

SYNTHESIS

Material recovery certification for construction workers

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Abstract

Low and zero-carbon building certification programmes typically focus on emissions caused by building operation and/or material extraction and manufacturing activities. However, ‘end-of-life’ issues involving the reuse, remanufacture or recycling potential of embodied energy-intensive components are often overlooked. As a result, training and certification in this field tends to be diagnostic and observational rather than proactive and anticipatory. To ensure that vocational workers have appropriate capabilities to recycle or reuse building components fully, a training and certification programme is necessary that focuses on end-of-life material recovery potential. A framework is presented for recovery of building products and the certification system for workers. The system rates recovery potential at both the material and assembly levels through a series of evaluation criteria. This assessment is translated into a product labelling scheme as well as a training and certification programme for vocational workers involved in the production, supply and installation chains of recovery-oriented products.

Practice relevance

Material recovery training in the built environment is currently limited and lacks a holistic view of the entire recovery chain. A certification system targeting material recovery could help propel a transition to circular consumption models in the built environment. Vocational training based on a full supply chain view of the end-of-life sector would be essential for a transition to a circular economy.

Keywords: buildings; certification; circular economy; embodied emissions; end of life; material recovery; vocational education and training

1. Introduction

Definitions of zero-carbon building design have expanded to include not only the operational emissions but also the embodied emissions (*e.g.* CO₂ originating from the creation of building materials and components). Over the last decade, substantial research has been carried out in an effort to outline this expanded definition (Lobaccaro *et al.* 2018; Balouktsi & Lützkendorf 2016; Giordano *et al.* 2015; Lützkendorf *et al.* 2015; Hernandez & Kenny 2010). While these developments undoubtedly bring the construction industry closer to eliminating the environmental impacts of the construction site as well as upstream in the supply chain, they offer a somewhat short-sighted approach to impact reduction. For the most part, these definitions place an emphasis on avoiding present emissions, but overlook future emissions—those that may result from opting for component replacement with new production or recycling instead of remanufacturing or reuse. Studies find that in a life-cycle perspective, remanufacturing and reuse can lead to 45–100% energy savings over new production, depending on the type of product used, and as long as recovery does not lead to increased consumption (Cooper & Gutowski 2017).

Remanufacturing of photocopiers, for example, where there is considerable use-phase material consumption (toner, paper, *etc.*), leads to approximately 45% energy savings (Kerr & Ryan 2001), while cell phone remanufacturing, where there is virtually no use-phase material consumption, yields close to 100% energy savings over new production (Skerlos *et al.* 2003). In the construction sector, it is estimated that a transition from recycling to a reuse production pattern for structural steel would result in approximately 60% energy and 35% cost savings (Geyer *et al.* 2002).

The inclusion of material recovery potential into the design and construction of zero-carbon buildings might allow a further reduction of emissions in a life-cycle view. For example, if all new reinforced concrete building construction in Australia were to transition to using recovered content instead of content originating in primary production, a reduction of 26 Mt CO₂e is calculated to occur by 2050 (Yu *et al.* 2017). In order to do so in a consistent manner

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across a range of building and material types, the industry needs a roadmap consisting of (1) a method for evaluating the material recovery potential of building materials and components; (2) a certification system for material recovery potential; and (3) professional training for implementing recovery-oriented zero-carbon construction in practice.

This paper sets out a quality assurance system (QAS) consisting of a certification scheme and a matching training system for material recovery professionals in zero-carbon construction. QASs are defined by the International Organization for Standardization (ISO) as a quality management apparatus focused on providing confidence that quality requirements will be met in full (ISO 9000:2005, 2005). To guarantee the expected level of outcome in QASs, certification, labelling, training programmes, and accreditation and certification bodies are needed to oversee conformity with standards.

This paper proposes a certification and training ecosystem. It is structured as follows. A brief literature survey is next presented. Based on this, the problem is described and a proposed scheme presented. The barriers and opportunities for implementation are considered.

As the paper focuses on the execution (rather than the design) of recovery-oriented construction, the emphasis is on vocational workers and construction professionals (and not on design professionals). Vocational workers are defined as employees who are technically trained to perform a specific set of applied tasks in the workplace (Bosch & Charest 2008). These would be workers in product manufacturing, builders' merchants employees working with reclaimed materials, disassembly workers and reassembly workers.

2. Literature review

End-of-life material recovery in the built environment has generated a diverse discourse and a wide range of investigation domains over the years—work that is too broad to survey in its entirety here. As the paper centres narrowly on certification and training approaches within this field, it looks at three specific areas of study: material recovery potential evaluation, material recovery in building certification systems and worker training in material recovery.

2.1 Material recovery potential evaluation

Design for disassembly (DfD) has been a topic of research since the 1990s. Early studies focused on developing DfD strategies for consumer electronics (Boothroyd & Alting 1992), automotive (Wittenburg 1992) and furniture (Schmaus & Kahmeyer 1992) applications. In construction, early studies focused on the environmental benefits of DfD (Kibert 2003), on developing recovery-oriented design techniques (Crowther 1999), and on communicating about DfD with various stakeholders in the design and construction process (Thormark 2007). The relatively recent introduction of modern methods of construction (MMC) and custom build present new opportunities for reducing environmental impact (Monahan & Powell 2011) and implementing DfD. Fulfilling this potential at an industry-wide level, however, requires more than merely developing DfD techniques. In order to set and meet recovery performance goals, one must be able to analyse, assess and compare accurately the impact of specific design decisions on material recovery potential (Schvaneveldt 2003). The ISO led this activity in the early 2000s in several disciplines by issuing calculation methods for material-recovery potential assessment of earth-moving machinery (ISO 16714:2008, 2008), road vehicles (ISO 22628:2002, 2002), rolling stock (ISO/TC 269/AG 6, 2010), *etc.* This action has been followed by efforts to introduce recovery potential quantification strategies for a variety of raw materials, mechanical assemblies and consumer products. Namely, these studies looked at: measuring the disassembly difficulty of mechanical connectors (Kroll & Carver 1999); evaluating the unfastening effort of widely used fasteners (Sodhi *et al.* 2004); estimating the product end-of-life disassembly potential during early design phases (Germani *et al.* 2014); assessing the end-of-life recycling feasibility of consumer products (Dahmus & Gutowski 2006); quantifying the end-of-life disassembly effort and cost (Das *et al.* 2000); predicting the total time of disassembly operations for a given product (Gungor & Gupta 1997); calculating the disassembly depth effectiveness (Giudice & Kassem 2009); comparing the recyclability potential of raw materials (Villalba *et al.* 2002); and developing a product end-of-life index for product designers (Lee *et al.* 2014).

Far less attention has been given to the assessment of material recovery in the built environment. Notable work includes the development of a decision-making framework for choosing demolition techniques to increase end-of-life material recovery (Abdullah *et al.* 2003), an evaluation scheme for the recycling potential of construction materials (Thormark 2001), and a method for assessing the loop potential for building materials (Rosen 2019). These sources propose evaluating recovery potential at either the material or the system levels, but not at both. Aiming to bridge this gap, Mayer & Bechthold (2017) propose an evaluation scheme that quantifies the recovery potential in buildings at both the product and assembly levels. The scheme relies on an existing market and liability distinction between building products (manufacturers) and building assemblies (designers and contractors).

At the product level, the scheme includes four evaluation criteria:

- *Recyclability*: The availability and efficiency of existing recycling technologies from a market and an environmental perspective.
- *Surface treatment*: The ability of coatings (*e.g.* fireproofing) to be easily removed during end-of-life recovery.
- *Binders*: The potential of adhesives and mortars to allow contaminant-free separation for reuse and recycling.
- *Material diversity*: The number of different components, coatings and binders as a potential obstacle for full material recovery.

At the assembly level, the scheme also includes four evaluation criteria:

- *Average product scores*: For all products in the assembly.
- *Connection index*: Separation damage, tool type required for disassembly and disassembly time.
- *Access index*: The correlation between disassembly sequence and product life expectancy, as well as the existence of layers that limit access to other layers with shorter life expectancies.
- *Component integration*: The notion that prefabricated assemblies are likely to lead to higher recovery potential due to their ability to be easily removed from the building in one piece and allow full disassembly offsite.

The certification system and training programme that are the focus of this paper are based on this evaluation scheme.

2.2 Material recovery assessment in building certification systems

Environmental certification for buildings and building industry professionals has become common practice for projects of various types over the last two decades or so. At the building scale, four rating systems currently hold a majority of the global market: Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Deutsche Gesellschaft für Nachhaltiges Bauen e.V. (DGNB) and Bewertungssystem Nachhaltiges Bauen für Bundesgebäude (BNB). Given the commercial inclination of some of these rating systems and the relatively minor role that recycling and reuse play in shaping economic viability in the built environment, material recovery is generally not prominently featured. Its most recent release, LEED v4 (USGBC 2014) includes a focus on material consumption. Its 'Materials and raw materials' category allocates credits for disclosing material environmental impacts via environmental product declarations. Further credits can be obtained through the specification of recycled or reused materials. Also, a quantitative life-cycle assessment study indicating material environmental impacts is rewarded. LEED v4 also requires a waste management plan to minimise construction and demolition waste as a minimum requirement.

The international BREEAM system for new construction (BRE 2016) contains most of its recycling related credits in the 'Materials' and 'Waste' categories. A life-cycle assessment study is integrated into the system; however, its results do not influence the amount of credits gained. The 'Responsible sourcing of construction products' criterion awards projects for using BES 6001 (a BRE-developed standard for responsible material sourcing for building products), FSC (Forest Stewardship Council) and EMAS (the European Union's Eco-Management and Audit Scheme) certified products. Additionally, improving material efficiency by using recycled materials or reducing material consumption is rewarded under the 'Material efficiency' criterion.

The DGNB New Buildings system (German Sustainable Building Council 2018) has a strong focus on closing material cycles with 10 criteria referring to recycling and reuse activities. The use of recycled or reused materials is awarded in the 'Responsible use of resources' criterion. Responsible sourcing is included in that criterion as well. Unlike some of the other systems, the DGNB takes design for end-of-life material recovery into consideration. The criteria 'Selection of easy to recycle construction materials' and 'Easy to recover building structure' provide indicators to assess end-of-life material recovery potential based on whether or not components can be removed from the structure in their entirety without damage or inter-contamination of materials. The system also provides projects with a spreadsheet tool featuring a catalogue of structural elements and their weight based on their replicability and the proportion of the area they represent. To date, the system does not consider or reward end-of-life cost reduction—where the profits that could be made from reselling recovered materials is taken into account.

The German Federal Ministry of the Interior, Building and Community's (2015) assessment is based on a life-cycle approach where the construction, use and end-of-life phases are all considered, with the explicit exception of post-end-of-life recovery—which is beyond the scope of assessment for this certification system. In the construction phase, the 'Optimum use of recycled materials on building sites' and 'Building site/construction process' criteria require careful planning of waste and recycled content management. In the end-of-life phase, criterion 4.1.4 looks at three evaluation domains: dismantling, separation and recovery. The system provides a tabular catalogue of common components, their main layers and an evaluation of their expected end-of-life performance based on those three indicators. The components are then graded on a scale ranging from 'very unfavourable' to 'very favourable' (**Table 1**).

The described certification schemes also provide professional certification for design and construction professionals. In all cases, the certification allows an accredited professional to sign on and submit a project for evaluation by the respective green building council. In order to obtain professional certification, applicants are required to undergo online or face-to-face training and to pass an examination. Additionally, accredited workers are required to engage in continuing education activities in order to maintain their credentials.

Although some of the surveyed systems offer credits that relate directly to the act of dismantling and material recovery, for the most part they lack an understanding that successful material recovery is dependant not only on physical but also on economic and technological considerations. In order to truly facilitate end-of-life recovery, there needs to be a market as well as appropriate technologies to recycle or remanufacture a given material or component. There seems to be a clear need for both building and worker certification that takes into consideration the unique systemic challenges that are part of material recovery.

Table 1: Material recovery foci in common building rating systems.

Certification system	Construction and use				End of life				
	RM	MS	WM	LCA	EoLM	DfD	Dism	MSep	EoLC
LEED	■	■	■	■					
BREEAM	■	■		■					
DGNB	■	■			■	■			
BNB			■	■	■	■	■	■	

Note: DfD = design for disassembly; Dism = dismantling; EoLC = end-of-life cost; EoLM = end-of-life material recovery; LCA = life-cycle assessment; MS = material sourcing; MSep = material separation; RM = recycled/reused material utilisation; WM = waste management plan.

The barriers to material certification in the building sector show that at an industry level, three factors impede certification development and implementation:

- the fragmented structure of the industry and an absence of unified supply chains in particular (Futas *et al.* 2019)
- the lack of a single, clear and implementable framework for material deployment (Toxopeus *et al.* 2015) and
- a general inability to embrace rapid change (Pomponi *et al.* 2018).

The barriers to actual training indicate a lack of training to be itself a barrier to implementation of sustainable building practices (Chan *et al.* 2018; Gou *et al.* 2013). It is therefore safe to assume that an increased demand for sustainable practices such as material reutilisation would ease barriers to developing and executing material-recovery training programmes.

2.3 Worker training

End of life in the built environment comprises of two main modes of operation: demolition and deconstruction (Thomsen *et al.* 2011). The two differ in their approach to the ratio between removal time and output quality. Broadly, demolition techniques aim to remove the existing construction as quickly as possible, regardless of the condition of the waste output produced. Deconstruction techniques are geared towards salvaging reusable components in the best condition possible, regardless of the time it takes to do so (Napier 2011). Although demolition accounts for the vast majority of the end-of-life industry globally, in the context of this paper deconstruction is far more relevant. In most cases deconstruction requires only simple hand-held power tools and little formal education. It tends to be more accessible to unskilled workers and is composed of small community-based businesses (Grothe & Neun 2002). It should be noted that this insight refers primarily to residential deconstruction in the American Northeast context, where typically construction of single-family homes relies on timber framing. In other geographical contexts and building scales, deconstruction might involve sophisticated tools and require advanced skills (Jaillon & Poon 2014). Nevertheless, deconstruction training offers meaningful insights for material-recovery training in general. Deconstruction training can be roughly broken into two major subcategories that also correspond to target user groups: deconstruction contractor training and salvaged material retail operations training.

In most countries, deconstruction (unlike demolition) is not supported by a national federation, so deconstruction contractor training tends to be decentralised and community based. As deconstruction is not as regulated as demolition, the content of training might vary. But larger contractors tend to offer similar training content and scope. The Reuse People of America (TRP), which is one of the largest deconstruction contractors in California, for example, covers the following topics in its contractor training programme (TRP 2020):

- *Safety*: An introduction to best practices for deconstruction site safety with an emphasis on structural stability and hazardous material handling.
- *Tools*: Common hardware for deconstruction activities with an emphasis on hand-held power tools.
- *Equipment*: Deconstruction support equipment for organising the jobsite and storing salvaged materials.
- *Layout of jobsite*: Positioning material collection and storage bins and securing efficient and safe site access for vehicles and workers.
- *Sequence of work*: Maximising material yield through a planned sequence that typically works inward from the skin to the structure.
- *Deconstruction techniques*: Key methods for separating materials and maintaining salvaged components intact.
- *Layered materials*: How to deconstruct layered envelope systems efficiently.
- *Debris handling*: Separation and handling of non-salvaged components.
- *Maintaining salvage values*: How to plan deconstruction activities based on protecting salvaged components with relatively high value.

- *Handling & shipping*: Onsite separation, labelling, storage and shipping of salvaged materials.
- *Successful bidding*: Ensuring economic viability of deconstruction operations.
- *Identifying materials to be salvaged*: Pre-inspection of the property in order to maximise material yield from the project.
- *Identifying materials for recycling*: Finding recovery solutions for materials and components that are not fit for reuse.
- *Location and use of local reuse and recycling centres*: Mapping a return supply chain for all recovered materials and components.
- *Jobsite wrap-up*: Key steps for concluding a deconstruction job with an emphasis on handling components that are not designated for recovery (e.g. foundations).

The training for builder's merchants who sell salvaged material is slightly more institutionalised than deconstruction contractor training, mainly because these retailers are supported by larger national and international organisations. One such organisation is Habitat for Humanity, which runs a chain of salvaged material stores called ReStores (Habitat for Humanity 2020). This international non-profit organisation is committed to finding housing solutions for low-income families. Its chain of ReStores is meant to provide highly affordable home-improvement materials and items through reclamation and donation (Gresock *et al.* 2006). ReStores are owned independently and operated by local Habitat for Humanity organisations. The organisation offers two training workshops: one provides basic information about the field and the other provides advanced managerial content. The basic course covers the following topics:

- *Merchandising*: Strategising the type and scope of products to be sold.
- *Quality control*: Assuring that reclaimed materials are fit for direct reuse.
- *Safety*: Verifying that the products sold do not pose health hazards.
- *Store type*: The range of retail options for salvaged materials.
- *Procurement*: Strategies for obtaining reclaimed products for retail.
- *Receiving*: Sorting, cataloguing and storing reclaimed materials for reuse.
- *Inventory*: Management strategies for reclaimed product inventory.

The advanced course covers the following topics:

- *Manager roles*: Operational aspects of reclaimed material retail.
- *Warehouse characteristics*: Ideal location, size and format for storage.
- *Staffing*: Human resources structure for salvaged material retail.
- *Handling payments*: Receiving and processing payment as a non-profit.
- *Insurance*: Liability and protection aspects for salvaged material retailers.
- *Donations*: Handling material donations from deconstruction contractors.
- *Advertising*: Promotion strategies for salvaged material retail.
- *Budgeting*: Allocating funds for operations and business development.

In summary, although training structures exist for material recovery, they tend to lack a holistic supply chain view of the sector. A holistic approach would include jobsite operations and retail as well as upstream issues (e.g. recovery-oriented assembly) and downstream issues (e.g. remanufacturing of reclaimed components and construction techniques with reused materials). This gap suggests there is a need for structured material recovery training that follows the recovery process from design to redeployment. **Figure 1** shows a synthetic analysis of the recovery certification and recovery training themes discussed in this section along with the recovery professions to which they relate.

3. Proposed certification and training

As the literature review suggests, material recovery certification and training currently consist of a patchwork of rating system credits at the product end and local training programmes that cover only a fraction of the supply chain at the workforce end. In order to frame material recovery as an established and specialised vocation, there is a need for a unified certification and training structure that sees material recovery as a process that begins with design for recovery, continues with production and assembly, followed by disassembly and remanufacturing, and concludes with resale and reassembly. Each step implies a separate sub-profession and thus should include a separate training module. The sum of all modules would amount to full material-recovery vocational training.

Given the focus of this paper is on vocational workers in construction and deconstruction activities, the role of design activities is not discussed here.¹ This is not to understate the importance of design for recovery in determining to a large extent the quantity and quality of recovered material yields in products and buildings. Ample evidence shows that DfD and material recovery is a key component in achieving circularity (Harjula *et al.* 1996; Bogue 2007; Rios *et al.* 2015; Minunno *et al.* 2020). The existence of good design for recovery practices is assumed in this discussion as an underlying condition for recovery-oriented construction and deconstruction work.

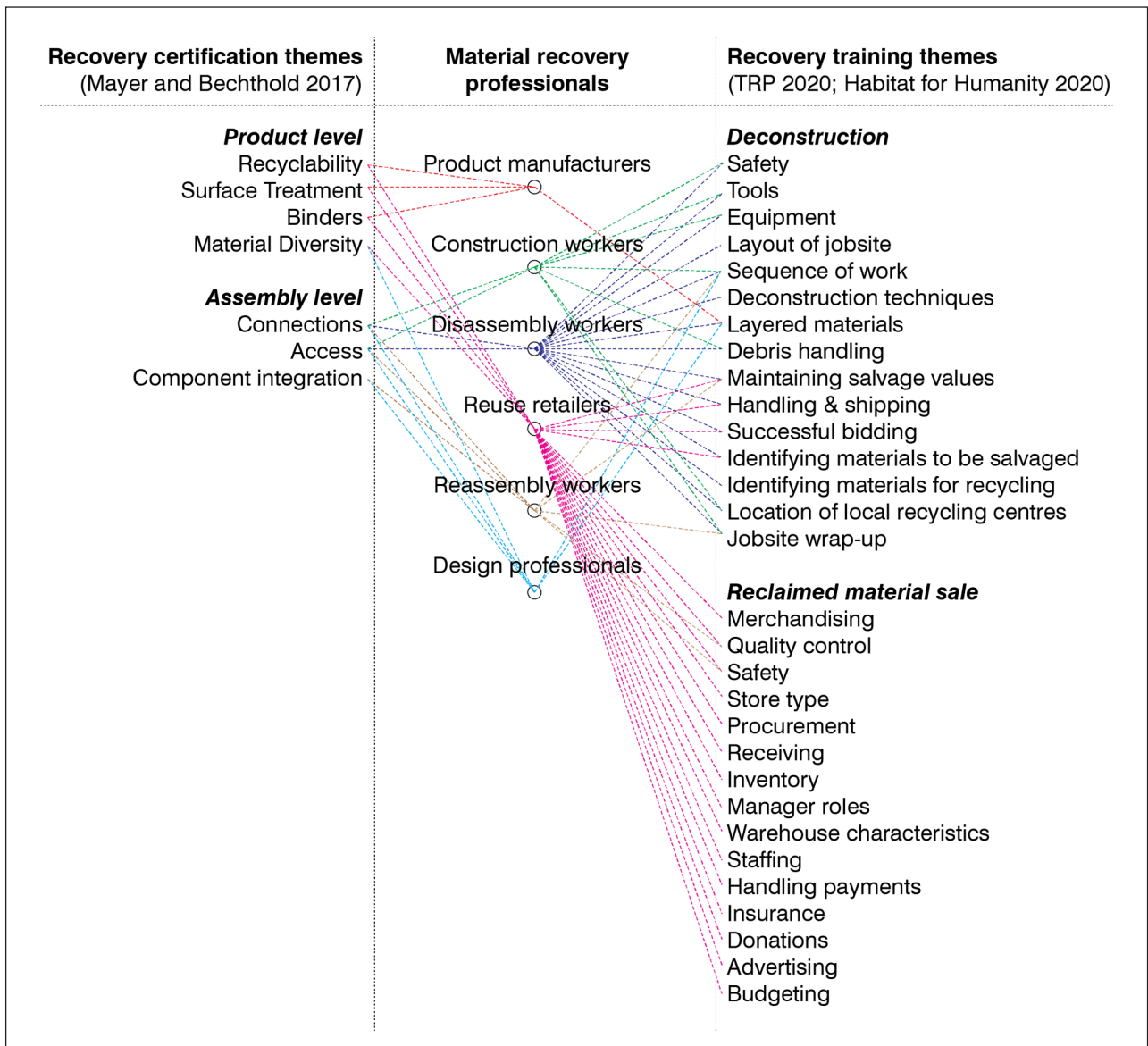


Figure 1: Synthetic summary of the themes showing the connections between certification, stakeholders and capabilities.

3.1 Certification

Certification is typically based on standardised assessment methods. The literature review shows there are currently no standardised assessment methods for material recovery potential in buildings. The proposed certification system, therefore, needs to be based on a peer-reviewed assessment method that has not yet been standardised. In light of its inclusive view of both material and assembly considerations in the context of material recovery, the certification ecosystem proposed here builds on the assessment framework developed by Mayer & Bechthold (2017). As the literature review indicates, their framework is comprised of two parallel assessment modules: one for products (materials) and one for assemblies. The modules define calculation methods that output a material recovery potential index (MRPI). The index ranks products and assemblies on a scale of 0.0–1.0, where a higher result indicates a stronger recovery potential. Given the difficulties demonstrated in the literature in conveying complex rating systems to a wide user audience, the proposed certification is communicated through labelling.

Studies suggest that environmental declaration labelling plays an important role in encouraging responsible consumption and ultimately reducing environmental impacts (OECD 2005). Primarily, eco-labels empower consumers with an ability to compare competing products impartially on a specific environmental basis. In the case of the MRPI, the focus is on recovery potential. Eco-labelling initiatives can be differentiated on two initial grounds: whether the labelling is mandatory or voluntary, and if the certification is granted independently (Horne 2009). Voluntary labelling, which includes most environmental labelling schemes as well as the MRPI, is broken down by the ISO into three types:

- Type I: Multi-product labels, such as the German Blue Angel label.
- Type II: Self-declaration manufacturer-specific labels, such as ‘recycled content’ or ‘CFC-free’ (chlorofluorocarbon).
- Type III: Industry-wide report card-format labels, such as food nutrition value labels.

While type I provides the simplest form of comparison between products (labelled versus unlabelled), type III offers the most detailed rating, allowing consumers to make highly informed decisions. By including both a single general score and individual category scores in one label, the MRPI product and assembly labels aim to be simple, legible and informative.

3.1.1 Product label

The product label intends to convey two layers of information. As **Figure 2** shows, at a first glance, the label is intended to provide a total product overview as well as a graphic bar overview of each category's performance. A second, detailed reading provides individual scores for each category and a verbal description of the total score: 0.00–0.25 = *Non-recoverable*; 0.25–0.50 = *Recoverable*; 0.50–0.75 = *Highly recoverable*; and 0.75–1.00 = *Recovery leader*.

3.1.2 Assembly label

The assembly label is meant to reflect certain spatial properties, namely component layering, connections, and ease of access for maintenance and end-of-life recovery operations. Similar to the product label, the assembly label aims to convey general score information and problematic category scores first, while revealing detailed information at a closer look. As **Figure 3** shows, the spatial configuration of the assembly is represented in the label as a stack, where connection types and their respective scores are sandwiched in between layers representing the various products making up the assembly. This form of representation is meant to draw attention easily to problematic constituents and connections within the assembly. Separately, the four main scores comprising the index are featured: Total product score, Connection type score, Access score and Level of integration score.

3.2 Training

Following the distinction the certification draws between products (or materials) and assemblies, the proposed training module addresses three phases: manufacturing, construction and disassembly. Each phase involves a range of professionals. The training scheme targets five recovery-oriented vocational domains: product manufacturers, construction workers, disassembly workers, reclaimed material retailers and reassembly workers (**Table 2**).

3.2.1 Manufacturers

Material and product manufacturers would be trained in five general topics that are closely linked to the guiding criteria for the MRPI product assessment:

- *Recoverability*: Transitioning to manufacturing materials and products that have an economically viable recovery market.
- *Recyclability*: Working with materials that are highly recyclable. This is closely tied to whether or not low-impact-recovery technologies are widely available for this specific material or product.

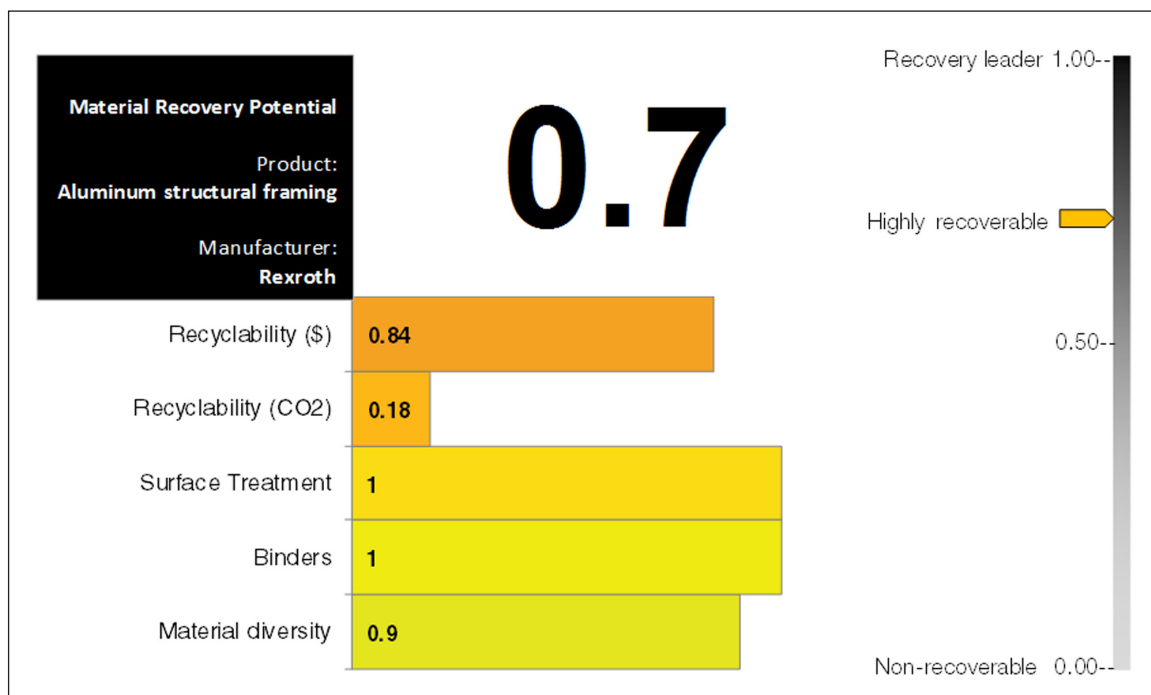


Figure 2: Material recovery product index (MRPI) product label.

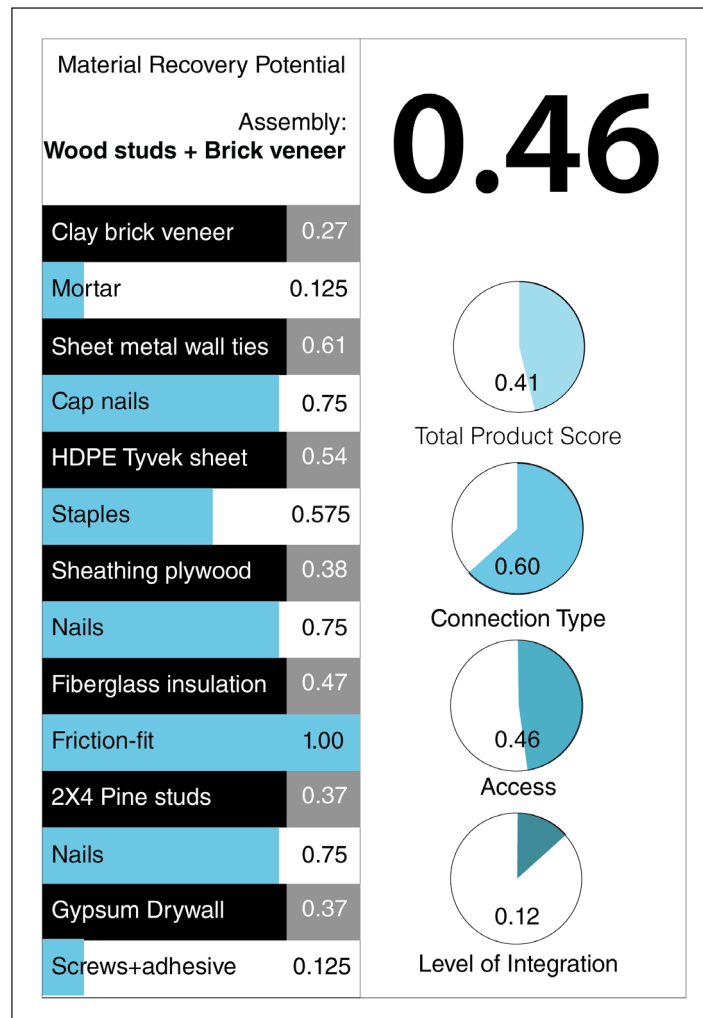


Figure 3: Material recovery product index (MRPI) assembly label.

Note: The assembly configuration is represented on the left; general scores appear on the right.

- *Surface treatment:* Paint and coatings are highly problematic for material recovery operations. Transitioning to minimal and detachable coatings is key to achieving higher recovery rates.
- *Binders:* In products, non-detachable binders drastically reduce recovery rates. Manufacturers who wish to produce recovery-oriented products need to transition to detachable binders.
- *Material diversity:* Typical building products contain a range of material groups within one assembly. Less material diversity in products increases the likelihood of recovery. Recovery-oriented manufacturers should transition to products with less material diversity.

3.2.2 Construction workers

Recovery-oriented construction differs from standard construction substantially, mainly because the emphasis shifts from aiming for a finished product to facilitating its eventual disassembly. Training for recovery-oriented construction workers follows the MRPI assembly assessment criteria and focuses on the following topics:

- *Sequence:* Recovery-oriented construction needs to take into the consideration the disassembly sequence of each component. Components need to be installed in such a way that their eventual removal is logical and simple.
- *Access:* Most disassembly operations are manual. Therefore, enabling easy manual access to connections should be a top priority for recovery-oriented construction workers.
- *Legibility:* More often than not, deconstruction professionals need to take apart assemblies without any guiding documentation. In these situations, assemblies that allow full legibility of the connections and disassembly sequence ensure efficient disassembly. Recovery-oriented construction workers should do what they can in order to facilitate this legibility.

In addition to these themes, workplace health and safety are primary concerns throughout the entire training scheme. In the case of recovery-oriented construction, dry joining methods (which in turn minimise cross-contamination and facilitate disassembly) pose a major handling risks on the construction site.

Table 2: Proposed training themes.

Vocation	Life-cycle phase				
	Manufacturing	Construction		End of life	
	Product manufacturers	Construction workers	Disassembly workers	Reuse retailers	Reassembly workers
Training content	Recoverability	Sequence	Sequence	Inventory management	Flexibility
	Recyclability	Access	Disassembly depth	Promotion	Sequence
	Surface treatment	Legibility	Labelling and storage		Labelling
	Binders	Jobsite preparation			
	Material diversity				

3.2.3 Disassembly workers

Disassembly differs from deconstruction because it takes apart assemblies that have been designed with material recovery in mind. Therefore, training for disassembly workers differs from deconstruction training. Following the MRPI product and assembly assessment criteria, this training focuses on the following topics:

- *Sequence*: Meticulous planning of the disassembly sequence in a given building is crucial for maximising material yield. A carefully planned disassembly process will also prevent damage to components and materials due to an incorrect disassembly sequence.
- *Disassembly depth*: Disassembly depth is defined as the ratio between the amount of labour required to retrieve a given component and the component's value (Giudice 2010). This value is not necessarily monetary. It can also be an environmental value, particularly in cases where recycling or remanufacturing is more environmentally harmful than new production. Disassembly depth is an important part of disassembly training as it ensures an environmentally benign process.
- *Labelling and storage*: Given that disassembly frequently leads to direct reuse of components and materials, the organisation of retrieved components in a way that would allow them to be reused easily is a key to a successful disassembly job.
- *Jobsite preparation*: The main foci in jobsite preparation for disassembly differs from that of deconstruction mainly in the fact that in disassembly an emphasis is put on retrieving components in a near-perfect condition. In order to do so, any intervention on the site (such as scaffoldings) should be planned in a manner that does not lead to any components being damaged.

Regarding jobsite preparation, some parts of the world currently require a pre-demolition audit for any building slated for removal. The European Union Waste Audit guidelines outline mandatory pre-demolitions inspections that are meant to guarantee the quality of material recovery and ensure sustainable treatment or disposal of non-recyclable waste (Wahlström *et al.* 2019; Sáez & Osmani 2019). Those requirements substantially influence deconstruction and material separation activities on site. The proposed training programme complements these existing practices by training professionals to separate components and materials with direct reuse in mind. Unlike conventional audits where auditors primarily rely on visual inspection, material recovery auditing in buildings that are designed for disassembly would likely be conducted with detailed design documentation as well. Additionally, in order to minimise emissions and potential trade-offs between sustainable waste management (decontamination) and CO₂ reduction, end-of-life solutions for recovered materials in this training programme will take into consideration comparative studies between different options.

3.2.4 Reclaimed material retailers

What are the differences between retailers who stock reclaimed material from DfD buildings versus materials from deconstructed buildings? The main differences between the two are the volume and condition of the retrieved components. The quality of reclaimed components from a building designed for disassembly could be very close to that of new components. In addition, there would be more reclaimed components compared with a deconstructed building. The main competitors to these retailers might not be salvaged material retailers but rather prefabrication retailers.

As mentioned above in section 2, the reclaimed material retail industry is decentralised in comparison with the construction material retail industry. Accordingly, supply chains for reclaimed materials are also typically informal and unpredictable in terms of volume and quality. Even Habitat for Humanity's Restore, the largest nationwide retail chain for reclaimed materials, relies on material donations from local deconstruction contractors (Habitat for Humanity 2020). Given that the volume and quality of materials reclaimed from DfD buildings would be substantially higher than materials reclaimed from other building types, retail centres for this new material stream can be expected to be larger and more centralised in terms of supply chain management. This difference will be reflected in the training scheme for retailers.

Research shows that the four issues most crucial to clients when choosing a reclaimed product are (in descending order): functional quality, aesthetics, customisation and sustainability (Espinoza & Pitti 2019). Training would therefore focus on paying attention to these aspects when purchasing reclaimed materials from suppliers. Significant health and safety risks are associated with the storage and handling of reclaimed materials. A substantial part of this training scheme would be dedicated to reviewing and mitigating these risks.

Sustained exposure to stresses (such as weather and load conditions) means reclaimed building components often experience performance degradation. In many cases, their structural or thermal properties are altered, which renders components unsafe or otherwise unfit for immediate reuse. Regulation requires end-of-life materials to undergo a remanufacturing, quality assurance and recertification process in order to be considered suitable construction products (Hobbs & Adams 2017). Reclaimed components (unless downcycled) would need to undergo remanufacturing and recertification before resale and reuse in building applications.

3.2.5 Reassembly workers

Reassembly differs from virgin construction in that given components are in limited numbers and not always in a virgin condition. This might require implementing ad hoc solutions on the jobsite and working with higher dimensional tolerances. For this reason, health and safety issues are a primary concern in this sector and would be present in each of the training aspects described below. This training module focuses on the following topics:

- *Flexibility:* Working with reused or remanufactured components requires some creativity in terms of the condition and dimensional tolerances of parts, particularly connections. These components are also unpredictable in terms of structural performance and therefore their introduction into buildings needs to be undertaken while taking extraordinary safety measures. Reassembly workers need to acquire these skills.
- *Sequence:* Reassembly must work with sequence logics that are appropriate to the components being used. This sequence might not always be the most natural one for the new use of these components. Reassembly professionals need to be able to negotiate these situations. Here as well, safety measures should be factored in when determining the right assembly sequence for reintroduced components.
- *Labelling:* Working with a limited inventory of existing components requires rigours management of labelling and distribution of components on the jobsite. Reassembly workers need to be aware of these challenges.

3.3 Certification and accreditation bodies

In order to assure consistency and quality control in the proposed certification and training programmes, this structure needs to include both a certification body and an accreditation body. Certification bodies are entrusted with issuing a written assurance (certificate) attesting to the fact that an assessed product or process have been audited and have met a predefined set of quality standards (Loconto *et al.* 2012). Certification bodies can be private or state-run third-party institutions, as long as they can maintain impartiality in the auditing process. Following these definitions, the certification body to be associated with the material-recovery apparatus described in this paper is envisioned to be a private entity with four roles:

- *Standards development:* Given the experimental nature of the system's roll out, further standards are expected to be developed as the system evolves.
- *Verification:* That the standards are implemented to ensure stakeholder compliance.
- *Certification:* Granting compliance certificates to stakeholders that are found to be in full compliance with the standards.
- *Auditing:* Ensuring continued compliance with the developed standards over the service lives of the certified products.

Accreditation bodies are charged with overseeing the work of certification bodies, particularly as it relates to standards development, certification and auditing. In the system proposed here, an accreditation body would ensure that individuals who are trained as material-recovery certifiers, auditors and standard developers will have received sufficient training in order to maintain the level of quality originally intended by the system's developers. This accreditation body would be run independently from the certification body and could be affiliated with an existing larger environmental accreditation agency.

4. Discussion

Once the case is accepted in principle for the need for the built environment to transition to a circular economy, the next step to realise the disassembly of buildings and reuse of components is a pilot programme involving an experimental implementation plan. This would create a roadmap of how a wider scheme could work and examine the ability of the proposed certification and training schemes to truly lead to a recovery-ready environment.

To start, the implementation should be limited in scale and open to experiment. This experiment will consist of a small-scale mock-up of the entire professional ecosystem that the certification and training cover. This will include a

Table 3: Experiment timeline.

Phase	Duration	Activity	Stakeholders	Deliverables
1	M 0–3	Mock-up design	Designers	Construction docs.
2	M 0–3	Manufacturer training	Trainers	Training certificate
3	M 3–9	Component production	Manufacturers	Components
4	M 9–10	Manufacturers interviews	Researchers	Report
5	M 6–9	Construction training	Trainers	Training certificate
6	M 9–12	Mock-up construction	Construction W	Constructed mock-up
7	M 12–13	Construction interviews	Researchers	Report
8	M 9–12	Disassembly training	Trainers	Training certificate
9	M 12–15	Mock-up disassembly	Disassembly W	Disassembled mock-up
10	M 15–16	Disassembly interviews	Researchers	Report
11	M 12–15	Retail training	Trainers	Training certificate
12	M 15–16	Retail operations	Retailers	Retail transactions
13	M 16–17	Retailers interviews	Researchers	Report
14	M 13–16	Reassembly training	Trainers	Training certificate
15	M 16–19	Mock-up reassembly	Reassembly W	Reassembled mock-up
16	M 19–20	Reassembly interviews	Researchers	Report
17	M 20–24	Data analysis	Researchers	Final report

Note: M = month; W = vocational workers.

series of physical structures designed for disassembly. Manufacturers who supply the components for the structures will undergo a manufacturer-training programme. Other stakeholders (construction workers who will put the structures together, the disassembly crew, the material retailers, and the reassembly professionals) will also undergo training. Throughout this process, participants will be interviewed regarding whether or not the training has proven to be beneficial. The structures will be assessed to determine whether the disassembly and reassembly processes have been satisfactory.

Currently the present author is in communication with a municipality in the autonomous region of Castilla y Leon, Spain, to secure a host for this experiment. If successful, the experiment could lead to broader rollouts of the system regionally and nationally. **Table 3** shows a breakdown of the activities, their duration and the responsible stakeholders within this experiment.

Several barriers may block the wider implementation of the certification and training schemes. First, clients have a limited set of legal and economic incentives to transition to design and construction for recovery. This trend is troubling for recovery-oriented certification and training as it implies a limited audience. Second, material recovery in the built environment is still far behind other consumer products in terms of public acceptance. Developers, funders and building owners might not be as enthusiastic about concrete reuse as they would be about plastic recycling, for example. Huuhka & Hakanen (2015) list lack of demand, social norms, lack of awareness and inadequate material properties among other factors that make concrete reuse challenging in some contexts.

The absence of monetary incentives to recycle and reuse building components is problematic for recovery certification and training (Shen *et al.* 2017). Tipping fees in landfills are an existing incentive. Other incentives could include rewarding developers for including design-for-recovery principles in their projects, and rewarding building owners for opting for selective deconstruction over demolition. Given the long-use cycles characteristic of buildings, in most cases the developer has limited financial interest in the end-of-life fate of the building, particularly when the financial gains from selling components for recycling and reuse are minimal. This situation is problematic for recovery certification and training, particularly for building types with long service-life spans.

5. Conclusions

A certification system and a matching training programme were presented for material-recovery vocational workers. A certification and labelling system for material recovery in buildings and a matching vocational training programme were proposed. The certification programme focuses on product labelling for material recovery applications; and the training programme focuses on five vocational fields within this domain: product manufacturers, construction workers, disassembly workers, reuse retailers and reassembly workers. The separate training needs of each actor is

considered. Product manufacturers require training that relates to the recovery potential of their output from material and assembly perspectives. Construction workers require training that focuses on the challenges of putting together building assemblies so they can be easily taken apart in future. Disassembly workers require training that focuses on dismantling strategies for building assemblies. Reuse retailers require training that looks at procurement, storage and sale of reclaimed components. Reassembly workers require training that focuses on the construction of reclaimed components in various conditions. A training module is developed for each field and a phased implementation plan for the systems is described.

Note

- ¹ This is not to understate the importance of design for recovery in determining to a large extent the quantity and quality of recovered material yields in products and buildings. Ample evidence shows that design for disassembly and material recovery is a key component in achieving circularity (Harjula *et al.* 1996; Bogue 2007; Rios *et al.* 2015; Minunno *et al.* 2020). The existence of good design for recovery practices is assumed in this discussion as an underlying condition for recovery-oriented construction and deconstruction work.

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Competing interests

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