variety of precast concrete elements: structural members (columns, beams, load-bearing and non-load-bearing walls, and shear walls provide structural support and stability to buildings), enclosure elements (facades, incorporating sandwich elements contribute to thermal performance and architectural expression), circulation elements (stairs, stair landings, and balconies facilitate movement and access within and around buildings), etc. In theory, these precast elements can be repurposed for the same intended use. During the pre-deconstruction phase, it was essential to gather data on the physical dimensions, shape, and potential damage of all elements. If the information was already accessible from archives, it was essential to verify its accuracy.

PEIKKO White Paper [14] reviewed a set of connections between precast concrete structures to determine their capacity to allow the dismount and reuse of the structures. Existing solutions must agree with the current norms recognising reuse, and their potential must be proven in practice. The benefits of reuse are also assessed from an economic and environmental point of view by presenting a study case for pre-cast concrete frame load bearing structures. However, the document highlights the need for new standards dealing with the topic, which would also help to verify the condition of old concrete structures for reuse.

Timber. After centuries of dominance by other materials, Europe witnessed a renaissance of timber construction in the late twentieth century, fuelled by the rise of light timber frame systems. Now, in the twenty-first century, innovative advancements are taking this sustainable building method to new heights, transforming the industry. Mass timber, such as CLT (cross-laminated timber), shattered the limitations of timber construction, paving the way for high-rise timber buildings in some countries. Although predominantly used in residential projects, timber is increasingly being used for office buildings, schools and hotels, transforming the construction landscape. The rise of off-site construction could be seen as an even more game-changing development, as it amplifies the benefits of timber, leading to even greater accuracy, material efficiency, speed, and waste reduction. Although modern construction methods gain traction across Europe, regional differences emerge in prefabrication, materials, and design styles. This requires adaptable Design for Deconstruction and Reuse (DfDR) guidelines that can effectively address the specificities of each partner country.

The InFutUReWood project [15] tackled the challenge of reusing wood from existing buildings, specifically focussing on its viability as a structural material. The following transformative recommendations stem from their work:

- For new buildings, local or building authorities could mandate the inclusion of deconstruction plans, prepared by designers, as part of the building permit application process. These plans would facilitate future disassembly and reuse of building materials.
- Minor tweaks to the design of timber buildings can significantly enhance the potential for deconstruction and material reuse. Deconstruction plans, when linked to data on material origin and environmental footprint, become powerful

tools to promote circularity in construction. This allows for targeted material reuse, informed selection of replacements, and minimised environmental impact throughout the lifecycle of a building. Mandatory deconstruction plans with material passports and recycling information should be integrated into the building permit process for new buildings, facilitating future disassembly and material reuse. Current financial incentives that favour biomass energy for building would create a major barrier to its reuse over multiple life cycles. To encourage such reuse, a shift towards tax advantages and subsidies specifically supporting timber reuse is crucial.
- Financial incentives should encourage "cascading use" of timber, prioritising renovation and reuse over virgin materials in new construction. Robust assessment methods are important to demonstrate the full impact of cascading, demonstrating its contribution to sustainability (environmental, social and economic), as well as circularity within the construction sector.
- Without harmonised standards and adaptable assessment documents, the construction industry faces limitations in advancing sustainable building practices. This impacts not only manufacturers and architects, but ultimately hinders progress towards meeting society's growing expectations for environmentally responsible construction. Stakeholders involved in the revision of the Construction Products Regulation should prioritise finding solutions to address this challenge.
- Instead of viewing upfront costs as mere expenditures, integrated policy frameworks are crucial for both the construction and recycling sectors to recognise them as investments in a global resource deposit, promoting long-term resource value and sustainability.

While the EU's Construction Products Regulation review tackles reuse, traceability of materials after first use, and standards, specific solutions are needed for timber due to its distinct natural properties compared to non-living materials. For low-risk circular economy products and applications, exploring alternative approaches like streamlined processes or targeted support programs can unlock their potential, even if broader solutions remain elusive.

Although building safety is paramount, it is equally important to consider its interdependencies and vulnerabilities within the larger urban ecosystem. Effective building safety strategies must be systemic, addressing how structures interact and impact each other. Buildings, major climate culprits, now face growing threats from the climate crisis itself, putting communities and livelihoods at risk. Storms, floods, and landscape-scale fires are just some of the increasing dangers.

Although certain outputs can be currently implemented, further research is required in all aspects of timber utilisation. Specifically, cross-laminated timber has been recognised as a construction material with significant potential for future reuse. Additionally, it can be manufactured using reclaimed timber. Collecting the necessary data for wood characterisation and product certification is a huge undertaking. Hence, project consortia working in this field should collaborate and share data to accumulate a substantial body of knowledge over time. The scope of wood quality and property research, as they are so variable, necessitates data sharing beyond individual projects, and therefore the involvement of multiple projects in sharing their data is crucial. In addition to data sharing, it is essential to compile a Guide to Good Practices that encompasses various circular design solutions. This guide should incorporate research projects and industry solutions and be tailored to meet the regulations of different countries. The transfer of knowledge to society and the education of building professionals are crucial aspects. Transitioning from the current state can pose numerous challenges and obstacles, including new building regulations and the need to adapt to harmonised standards.

One of the most effective waste reduction strategies is to prolong and diversify the use of the same resource through cascading. Risse [16] defines cascading as a resource strategy in which units serve various material applications sequentially, culminating in their final use (in the case of timber) for energy generation through incineration. As Risse explains "It follows a holistic perspective on the material's value chain and can include various reuse and recycling processes as well as end-of-life treatments". Cascading can reduce pollution, resource depletion, and energy consumption associated with manufacturing, while simultaneously extending carbon storage in products and delaying emissions for years, making it a valuable tool for environmental sustainability and climate change mitigation [17]. Cascading can reduce pollution, resource depletion, and energy consumption associated with manufacturing, while simultaneously extending carbon storage in products and delaying emissions for years, making it a valuable tool for environmental sustainability and climate change mitigation (e.g. Irle et al. [18]; Lesar et al. [19]; He et al. [20]). The success of high-value recycling for recovered wood hinges on overcoming the hurdles presented by its inherent heterogeneity and lower quality, which currently restrict yields [21].

Cascading wood effectively demands not only novel technologies but also a transformation in demolition and waste treatment practices to maximise material quality [22–27]. Ideally, product and building design should prioritise material preservation and straightforward and efficient recycling. Most of the wood from demolished buildings is incinerated for energy, primarily to heat power plants, with only a negligible amount diverted to landfills. This highlights the growing interest in timber buildings, which offer a more sustainable alternative.

Despite relying on wood waste for energy, many countries are missing a key opportunity: a massive amount of high-value wood products and assemblies, like structural components, end up incinerated instead of being cascaded for further use. Embracing design for reuse and recycling in wood construction could unlock a treasure trove of opportunities: timber structures could be readily reused, paving the way for practical implementation of wood cascading across the industry.

5.3 Evaluation of Reusability: Materials/Structural Components/Entire Primary and Secondary Structure

The reports of many studies consistently highlight innovative design concepts for deconstruction and reuse, which have the potential to be applied in contemporary buildings. The reports highlight that both the feasibility and the potential for reuse increase with the size of the reclaimed components. Larger elements save time, reduce greenhouse gas emissions, and minimise waste generation. By prioritising adaptability in volumetric and planar units, it not only reduces waste but also unlocks valuable opportunities for repurposing them in different contexts or modifying them within buildings as component lifespans differ. This results in long-term cost savings and improved sustainability. There are examples that demonstrate various design strategies for Design for Deconstruction and Reuse (DfDR) in buildings. Each example is accompanied by its specific design approach to facilitate the reuse and deconstruction process. In the given examples, the buildings are designed to be in one place for a specific period of time. They are constructed with the intention of being easily deconstructed and reassembled in another location without the need for component replacement. Buildings designed for disassembly and reuse often exhibit key features such as modular component systems, easily reversible connections, adaptable floor plans, and circular procurement strategies. Although it is clear that structural timber reuse is feasible, it has not yet been widely adopted as a common approach. The primary obstacles to the use of reclaimed structural components are primarily the absence of demand for salvaged materials, as well as restrictive building regulations and the absence of established design standards. The practices employed during the demolition phase also hold significant importance and should be taken into consideration during the design of buildings to prevent damage to the components.

Entire Structures. Relocating entire buildings in order to reuse a maximum of the components and structure is considered in PROGRESS project [8, 10, 11]. The SEGRO warehouse building in Slough, UK, for instance, built in 2000 was relocated in 2015 on the same business park, to make it possible to construct a new road bridge. The primary steel structure was relatively easy to recover with an intumescent coating removed and repainted on site. Reclaim of secondary steelwork was more challenging due to the large number of elements and their relative fragility. The precast concrete floor planks were easy to remove as there were no rebars between them but grouts; some of the planks were damaged during the deconstruction process and required repair. New composite steel cladding was installed due to the costs of reclaiming the bricks from the original cladding and the difficulty in reinstallation.

Other case studies from the PROGRESS [8] project include the Agrocolumna warehouse built in 2004 and initially located in Craiova and relocated to Copăceni, Romania in 2012 (see Fig. 5.1), and a warehouse building situated within the western harbour of Helsinki underwent a nearby relocation utilising crane technology, eliminating the need for disassembly etc.

Fig. 5.1 Deconstruction and relocation of a warehouse and office building [8]

A similar approach is followed by Capelle et al. [28]. Within their BAMB-Project, circular solutions for the building sector were analysed with the help of several pilot projects. Find hereafter a non-exhaustive list: BRIC–An educational transformable wooden building in Belgium, new building, disassembled and assembled twice, used as an office building in 2018, a shop in 2019 and an acoustic laboratory in 2020; GTB LAB–A novel building module constructed in the Netherlands that combines a steel frame with exchangeable components, enabling flexibility and transformation, which has already undergone its first functional change; REMs An indoor interactive and modular exhibition space on circular building materials, in Brussels, London, Watford, Amsterdam, Eindhoven, Westerlo, new construction, assembled, transformed, and relocated six times.

The 2015 Finnish project ReUSE, explored by Hradil [29], investigated the potential for reusing various building materials, including timber (with a particular focus on mass timber elements). Hradil observes that a substantial variety of load-bearing building elements possess reusability potential, either through recovery from construction and demolition waste or direct reuse from existing structures. He proposed a size- and complexity-based classification system, dividing projects into five distinct categories: (1) building (2) structures, (3) structural elements, (4) basic structural elements, (5) building blocks. Hradil leverages the summarized building element definition to establish a criteria-driven approach for categorizing and evaluating individual elements. Hradil [29] identified these key features of mass timber building components as:

A: sports halls, modular houses, towers, bridges;
B: roof trusses, glulam frames;
C: sandwich panels, ceiling joists, curved glulam beams;
D: wood-based panels, straight solid or glulam beams;
E: boards.

Structural components: Steel. It is not always reasonable to relocate entire buildings. However, single building components such as roofing, cladding, floors or load bearing structures can be recovered and reused. Flat steel construction products for

Steel metal sheeting PIR sandwich panels Mineral wool sandwich panels

Fig. 5.2 Flat steel construction products

the building envelope cover inter alia steel metal sheeting, PIR sandwich panels and mineral wool sandwich panels (see Fig. 5.2).

The steel metal sheeting products are 100% recyclable with 16.74% average of recycled content. With choosing special steel from selected producers, options with e.g. a minimum of 75% of recycled content and thus significant CO_2 savings can be chosen. Recycling of the foam of PIR sandwich panels is technically feasible into raw materials to produce again PIR foam sandwich panels. For mineral wool sandwich panels, steel and mineral wool are separable and both are recyclable. Mineral wool can contain between 30 and 50% of recycled content. Also, mineral wool production waste is mainly recycled (up to 90%). The industry is currently looking into an enhancement of circular economy on each step of the products life of steel construction products by:

1. Recycle production waste in particular for PIR sandwich panels as well as waste on site;
2. Use of environmentally friendly surface coatings;
3. Concepts to promote separation into mono-materials;
4. Innovative deconstruction concepts.

Further carbon equivalent savings can be achieved by value engineering with optimised design and related steel thicknesses. Innovative deconstruction concepts promote the reuse of steel construction elements. The construction as such as planned with mechanical fastening techniques. The fastening elements are to be placed from one-side only to facilitate easy deconstruction layer by layer. Riveted connections can be opened by drilling. Setting pins can be loosened by hammering. Bore holes remain in the elements.

Sealing tapes and other sealing products at element edges or intersections may not be removed residue-free. Impacted edges of used panels can be refitted respectively needs to be cut-off from the product being reused. Loss of material can be recycled. It is to be noted that standard element sizes may not remain. It is to be noted that producers do not have a business model in place accounting for reuse of construction elements, mainly due to the challenge of warranty respectively product responsibility. The assessment for fitness-of-purpose of the product to be reused is to be agreed between the party selling product, the designer as well as the purchaser as no legal framework does exist for this case.

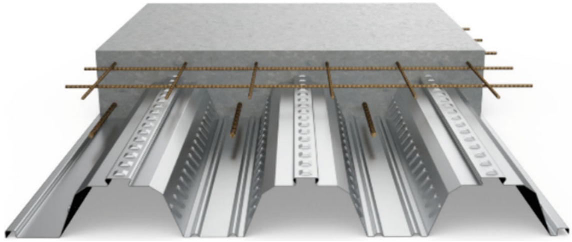

Fig. 5.3 Composite concrete floor

Reclaiming and reusing concrete floors as components are not easy tasks. In current practices, concrete floors are crushed for recycling or landfilling. Precast floor slabs may be easier to reclaim and reuse from existing buildings, compared to cast in-situ applications. Hollow core slabs are prefabricated concrete slabs pre-stressed for strength, commonly used in residential construction for fast and efficient floor systems. In one pilot project in Oslo, hollow core concrete slabs were carefully removed from a demolished multi-storey building to be reused in a new building [30]. Norwegian standard NS 3682 issued in 2022 [31] has provided guidance on reuse of hollow core slabs, from dismantling to assessment.

Composite concrete floors (see Fig. 5.3) comprise reinforced concrete and profiled steel deckling as formwork during concreting and as reinforcement in a final stage. They are commonly designed with composite beams with steel connectors, such as welded shear studs, in steel framed buildings usually non-residential multi-storey buildings. Reclaiming steel sections from such applications is possible, with concrete crushed and studs cut. One easy and elegant way to make this type of composite solution fully deconstructable (floor slabs detachable from composite beams) is to use demountable connectors such as bolts, however, the design of such solution is not covered by Eurocodes.

Using high-strength structural bolts as shear connectors is acceptable in Australian/New Zealand standard AS/NZS 2327 [32]. Within the EU-funded project REDUCE, a total of twenty different demountable shear connection systems have been identified with selected solutions tested, and a design guide on demountable composite construction has been published [33, 34]. Reuse scenario of composite beams with composite floors and demountable connectors has been tested in the UK by Lam et al. [35]; cast in-situ composite floors was cut along the troughs of steel decking after first use, detached, reassembled, and tested to failure, to create a reuse phase. Demountable composite construction has the merits of resource efficiency in first use due to improved strength and stiffness and thus reduced material consumption, and time, labour, carbon savings during assembly and disassembly in first use and subsequent uses of components or structure.

A steel-timber composite flooring system as described by Romero et al. [36] has been developed recently; using demountable shear connectors between timber floor and steel beam to form composite action. Timber panels can be detached from the beams and potentially reused with the same or new beams or repurposed as non-structural elements.

Stockists in the UK have a growing business on reclaimed steel sections thanks to the newly developed steel reuse protocols and the increasing demand on low carbon steel. Before, finding reclaimed steel sections in good quality was not easy and a systematic assessment method was lacking. Completed in 2002, the BedZED project in London used reclaimed steel as frames amounts to 95% of the structural steel [37]. In retrofitting projects, steel is usually the right and light weight material to use for load bearing; the Holbein Gardens project in London, for instance, used reclaimed steel for extension of the frame [38].

A demonstration project in Luxembourg demonstrates opportunities on how to reuse steel load bearing structures. The Project Petite Maison contributes to the concept of design for deconstruction, reuse, and circularity. The project has three phases named: construction phase, use phase (and open for public visits), and deconstruction phase. The load-bearing structure is steel framed with the demountable composite solutions and adaptable steel connections developed within the REDUCE project [39]. The elements adhere to a standardized 1.35-m grid system, prevalent in European construction. Noted that, using a higher grade of steel from S355 to S460 saves approximately 24% of material consumption thus reduced embodied carbon. The developed systems are designed as modular, demountable, standardised, and potentially reusable. Each building element has been linked with a QR code and virtual platform containing material passport data such as technical properties and manufacturers to facilitate tracking and future reuse.

Steel foundations consist of bearing piles and sheet piles and can be found mainly as deep foundation elements in structures as bridges, industrial facilities, housing, underground car parks or quay walls (see examples in Fig. 5.4). The purpose of the foundation can be temporary or permanent, which results in a service-life ranging from some months up to 100 years. Two main modes of action for steel foundations are identified:

1. Vertical load bearing elements,
2. Retaining walls with limited vertical bearing capacity.

Fig. 5.4 Steel as a reclaimable foundation element

The vertical load bearing is assured by steel bearing piles that are generally combined with a shallow concrete foundation. Retaining walls, constructed with sheet piles take horizontal loads, but also have a certain bearing capacity, which allows an efficient use of material. Steel sheet piles are modular, prefabricated elements. For either case, steel elements can be reclaimed after the service life of the structure. Three options are identified for reuse of steel foundations:

1. Reuse steel foundation on the same site (in-situ reuse);
2. Reuse steel foundation on the same site (ex-situ reuse);
3. Reuse steel elements on another site (off-site ex-situ reuse).

Reuse steel foundation on the same site (in-situ): It is possible to reuse vertical bearing piles. As described by Sangiuliano et al. [40], the Ministry of Transportation of Ontario in Canada, is assessing existing bridge abutments that need to be rehabilitated/replaced. The aim is to reuse the existing steel foundations. The authors describe the assessment procedure to check if an existing, 50-year-old, steel foundation, could be maintained and used to support a new superstructure for another 75 years. The procedure considers corrosion as well as geotechnical and structural assessment. The positive result leads to substantial savings in cost, construction time and natural resources.

Reuse steel foundation (ex-situ): Sheet piles can be used for temporary applications and then reused on the same site for further construction stages or on another jobsite. They can be reused up to ten times [41]. The multiple reuses allow the efficient use of a steel element. Being reused multiple times, the steel element is kept on a high level of circularity over several lifecycles. Manufacturers as well as contractors offer rental services and buy-back schemes for sheet piles. Vertical bearing piles are generally used in permanent applications. After reclamation they would be used on another site.

After deconstruction of the superstructure, the use of vibratory hammers, typically used for pile installation, facilitates the efficient extraction of sheet and bearing piles. For steel used in infrastructure, other than quay walls, very limited corrosion is to be expected as the elements often emerge in the soil [42]. Steel foundations are ideal for reuse, due to their integrity and ease of reclamation and storage. Reusing steel foundations significantly reduces the use of raw material, waste, and energy. Today, the reuse of steel foundations, in the form of sheet piles, is common. Around 25% of sheet piles in Europe are reused at least once.

Reuse of steel is technically viable: steel is inherently reusable and durable; and steel construction is easily reversible to facilitate reclamation of materials and components. Reuse of steel is already common practice in shoring, excavation, and the railway industry. Case studies indicate that salvaged steel can be repurposed as structural elements: over 40% of structural steel used in the Brent Cross Town substation project (see Fig. 5.5) was salvaged from surplus oil pipelines [43].

Steel can also easily serve as an intermediary to improve the reuse potential of other materials such as concrete, brick, and timber through connections [44].

Structural components: Concrete. In practice, the elements most commonly used in concrete constructions can be reused. These are:

Fig. 5.5 Brent Cross Town primary substation [43]

- Columns: serving as vertical supports for a structure, columns transfer the compressive forces and bending moments from upper floors, through foundations, to the ground. Square, rectangular, and circular are the most common cross-sectional shapes for these vital structural members;
- Beams: characterised by their rectangular cross-section, beams serve to transfer primarily transversal loads to supporting elements. Their reinforcements enable them to effectively resist both shearing forces (frames) and bending moments (longitudinal steel bars);
- Walls: these vertical elements, carry vertical loads and, due to their inherent strength, also resist horizontal forces generated by wind and earthquakes;
- Floors: characterised by their horizontal orientation and primarily subjected to bending moments, floors are categorised according to the direction of their spans (unidirectional or bidirectional) and construction style (solid, ribbed, or mixed);
- Façade panels: relatively thin, flat elements of uniform thickness, employed primarily to fill the spatial gaps between structural columns. Primarily serving aesthetic and environmental purposes, these non-structural components do not contribute directly to the building's load-bearing capacity.

Küpfer et al. [45] presented an original collection of 77 concrete component reuse cases in new construction projects in Europe and the United States, spanning projects built between 1967 and 2022. Employing a chronological approach, the authors identified seven distinct trends categorised across three main time intervals: (a) the early, pioneering period (1967–1998), (b) the intermediate, development period (1999–2010), and (c) the recent, diversification period (2011–2022).

Within the study, the authors established a three-tier value recovery framework for concrete component reuse, based on the disparity between the structural demands of the components in the new design and their original roles in the donor structure, i.e.:

(a) equivalent reuse of components when the reuse is for the same purpose,

The residential quarter before refurbishment

The residential quarter after refurbishment

Fig. 5.6 Residential quarter before and after refurbishment [47]

(b) downcycling reuse when the reuse of concrete components in new applications are subjected to a less diverse or less intense spectrum of loads or stresses compared to their original design specifications, and
(c) upcycling reuse, when the reuse of concrete components in the receiver structure is required, is subjected to more intense spectrum of loads or stresses compared to their original design specifications.

Asam [46, 47] presented the latest developments in the area of reuse of building parts from disassembled concrete prefabricated parts from housing construction in eastern Germany. He presented four pilot projects implemented between 2005–2007 in the Berlin area. The slab and wall components were supplied by donor buildings in an area of 35 km around Berlin (see Fig. 5.6).

In 2015, Huuhka et al. [48] conducted a study to evaluate the reusability of concrete panels prevalent in the Finnish mass housing stock. The research focused on assessing the dimensional compatibility of these panels with the requirements of contemporary architectural design paradigms. Analysing multi-story housing built between 1968 and 1985, the study discovered that a single, average-sized apartment building could provide enough materials to construct up to nine detached houses.

In his study, Glias [49] investigated the feasibility of reusing existing structural concrete elements. His findings confirmed the technical practicality of this approach while highlighting its potential for cost reduction and environmental benefits compared to the use of new construction materials. In addition to its other applications, this strategy presents a potentially valuable solution for vacant office buildings. These encouraging findings warrant further research to fully explore the full potential for reuse and to realise a pilot project that utilises reused elements in the foreseeable future.

Several noteworthy examples, including the Kummatti housing estate rehabilitation project in Raahe, Finland (2008–2010), have provided concrete evidence of the environmental, economic, and construction time advantages associated with the reuse of concrete elements; a small-scale initiative involving the reuse of wall panels resulted in a noteworthy 36% reduction in construction costs [48]. The design of new housing in Mehrow, near Berlin, exemplifies another successful implementation of circular construction principles. Precast concrete elements from unwanted buildings were repurposed for the project, resulting in a 30% cost reduction, highlighting the potential of resource conservation in the construction industry [50].

In 2001, a research project titled "Recycling Prefabricated Building Components for Future Generations" was initiated by the Federal Ministry of Transport, Building, and Housing in Germany. This initiative aimed to assess the feasibility and potential of dismantling and reutilising prefabricated concrete elements in the construction of new houses. The project yielded significant findings regarding the viability of reusing building elements. The use of hand procedures with light machinery proved to be more cost-effective compared to heavy-duty equipment. Furthermore, measurements ensured the quality of the dismantled elements and the reused components were demonstrably 50% less expensive than their new concrete counterparts. In particular, total building costs were observed to be 26% lower when using reused elements [49].

Salama [51] conducted a comprehensive analysis of contemporary issues concerning concrete technologies and their influence on building assembly and disassembly processes. Recognising the environmental implications, he delves into the potential of design-for-disassembly (DfD) principles and explores theories for future advancements. Ultimately, his work aims to guide the construction design of concrete buildings towards a more environmentally responsible future. The study concluded that the implementation of the design for disassembly (DfD) criteria in precast concrete systems and elements presents a feasible and effective solution to transition their linear life cycle to a circular model.

Drawing upon insights from pilot projects conducted in Finland, Sweden, Germany, and the Netherlands, the ReCreate project [13] is currently in progress. This research initiative investigates the feasibility of transitioning from a traditional build-and-demolish approach to a model where elements from dismantled structures are repurposed to construct new buildings. As the project is still under development, further details and results are not yet available.

Structural components: Timber. "Building elements of higher category can be often separated into several elements of lower category. Even though the higher category elements have typically higher value than their parts together, the separation would make sense, because it may be more difficult to find a suitable application of higher category elements. The re-using complexity depends on many factors" [29]:

(a) the substantial weight of certain elements may employ difficult handling,
(b) architects may deem design modifications necessary,
(c) cleaning/separation or disassembly/reassembly processes may be required,
(d) revised or new structural designs are needed,
(e) adaptation to alternative applications should be evaluated,
(f) quality/geometry assessments are needed, particularly for smaller pieces lacking documentation.

Hradil's research [29] underscores the critical role of time in the entire construction process, encompassing design, construction, deconstruction, and reuse. This study highlights that time directly translates into both labour costs and environmental impact, positioning it as a decisive factor in the move towards circular construction models within the building industry chain. The implementation of a comprehensive DfDR strategy demonstrably contributes to time optimisation within the construction process. This approach facilitates expedited decision-making, enhances the efficiency of element categorisation based on size and complexity, streamlines disassembly procedures, promotes the timely identification of optimal reuse opportunities, and expedites the reconstruction phase, resulting in significant time savings across the entire project lifecycle.

The implementation of a successful design for deconstruction and reuse (DfDR) strategy is contingent on a nuanced understanding of several key factors, primarily the 'scale' of the element under consideration. This scale encompasses both the size of the individual element and the size of the intended reuse unit. For example, the complexity of deconstructing and reusing structures changes based on the design. Choosing to reuse entire volumes presents different hurdles than focussing on individual planar components. Similarly, the deconstruction of stud-and-chipboard units versus CLT elements involves tackling distinct challenges. Deconstructing a stick-frame building to reuse separate studs involves distinct issues compared to other systems. These challenges include meticulously separating the studs without damaging neighbouring elements, managing the sheer number of smaller components, and ensuring their viability for reuse. The implementation of design for deconstruction and reuse (DfDR) strategies requires careful consideration of a multitude of interrelated factors. These include the scale and type of the building that is deconstruction, the intended objectives of the reuse process, the perceived quality and potential resale value of the salvaged elements (whether planar, modular or individual), the inherent ease of disassembly associated with different materials and joint types, the feasibility and cost of transportation, and the associated labour costs. By comprehensively evaluating these factors, stakeholders can make informed decisions regarding the most appropriate DfDR approach for each specific project, maximising the potential for resource conservation and promoting the reuse of valuable building materials beyond commonly used options such as slates and bricks.

The implementation of design for deconstruction and reuse (DfDR) strategies in the context of timber construction requires a flexible and adaptable approach. This requires moving beyond a one-size-fits-all model and tailoring the DfDR principles to the specific characteristics of the elements under consideration. A three-tier framework can be used to guide this adaptation, which includes Level 1 (linear elements, such as studs, joists and trusses), Level 2 (planar units, such as walls, floors, and roofs), and Level 3 (volumes, such as rooms or entire buildings).

Level 3 deals with buildings as complete volumes in DfDR for timber. Such structures can be deconstructed and reused either on the larger scale of entire units or broken down into smaller components such as walls and floors, allowing for adaptable reuse based on project needs. Level 2 delves into timber structures composed of planar elements such as walls, floors, and roofs. Here, the emphasis lies on exploring various DfDR strategies to disassemble and reuse these individual components with maximum effectiveness. Level 1 within the DfDR framework for timber constructions applies familiar principles found in traditional light-frame stick building practices. However, post and beam systems introduce additional considerations due to the frequent use of engineered timber elements. These elements often possess unique shapes and configurations, such as portal frames commonly used in sports halls, industrial buildings, and commercial structures. The aim of retrieving larger components during deconstruction presents several compelling advantages. Each additional dismantling step requires increased time, labour, and equipment, leading to higher costs and associated greenhouse gas emissions.

Examples:

Level 1: A building that can be reused: Brummen Town Hall [52]

Opened in 2013, the town hall stands as a testament to sustainable design, earning a Dutch Award for Sustainable Architecture. Its architectural concept bridges generations, meticulously preserving its historic foundation (dating back to 1890) while seamlessly integrating a contemporary, modular space beneath a captivating glass roof. Approximately 90% of the materials utilised in the recently constructed modular addition exhibit the remarkable capability of being dismantled and subsequently reused. Furthermore, the adoption of a modular design strategy not only facilitated a significant reduction in the overall construction timeframe but also contributed to the environmentally responsible approach employed in the building expansion. The existing structure incorporates a foundation dating back to 1890, serving as the historical cornerstone of the building. This foundational element will remain preserved and unaltered even after the dismantling of the recently constructed circular extension (Fig. 5.7). Equipped with the first materials passport, the town hall transforms into a transparent "depot" revealing the history and future potential of every element, some already earmarked for a new purpose. Collaborating with suppliers from the beginning streamlined the sourcing of recycled and recyclable materials, contributing to the high degree of circularity of the building. The initial decision to utilise thicker wooden beams, rather than adhering to a "less is more" mentality, prompted a pivotal realisation within the project team. This experience illuminated the inherent differences between key performance indicators (KPIs) employed within a linear economic model, focused on minimising material usage, and those essential for success within a circular economy framework, which prioritises durability, reusability, and the potential for future use cycles. This shift in perspective underscores the crucial role of re-evaluating traditional metrics and establishing new, circularity-aligned KPIs to facilitate responsible resource management and achieve long-term sustainability goals within the construction industry. Implementing the concept of a novel materials passport faced hurdles in customer persuasion and supplier data accessibility, reflecting the challenges inherent in pioneering sustainable practices.

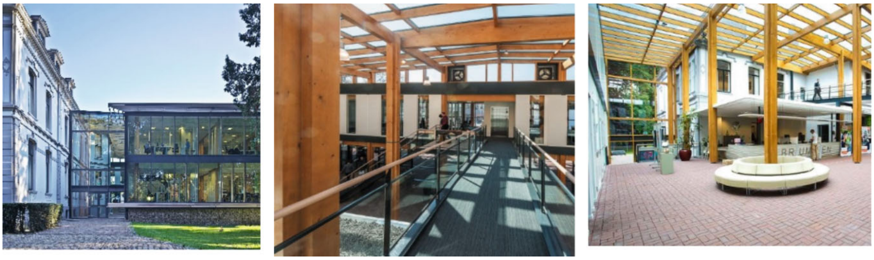

Fig. 5.7 Brummen Town Hall (*photo source* https://www.rau.eu/portfolio/gemeentehuis-brummen/)

Level 1 and 2: Fielden Fowles Architecture Studio [53]

This demountable studio, crafted from sustainable Douglas fir timber and clad with rugged corrugated bitumen sheets, minimises cuts, waste, and optimises resource use through a carefully chosen 2440 mm internal datum and 1830 mm structural grid, utilising full and three-quarter plywood sheets to perfection. The internal walls employ 610 mm plywood boards, corresponding precisely to a quarter of a standard plywood sheet. The structural framework utilises paired beams and columns measuring 300 × 600 mm, all supported by a modular grid system defined by 1800 mm (for primary beams), 600 mm (for purlins), and staggered 2400 mm (for noggins) spacings. This strategic alignment seamlessly integrates with the plywood butt joints, minimising material waste and facilitating efficient disassembly. Additionally, the inclusion of steel T-sections for window frames further exemplifies the focus on both structural integrity and adaptability, highlighting the design's commitment to sustainability and future-proof functionality (see Fig. 5.8). Although initially set for a specific lease period, this structure is designed to be dismantled and reassembled elsewhere, offering long-term possibilities beyond its current location.

Level 2: Temporary Market Hall, Östermalm, Stockholm [54]

Fig. 5.8 Fielden Fowles architecture studio (*photo source* https://www.woodawards.com/portfolio/feilden-fowles-studio-2/)

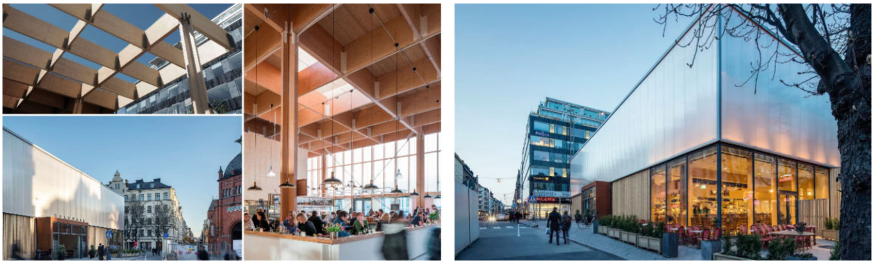

Fig. 5.9 Temporary Market Hall, Östermalm, Stockholm (*photo source* https://hicarquitectura.com/2017/03/tengbom-ostermalms-temporary-market-hall/)

During the refurbishment of the existing market hall, in 2017, a temporary solution was implemented to shelter the traders. The façade utilizes untreated cedar cladding on plywood at the lower level, while the clear-storey incorporates modular polycarbonate sheeting for ample natural light. Internally, the structure remains exposed, showcasing a visually striking latticework of glulam beams supported by columns constructed from cross-laminated timber (CLT) (see Fig. 5.9).

This building uses a modular mounting system, which facilitates efficient erection and dismantling for potential reuse at alternative locations. The sustainable choice of timber construction results in a lightweight structure that minimises the need for heavy foundations. The roof structure is comprised of sturdy 1.2-m LVL beams supported by glulam columns, offering a robust and weatherproof solution.

5.4 Ease of Recycling

Significant greenhouse gas emissions associated with the production of building materials, notably cement, steel, aluminium, glass, and insulation materials, contribute substantially to the embodied carbon footprint of buildings, highlighting the need for sustainable construction practices that minimise this environmental impact.

Steel. If steel elements are not reclaimed for reuse, a recycling strategy is generally followed for steel elements from construction. Recognised as the most recycled material globally, steel exhibits remarkable circularity within the construction industry. This assertion is supported by the European Steel Association's 2012 survey, which analysed steel recovery rates from building demolition sites, revealing a significant percentage of material being salvaged and diverted from waste streams. The average recycling rate for steel across all products was found to be 92%. Taking into account all steel products, also those products that are not used in construction, a recycling rate of 85% is realised.

Since steel scrap has a financial value, it is generally not landfilled. For post-consumer scrap, the recycling loop starts in the end-of-life of a steel element. The lifetime of a steel product in construction or infrastructure can vary from 50 to100 years. If it's not intended to reuse the steel elements, they are reclaimed to enter the recycling loop. Big metal recycler collect scrap and process it, to sell it again to the steel industry where it's used as input for new steel production. The processing mainly consists of shredding, or shearing of the steel elements, to sort them and remove plastics or non-ferrous materials. Large beams are cut with a high-temperature torch cutter, to assure an easy handling.

Steel recyclers are constantly upgrading their (mechanical) sorting systems to assure reliable and homogenous scrap qualities. Steel scrap comes not only from demolitions sites, but also from ferrous consumer goods (e.g. washing machines, vehicles etc.). It is from highest importance that the sorted steel scrap is not containing high amounts of copper, which could contaminate the required chemistry for steel grades in the new production. Steel is 100% recyclable and can be infinitely recycled without loss of properties. This means that no 'downcycling' occurs, even when steel is recycled repeatedly. It is a truly circular material. Every steel plant is a recycling plant, as steel scrap is used in the production. Besides, by-products from the production like slag or dust are used in many other industries, which leads to an overall efficiency of 97.5% in the steel industry. Slag is widely used in the concrete industry, where it's defined as secondary cementitious material (SCM) and allows to create low carbon concrete. The use of SCM is for the moment the only way to decarbonise the cement mixture on an industrial scale.

Concrete. The manufacture of cement, characterized by its energy-intensive chemical processes, contributes significantly to greenhouse gas emissions, depletes natural resources like sand, and negatively impacts ecosystems. Cement, the critical binding agent in concrete, stands out as the material requiring the highest energy input during production, contributing significantly to the overall environmental impact of the concrete industry [55]. Its manufacturing process currently accounts for a 3% of global energy consumption [56].

Concrete recycling is the process of reusing crushed and recycled concrete materials in various construction projects. It is an environmentally sustainable practice that helps reduce the demand for new concrete production and minimises waste disposal in landfills. However, recycling concrete is an energy-intensive process.

Recycled concrete has established itself as a valuable source of aggregate, demonstrating successful applications in various contexts, including granular subbases, soil–cement, and even new concrete production. Notably, these repurposed materials are classified into two distinct categories:

1. Recycled Aggregate (RA), and
2. Recycled Concrete Aggregate (RCA).

Below it will be shown some benefits of concrete recycling and the various methods used in the recycling process.

One of the primary advantages of concrete recycling is the conservation of natural resources. The use of crushed concrete as aggregate offers a significant environmental advantage by reducing the need for the extraction and processing of virgin raw materials such as gravel, sand, and cement. This approach contributes to resource conservation, reduces the environmental footprint associated with mining activities, and even alleviates the demand for energy-intensive cement production.

The implementation of concrete recycling practices presents another environmental benefit, such as reducing the amount of waste deposited in landfills. Concrete waste can take up significant space in landfills and its disposal can be costly. By recycling concrete, the volume of waste sent to landfills is reduced, contributing to a more sustainable waste management system.

The concrete recycling process involves several steps. The first step is the collection and transportation of concrete waste to a recycling facility. Once at the facility, the concrete is crushed into smaller pieces using heavy machinery. The crushed concrete is then screened to remove any contaminants or debris.

After the initial processing, the crushed concrete is further processed to create recycled aggregate. Recycled aggregate can be used in various construction applications, such as road base, drainage systems, and as a substitute for natural aggregate in new concrete production. The quality of recycled aggregate is tested to ensure it meets the required specifications and standards.

In addition to recycling concrete as aggregate, it is also possible to recycle the cementitious materials present in concrete. This process, known as cementitious material recycling, involves separating cement paste from the aggregate through mechanical or chemical methods. The recovered cementitious materials can then be used in the production of new cement or other construction materials.

In conclusion, concrete recycling is an essential practice that promotes sustainability in the construction industry. By reusing crushed concrete as aggregate or recycling cementitious materials, natural resources can be conserved, reduce waste in landfills, and minimise the environmental impact of concrete production.

5.5 From Recycling to Upcycling

Steel. Construction industry is using more and more high-strength steel (up to S700) to assure lightweight, durable, environmentally friendly, and efficient steel structures. Steel scrap is used as input in every steel production route. In the Blast Furnace route currently up to 20%, and in the Electric Arc Furnace route up to 100% is used. Decades ago, the used steel grades were less efficient (up to S275), however exactly these steel elements are now entering the recycling loop and are used for new production. To achieve high-strength steel grades, alloying elements may be added to this steel scrap.

Steel stands out as a unique material because of its closed-loop recycling potential. Unlike most materials, which experience some level of degradation during recycling, steel retains its strength and quality indefinitely, allowing it to be perpetually reused. In particular, the recycling process can even enhance its strength and value (it can be "upcycled") in certain applications, further highlighting its sustainability credentials within the circular economy. As a result of a high demand for high-strength steel, steel scrap is achieving higher quality, and this phenomenon will continue to develop.

Timber. Upcycling of timber is a creative and environmentally friendly approach to repurposing discarded or old wood materials into new and useful products, rather than sending them to landfills or incineration. The practice of reusing timber contributes significantly to environmental sustainability by reducing waste generation, conserving natural resources, and minimizing the carbon footprint associated with the production of new wood products.

Other promising avenues for the use of recycled secondary wood in prefabrication, modular construction, and methods for the design of demountable wood products have been identified. The utilization of large cross-laminated timber (CLT) panels often presents challenges due to their size. Fortunately, deconstruction techniques allow panels to be disassembled and cut to desired lengths, facilitating their repurposing in various construction applications. Although a small amount of waste is unavoidable, the implementation of efficient deconstruction processes and the exploration of creative reuse strategies can significantly reduce its impact. To fully maximise the environmental and economic benefits of sustainable construction practices, it is essential to provide readily available guidance on both materials' disassembly methods at the end of their initial life cycle and potential reuse applications in subsequent projects. To encourage a closed-loop economy, manufacturers or main suppliers could offer take-back programs for end-of-life products, enabling their reclamation and reintroduction into the market. The certification of upcycled secondary timber presents several unique challenges. First, the visual quality of the material often varies significantly compared to cross-laminated timber (CLT) produced from virgin wood, making the adherence to established aesthetic standards difficult. Secondly, the inherent flammability of wood requires the implementation of robust fire safety measures to meet the certification requirements.

5.6 Efficient Waste and Circular Resource Management

Steel. Only a small part of steel elements from construction industry is not recycled or reused. In average it's about 4%, that are mainly generated by rebars or light structural steel. For heavy structural sections a survey shows a 100% reuse and recycling rate, hence no landfill is generated [57]. Compared to other construction materials, steel in construction generates no or only small amounts of waste. The production phase of steel is also minimizing waste, as by-products are used in several other industry sectors.

Steel and metal recycler treat steel scrap from different sources. As consumer goods can contain as well non-ferrous elements, these are separated from the ferrous elements and fed to their own recycling chain (e.g. copper, plastics).

References

1. Crowther P (1999) Design for disassembly to extend service life and increase sustainability. In: Lacasse MA, Vanier DJ (eds) Durability of building materials and components 8: service life and asset management. NRC Research Press, Vancouver, Canada, pp 1983–1992
2. European Commission (2016) EU construction and demolition waste management protocol. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs
3. European Commission (2018) Guidelines for the waste audits before demolition and renovation works of buildings. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs
4. DRG102 (2022) Deconstruction of structures from top down, guidance notes. National Federation of Demolition Contractors (NDFC). https://demolition-nfdc.com
5. Wahlström M, Hradil P, zu Castell-Rudenhausen M, Bergmans J, van Cauwenberghe L, Van Belle Y, Sičáková A, Struková Z, Li J (2019) Pre-demolition audit–overall guidance document: PARADE. Best practices for pre-demolition audits ensuring high quality RAw materials. EIT RawMaterials
6. FCRBE (2022) A guide for identifying the reuse potential of construction products. Project Interreg NWE 739: Facilitating the Circulation of Reclaimed Building Elements (FCRBE), October 2018–January 2022
7. Building and Construction Authority—BCA (2019) Guidelines for pre-demolition audit, sequential demolition and site waste management plan. A Singapore Government Agency. https://www1.bca.gov.sg/docs/default-source/docs-corp-buildsg/sustainability/sc_demoprotocol.pdf
8. PROGRESS: Provisions for a Greater Reuse of Steel Structures (2017–2020) Research fund for coal and steel. https://www.steelconstruct.com/eu-projects/progress/
9. EN 1090-2 (2018) Execution of steel structures and aluminium structures–part 2: technical requirements for steel structures. European Committee for Standardization (CEN), Brussels, Belgium
10. Girão Coelho AM, Pimentel R, Ungureanu V, Hradil P, Kesti J (2020) European recommendations for reuse of steel products in single-storey buildings. ECCS—European Convention for Constructional Steelwork. ISBN: 978-92-9147-170-6
11. Hradil P, Talja A, Ungureanu V, Koukkari H, Fülöp L (2017) Reusability indicator for steel-framed buildings and application for an industrial hall. ce/papers 1(2–3):4512–4521. https://doi.org/10.1002/cepa.511
12. ReCreate: Reusing precast concrete for a circular economy. Horizon 2020, grant agreement no. 958200, 2021–2025. https://recreate-project.eu/
13. Vullings MWF, Wijte SNM, Huuhka S (2022) D2.1: guidelines for a BIM-aided pre-deconstruction audit. The ReCreate Project. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5f54ee881&appId=PPGMS
14. PEIKKO White Paper (2022) Dismount and reuse of precast concrete frame. https://media.peikko.com/file/dl/i/leyTcQ/ffmXgWD9GursZAo0ltziIg/PeikkoWhitePaper_Dismountandreuseofprecastconcreteframe.pdf?fv=6b8a
15. InFutUReWood: Innovative design for the future–use and reuse of wood (building) components. ERA-NET Cofund ForestValue, grant agreement no. 773324, 2017–2023. https://www.infutürewood.info/
16. Risse M (2019) Resource and eco-efficiency assessment of utilizing recovered solid wood in cascades. Dissertation. Technical University of Munich (TUM), Munich, 129 pp
17. Maguire J (2018) Cascade use of Ireland's harvested wood resource: the impact of resource efficiency on harvested wood pool carbon flux dynamics. Dissertation. University College Dublin, Dublin, 155 pp
18. Irle M, Privat F, Deroubaix G, Belloncle C (2015) Intelligent recycling of solid wood. Pro Ligno 11(4):14–20

19. Lesar B, Humar M, Hora G, Hachmeister P, Schmiedl D, Pindel E, Siika-aho M, Liitiä T (2016) Utilisation of recycled wood in biorefineries: preliminary results of steam explosion and ethanol/water organosolv pulping without a catalyst. Eur J Wood Prod 74(5):711–723. https://doi.org/10.1007/s00107-016-1064-8
20. He P, Hossain MU, Poon CS, Tsang DCW (2019) Mechanical, durability and environmental aspects of magnesium oxychloride cement boards incorporating waste wood. J Clean Prod 207:391–399. https://doi.org/10.1016/j.jclepro.2018.10.015
21. Privat F (2019) Faisabilité du recyclage en boucle fermée des déchets post-consommateurs en bois massif. Dissertation. École supérieure du bois, Nantes, 163 pp
22. Kalcher J, Praxmarer G, Teischinger A (2017) Quantification of future availabilities of recovered wood from Austrian residential buildings. Resour Conserv Recycl 123. https://doi.org/10.1016/j.resconrec.2016.09.001
23. Llana DF, Íñiguez-González G, Arana-Fernández M de, Uí Chúláin C, Harte AM (2020) Recovered wood as raw material for structural timber products. Characteristics, situation and study cases: Ireland and Spain. In: Proceedings of the 63rd international convention of society of wood science and technology, July 13–15, pp 117–123
24. Llana DF, González-Alegre V, Portela M, Íñiguez-González G (2022) Cross Laminated Timber (CLT) manufactured with European oak recovered from demolition: structural properties and non-destructive evaluation. Constr Build Mater 339:127635. https://doi.org/10.1016/j.conbuildmat.2022.127635
25. Martínez E, Nuñez Y, Sobaberas E (2013) End of life of buildings: three alternatives, two scenarios. A case study. Int J Life Cycle Assess 18(5):S.1082–1088. https://doi.org/10.1007/s11367-013-0566-4
26. Nasiri B, Piccardo C, Hughes M (2021) Estimating the material stock in wooden residential houses in Finland. Waste Manag 135:318–326. https://doi.org/10.1016/j.wasman.2021.09.007
27. Sakaguchi D, Takano A, Hughes M (2017) The potential for cascading wood from demolished buildings: potential flows and possible applications through a case study in Finland. Int Wood Prod J 8(4):208–215. https://doi.org/10.1080/20426445.2017.1389835
28. Capelle T et al (2019) Testing BAMB results through prototyping and pilot projects, D14-4 pilots built and feedback report. Building as Material Banks project report. https://www.bamb2020.eu/wp-content/uploads/2019/03/20190228-BAMB-D14.pdf
29. Hradil P (2014) Timber re-using. Barriers and opportunities of structural elements re-use. Research report VTT-R-01363-14. VTT Technical Research Centre of Finland, Espoo
30. Skanska (2020) Taking a pioneering approach to re-using concrete decks. https://group.skanska.com/media/articles/taking-a-pioneering-approach-to-re-using-concrete-decks/
31. Norwegian Standard NS 3682 (2022) Hollow core slabs for reuse. Standards Norway, Oslo, Norway, p 24
32. Australian/New Zealand Standard AS/NZS 2327 (2017) Composite structures—composite steel-concrete construction in buildings. Standards Australia/Standards New Zealand, Sydney/Wellington, Australia/New Zealand
33. Sansom M, Girão Coelho AM, Lawson RM et al (2019) Reuse and demountability using steel structures and the circular economy. REDUCE Final Report. Project 710040
34. Girão Coelho AM, Lawson M, Lam D, Yang J (2020) Guidance on demountable composite construction systems for UK practice. SCI P428. The Steel Construction Institute, Ascot, UK
35. Lam D, Yang J, Wang Y, Dai X, Sheehan T, Zhou K (2021) New composite flooring system for the circular economy. Steel Compos Struct 40(5):649–661. https://doi.org/10.12989/scs.2021.40.5.649
36. Romero A, Yang J, Hanus F, Odenbreit F (2022) Numerical investigation of steel-LVL timber composite beams. Ce/papers 5(2):21–30. https://doi.org/10.1002/cepa.1694
37. Lazarus N (2002) BedZED: Toolkit part I–a guide to construction materials for carbon neutral developments. BioRegional Development Group. https://library.uniteddiversity.coop/Ecological_Building/BedZED-Toolkit-Part-1.pdf
38. ASBP (2023) Case study—Holbein Gardens. The alliance for sustainable building products. https://asbp.org.uk/case-studies/holbein-gardens. Accessed 26 July 2023

39. Odenbreit C, Yang J, Kozma A, Romero A, Popa N, Hanus F, Obiala R (2023) Design for disassembling, reuse, and the circular economy: a demonstration building, "Petite Maison". ce/papers 6:369–373. https://doi.org/10.1002/cepa.2537
40. Sangiuliano T, Staseff D, Chatterji PK, Shi K, de Castro R (2023) Reuse of existing steel pile foundations—Greenock Creek Bridge, Walkerton, Ontario, Canada. In: Proceedings of the Institution of Civil Engineers–Forensic Engineering. https://doi.org/10.1680/jfoen.22.00025
41. Fohl F, Hechler O (2024) Reuse of steel sheet piles—best practice. In: Bragança L et al (eds) Creating a roadmap towards circularity in the built environment, springer tracts in civil engineering. https://doi.org/10.1007/978-3-031-45980-1_325
42. EN 1993-5 (2007) Eurocode 3–Design of steel structures–part 5: Piling. European Committee for Standardization (CEN), Brussels, Belgium
43. Arup (2023) Brent Cross Town substation, London. https://www.arup.com/projects/brent-cross-town-substation
44. Durmisevic E, Noort N (2003) Re-use potential of steel in building construction. In: Chini AR (ed) Deconstruction and materials reuse CIB publications 287. University of Florida, pp 1–10
45. Küpfer C, Bastien-Masse M, Fivet C (2023) Reuse of concrete components in new construction projects: critical review of 77 circular precedents. J Clean Prod 383:135235
46. Asam C (2007) Recycling prefabricated concrete components–a contribution to sustainable construction. In: International conference on sustainable buildings 2007: sustainable construction. Materials and Practices, Lisbon, Portugal, 12–14 September 2007. IOS Press. ISBN: 978-1-58603-785-7
47. Asam C (2007) Typical measures on load bearing building elements during modernisation. In: Research in architectural engineering series: COST C16 improving the quality of existing urban building envelopes, vol 4. IOS Press, pp 203–210
48. Huuhka S, Kaasalainen T, Hakanen JH, Lahdensivu J (2015) Reusing concrete panels from buildings for building: potential in Finnish 1970s mass housing. Resour Conserv Recycl 101:105–121
49. Glias A (2013) The "Donor Skelet" designing with reused structural concrete elements (Master Thesis). TUDelft University
50. Stacey M (2011) Concrete: a studio design guide. RIBA, London
51. Salama W (2017) Design of concrete buildings for disassembly: an explorative review. Int J Sustain Built Environ 6(2):617–635
52. Ellen MacArthur Foundation (2022) A building that can be reused: Brummen Town Hall. [Online]. https://www.ellenmacarthurfoundation.org/circular-examples/brummen-town-hall
53. Young E (2019) Feilden Fowles: a learning experience. Damn Magazine. https://www.feildenfowles.co.uk/FF/wp-content/uploads/2019/10/2019_07_Damm_Mag-1.pdf
54. Temporary Market Hall, Östermalm, Stockholm. https://hicarquitectura.com/2017/03/tengbom-ostermalms-temporary-market-hall/
55. Habert G, Miller SA, John VM et al (2020) Environmental impacts and decarbonization strategies in the cement and concrete industries. Nat Rev Earth Environ 1:559–573. https://doi.org/10.1038/s43017-020-0093-3
56. Miller SA, Moore FC (2020) Climate and health damages from global concrete production. Nat Clim Chang 10:439–443. https://doi.org/10.1038/s41558-020-0733-0
57. Sansom M, Avery N (2014) Reuse and recycling rates of UK steel demolition arisings. Proc Inst Civ Eng Eng Sustain 167(ES3):89–94. https://doi.org/10.1680/ensu.13.00026