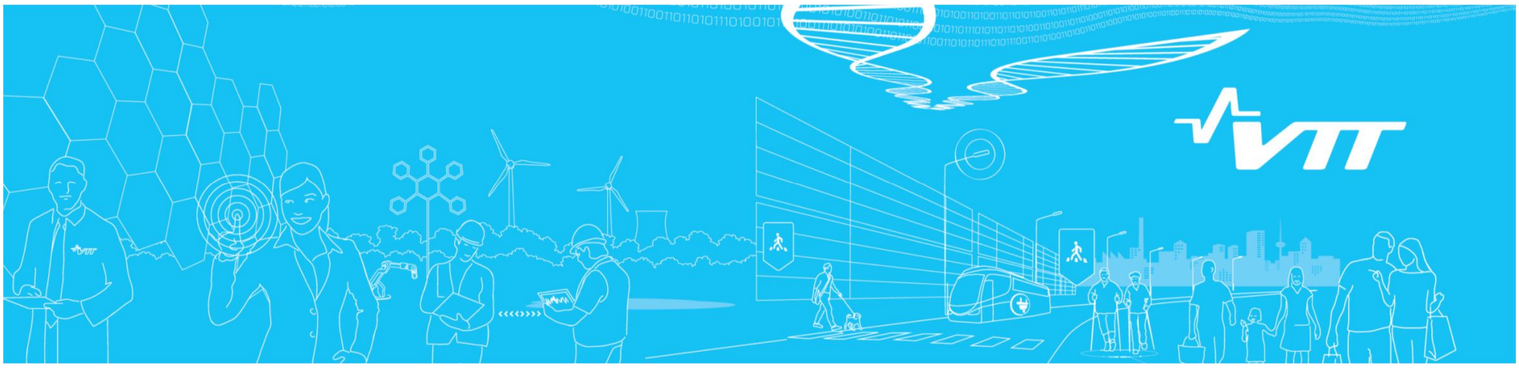

RESEARCH REPORT

VTT-R-01364-14

Barriers and opportunities of structural elements re-use

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Summary

The building industry consumes a great amount of natural resources and a significant part of waste production is contributed to building construction, maintenance and demolition. Moreover, production of building materials (even those with a high recycled content) consumes a lot of energy and produces harmful emissions. Therefore the efficient use of resources means that the durable building materials and elements produced from such materials should be used as long as possible regardless of the limitation of the building service life. There are many practical and technical barriers that prevent building elements re-using. The most challenging building parts are the load-bearing structures since they need to satisfy high quality and structural safety requirements.

This report identifies the most important barriers to successful re-use of building components and the opportunities that can be exploited in the re-using projects. It focuses on the steel and timber structural components; however, most of the principles presented in this report can be extended to other materials as well. The estimation of the environmental impacts of component re-using is presented in the report using standard LCA (life-cycle assessment) calculation of a single building element and dynamic MFA (material flow assessment) simulation of a small neighbourhood where the re-using policy is gradually being implemented.

Confidentiality	Public

Espoo 14.3.2014

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Distribution (customer and VTT)

Electronic (pdf) copy for the ReUSE project partners and VTT. The report will be accessible online from VTT's website and the project site.

Preface

This report was created within the Ministry of the Environment research project ReUSE *Rakennuselementtien uudelleenkäyttö*. The project aims at C&D waste reduction, preservation of natural resources and overall decrease of environmental impacts of buildings by encouraging the re- use of the building components. It is closely related to the national programme promoting resource and material efficiency *Kestävää kasvua materiaalitehokkuudella*. The project is jointly funded by the Ministry of the Environment, VTT Technical Research Centre of Finland, Tampere University of Technology, Ekokem and Finnish Wood Research. The following members of the project Steering Group were appointed to supervise the implementation of the project goals:

Else Peuranen, Ministry of the Environment
Jaakko Lehto, Finnish Wood Research Oy
Toni Andersson, Ekokem Oy Ab
Ari Hynynen, Tampere University of Technology
Henna Luukkonen, Association of Finnish Local and Regional Authorities
Laura Majoinen, NCC Rakennus Oy
Eila Lehmus, VTT

In addition, five seminars are organized within the project for the broader audience including the External Advisory Group which consist of the representatives of the Finnish Concrete Industry Association, Finnish Forest Industries, Rautaruukki, Kuusakoski Recycling, Metsänkylän Navetta, Forssa Region Development Centre, City of Kotka, City of Lahti, Kouvola Innovation, Umacon, Finnish Environment Institute and Finnish Funding Agency for Technology and Innovation.

I wish to express my gratitude to the project sponsors and the members of the Steering and External Advisory Groups and other participant of the project seminars.

Espoo 17.3.2014

Petr Hradil

Contents

1. Introduction

A large quantity of waste is generated during the production of building components and after the building demolition. Construction and demolition activities in Europe are responsible for 40 - 50% of solid waste production which was estimated over 460 million tonnes per year in EU-27 (about 1.1 tonnes per person per year) excluding excavations [1]. It contains mostly minerals from the structures.

The construction sector also consumes about half of all natural resources extracted in Europe yearly, that have very high energy demands on their transformation into building products. It has been estimated that 40 - 50% of all extracted raw materials are transformed into building products. The construction sector uses vast amounts of energy in the first three stages of the production process: resource generation, resource extraction and intermediate product manufacture.

Therefore the focus of today's environmental policy is on the building end-of-life scenarios and material efficiency. Recycling and material re-use becomes the common practice, but it is not always environmentally efficient, and material separation of composite structures is very challenging.

Building elements have often longer service life than the building itself and are, therefore, suitable for recovery and re-use after deconstruction. However, component re-use is still not widespread practice because of technological and institutional barriers. Structural components are not usually designed to be re-used, even though they are designed for deconstruction in some cases.

1.1 Scope of the report

This report aims to evaluate the barriers and demonstrate opportunities in re-using of building structural elements. In this report the re-use term is defined as:

"the process when structural element is used again for the same structural purpose or another purpose in the built environment".

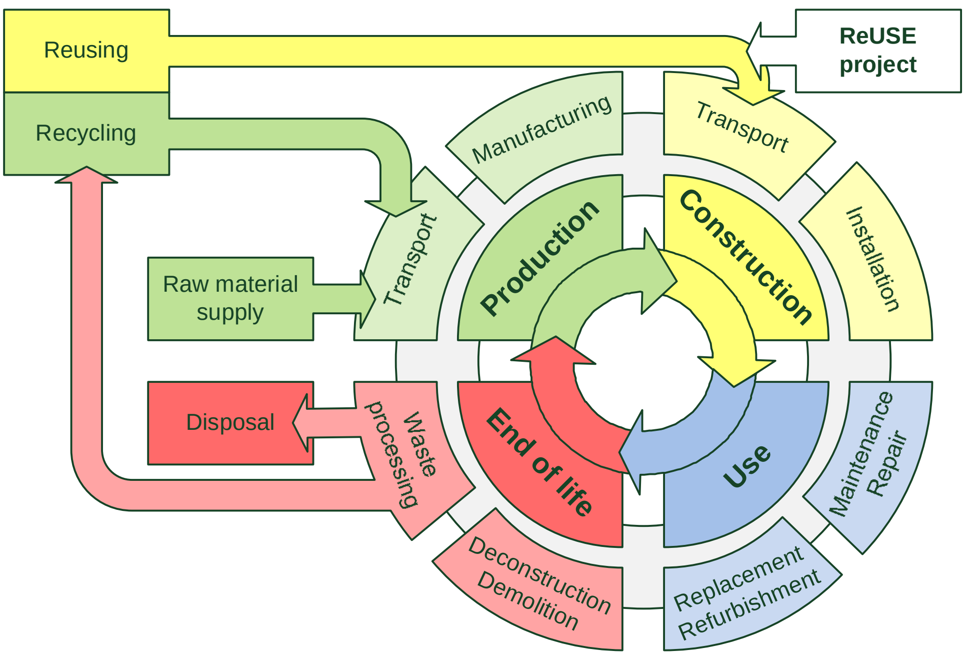

Figure 1. The scope of ReUSE project.

The structural elements are parts of the load-carrying structure of the building or the secondary elements such as cladding and roofing panels. As a special case the whole structure can be considered as a single re-usable object if it is removed to a different location in exactly the same configuration as it was originally designed.

The basic materials covered in the presented studies are divided into three groups:
(1) Timber - structural timber, engineered wood products (such as glulam, LVL) and wood based panels
(2) Steel - structural carbon and stainless steels, other alloys used in load-carrying structures may be also included
(3) Concrete - plain, reinforced or pre-stressed concrete elements or similar masonry products.

This report focuses mostly on steel and timber elements while the concrete buildings are discussed in more detail in the report provided by TTY.

1.2 Building materials efficiency in EU

The European Parliament and Council published the revised directive on waste in 2008 [2] laying down the measures to prevent the negative effects of waste generation and to set up the overall rules for waste management.

Waste is defined in this directive as "*any substance or object which the holder discards or intends or is required to discard*". **Re-use** means according to the directive "*any operation by which products or components that are not waste are used again for the same purpose for which they were conceived*". **Preparing for re-use** means "*checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing*".

In that sense, the scope of the project can be divided into two cases: (a) objects that are discarded, recovered and prepared for re-use, and (b) objects that are not discarded and their holder is arranging the re-use instead. It should be noted that the definition of "re-use" in the directive is rather narrow (see Figure 2) and components that are not becoming waste, but are used for the different purpose are not covered by the definition. In the first case (object becoming waste), the **end-of-waste criteria** have to be fulfilled for successful re-using, especially that "(a) the substance or object is commonly used for specific purposes, (b) a market or demand exists for such a substance or object, (c) the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and (d) the use of the substance or object will not lead to overall adverse environmental or human health impacts." The conditions (a) and (b) are common prerequisites for both re-using paths, but the conditions (c) and (d) do not have to be necessarily fulfilled if the object is not discarded and therefore not becoming waste.

The waste management policies should follow the hierarchy defined in the directive: (a) prevention, (b) preparing for re-use, (c) recycling, (d) other recovery and (e) disposal. However, when the overall impacts are justified by the life-cycle calculations, different hierarchy may be applied. The directive sets a goal of minimum 70% of construction and demolition waste (by weight) shall be prepared for re-use, recycled or recovered by 2020. Unfortunately, this goal does not take into account waste prevention, and therefore all the building elements re-used without becoming a waste decrease the percentage of recovered waste by decreasing the overall amount of waste. We recommend the directive to be amended to correct this drawback.

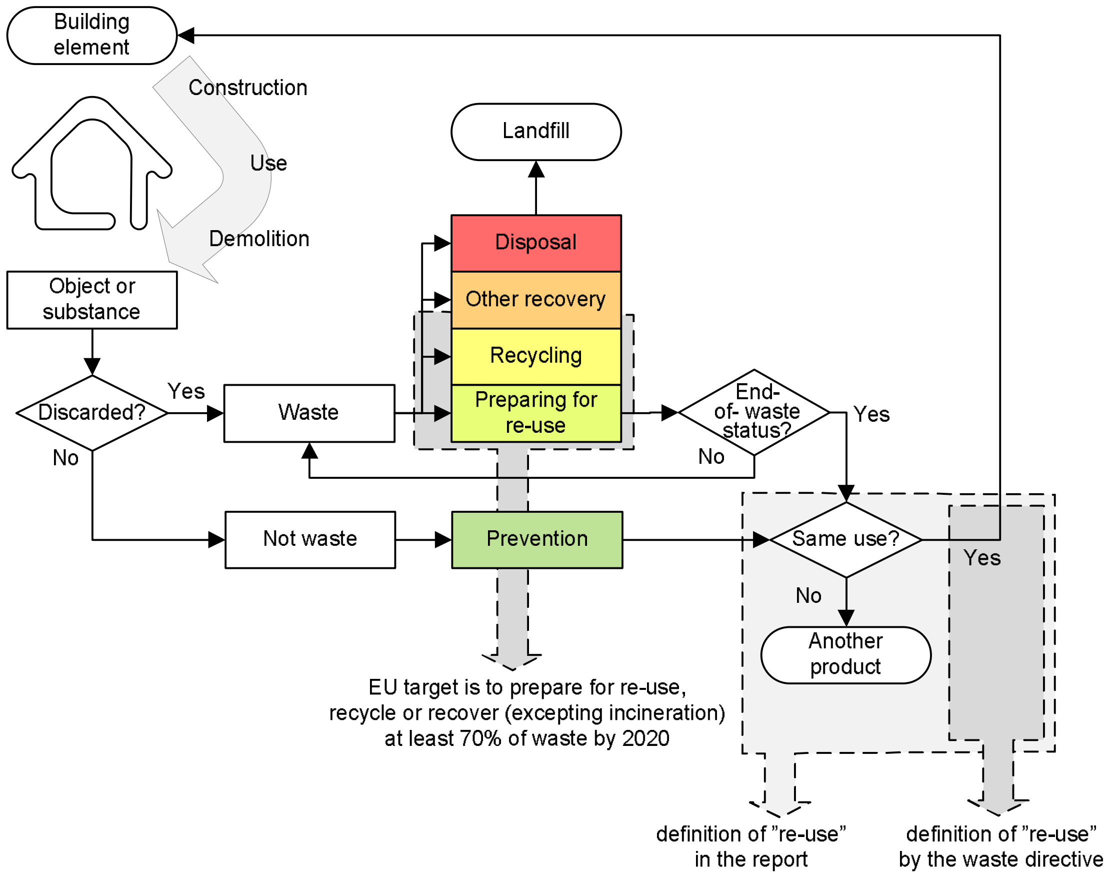

Figure 2. End-of-life scenarios according to the European Waste Framework Directive.

Construction and demolition waste is covered by the European Waste Catalogue (EWC), chapter 17 [2]. However, there is not clear provision for such objects that are combined from more materials such as reinforced concrete elements or sandwich panels. This indicates that the elements should be decomposed down to basic materials before EWC classification.

In 2011 the Communication from the European Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions was published [3]. The communication supports the milestones for 2020 to achieve the vision of sustainable Europe in 2050. The indicator of resource efficiency is so called "Resource productivity" (the ratio of GDP to DMC expressed in Euro/tonne). The Domestic Material Consumption (DMC) is "*annual quantity of raw materials extracted from the domestic territory, plus all physical imports minus all physical exports*" and the Gross Domestic Product (GDP) is expressed as Purchasing Power Standard (PPS) per capita according to the Eurostat definition. Extending the life of building components by re-using directly contributes to the lower DMC value.

1.3 Building materials efficiency in Finland

More than 4 tonnes of construction and demolition waste (CDW) per capita is generated in Finland every year. This waste contains over 75% of soil and other excavation which is normally not being accounted for. Therefore the estimated amount of CDW in Finland 1 ton per capita is below the EU-27 average of 1.1 tons per capita [4]. Approximately 77% of this waste is recovered according to the VTT's study [4], and 26% is re-used or recycled according to the BioIS estimation [1] based on 2009 data. The construction waste is there about 16% of the total C&D waste (excluding excavation).

Table 1. Construction and demolition waste recovery in Finland.

	fraction of CDW	**Sorted**	**Recovered from mixed waste**
Timber	41%	70% (29% of total)	18% (7.4% of total)
Steel	14%	75% (11% of total)	16% (2.2% of total)
Concrete	33%	70% (23% of total)	14% (4.6% of total)
		not sorted 38% of total	*landfilled 23% of total*

The problematic fraction of recovered waste is wood. According to the Finnish national strategy to recover 70% of CDW by 2016, energy recovery was included. That changed by 2013 when the European policy excluding incineration in the 70% target was adapted.

The Finnish Waste Act was revised in 2012 [6] adapting most of the European Waste Directive [2]. According to Eurostat data [5], the Domestic Material Consumption (DMC) in Finland is the second highest in Europe, and therefore the Resource productivity value in Finland 0.85 €/kg is way below the European average 1.72 €/kg (see Figure 3). This rather alarming indicator is partly the result of heavy industry, mining and forest depletion, but it also shows that there is a lot of space for improvement in Finland to reach more resource efficient countries like Sweden (productivity was 1.44 €/kg in 2011), Germany (1.85 €/kg) or Netherlands (2.84 €/kg).

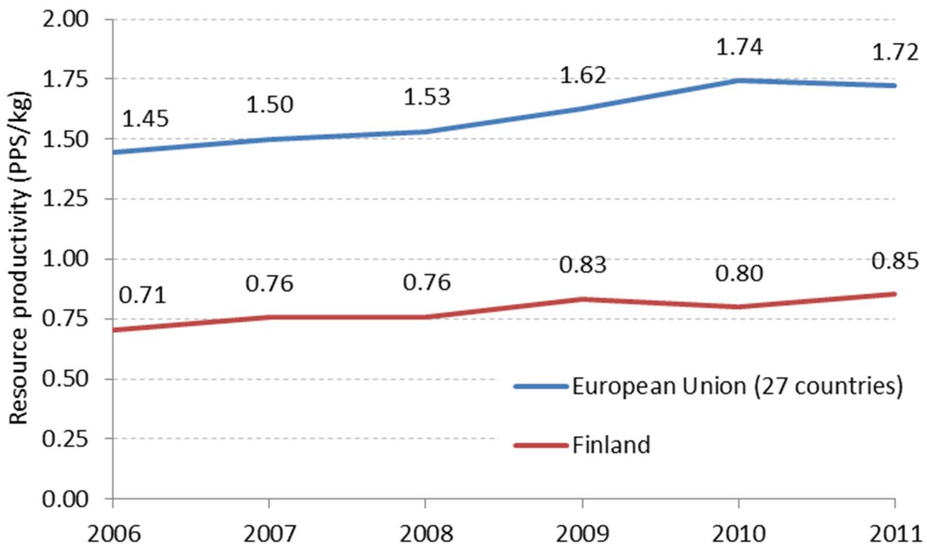

Figure 3. Resource productivity in Finland compared to EU-27 average calculated from Eurostat data [5].

2. Structural elements

There is a large variety of building elements that are part of load-carrying structure and can be re-used. Some of them are successfully salvaged from the construction and demolition waste, some are even re-used without becoming a waste. They can be divided according to their size and complexity into the following five categories (see Figure 4).

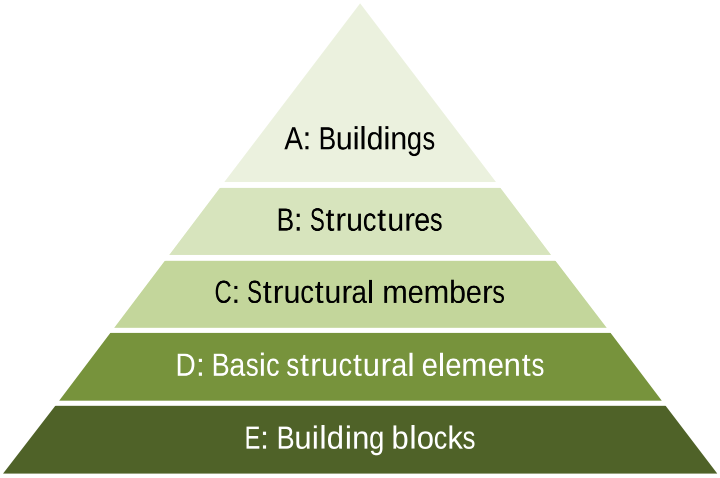

Figure 4. Re-usable structural element categories.

(a) Category A: Buildings

The whole buildings or standalone building modules can be technologically very easy to disassembly and re-use. However, the flexibility of new design is very limited. Typical representatives are:

Timber:	modular houses, sports halls, bridges, towers
Steel:	industrial halls, container buildings, bridges, towers
Concrete:	industrial halls, shopping centres, bridges

(b) Category B: Structures

Structures are typically composed of more structural members and need to be disassembled before re-using. They can be re-used in a different building design, but their spans and connection points should be carefully taken into account. Typical representatives are:

Timber:	glulam frames, roof trusses
Steel:	portal frames, truss girders
Concrete:	prefabricated systems for commercial, industrial or office buildings

(c) Category C: Structural members

Such elements are designed with well-defined shape and fitted connections. They can be composed from more materials or smaller elements. The members can be repaired if they are damaged during the disassembly, but their modification needs to be carried out in the workshop. Typical representatives are:

Timber:	sandwich panels, curved glulam beams, ceiling joists
Steel:	sandwich panels, hollow beams, beams with corrugated webs
Concrete:	pre-stressed beams and panels, ceiling joists, sandwich panels

(d) Category D: Basic structural elements

The basic elements can be used and designed alone to carry the load. It is possible to trim and cut such elements to smaller sizes on site to fit the new design. Typical representatives are:

Timber: straight solid or glulam beams, wood-based panels
Steel: hot-rolled and cold-formed sections, steel mesh
Concrete: reinforced beams, columns and panels, hollow-core slabs

(e) Category E: Building blocks

These elements are typically small and lightweight blocks that are joined together to form a bigger part. They can be re-used for a large variety of structural and non-structural applications. Typical representatives are:

Timber: boards
Steel: plates, bars and rods
Concrete and masonry: bricks and blocks

The basic definition of building element categories is summarized in Table 2. The conditions of the table don't have to be strictly fulfilled. However, the table provides the indication about the most important criteria in the decision about the element category.

Table 2. Re-usable structural element categories.

Elements in the category …	**A**	**B**	**C**	**D**	**E**
... resist all structural loads and transfer them to the foundations.	x				
… have a single defined purpose.	x	x			
… have a defined size (usually including connection points).	x	x	x		
… resist some loads (excluding small loads e.g. on cladding).	x	x	x	x	
… are part of a larger system.		x	x	x	x
… can be used for more than one purpose.			x	x	x
… allow for the easy (on-site) modification of their size.				x	x
… need to be joined together to form a load-bearing part.					x

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. Handling of heavy parts may be difficult; architects may require modification of the element; structural part has to be cleaned or separated from the other materials or it has to be disassembled and assembled again; the structural design has to be provided again; the element may be used in other application than in the previous building; the quality and geometry has to be re-evaluated because of the missing documentation (especially for smaller elements reclaimed from waste).

We have assigned to each of the categories the difficulty of each of the process as (0) not needed, (1) very easy, (2) easy, (3) moderate, (4) difficult and (5) very difficult (see Table 3).

Table 3. Re-using complexity evaluation.

	Category A	Category B	Category C	Category D	Category E
Handling	difficult	moderate	moderate	easy	very easy
Modification	very difficult	difficult	difficult	very easy	not needed
Separation/Cleaning	very easy	easy	moderate	difficult	difficult
Disassembly	difficult	difficult	easy	not needed	not needed
Redesigning	very easy	easy	moderate	moderate	moderate
Other application	very difficult	difficult	moderate	easy	very easy
Quality check	very easy	easy	moderate	moderate	moderate
Geometry check	very easy	moderate	moderate	moderate	easy

Figure 5 shows the average results of the evaluation. The current situation reflects the level of current practices in re-using (the categories below the line are already being offered for re-selling online). It is clear that Category E elements are the easiest ones to re-use which confirms the number of salvage yards worldwide. It is also possible to find Category D elements on internet shops, especially steel sections and structural timber. Interestingly, the largest categories tend to decrease the complexity, which is mainly due to the decreased need for modifications and redesigning when the whole structure is relocated to another place. Companies selling the whole "pre-used" buildings (Category A) already exist in some countries [7], [8]. Figure 5 also indicates that it is currently needed to overcome only few obstacles to start efficiently re-using elements of Categories B and C.

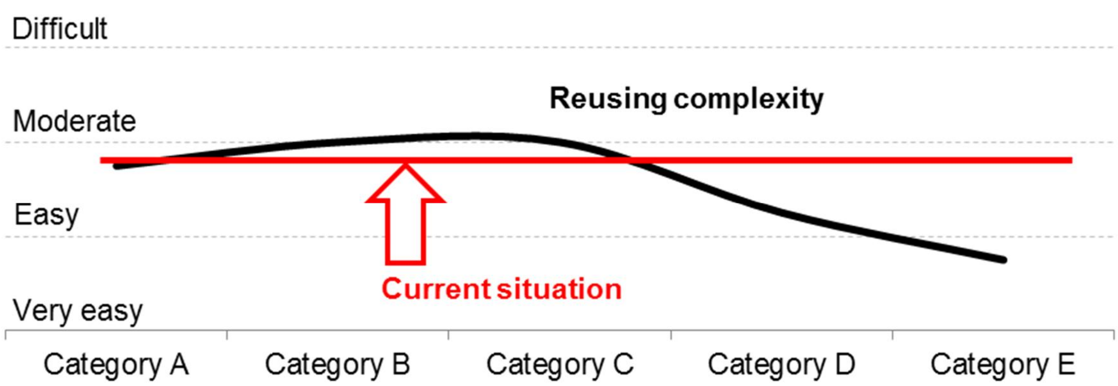

Figure 5. Re-using complexity average values.

3. Environmental certification systems for sustainable buildings

A great number of certification systems to assess the environmental quality of buildings was introduced during the last decades. They have a significant impact on many project decisions worldwide. The following chapter is based on the Simply Green publication [10], FORCE report [11] and the data provided by certification authorities on their internet portals. It summarizes the most important certification systems with the focus on building resource efficiency, materials and waste management.

The certification systems are being developed and promoted mostly by the national branches of the Green Building Council (GBC) or by the similar organizations. Finland's own certification system PromisE is outdated and not used anymore. Even though there is not any localization of the most common foreign certificates in Finland, it is still possible to assess the building by the international versions of several systems such as BREEAM, LEED, DGNB and HQE (see Table 4).

Table 4. The selected environmental certification systems.

Certification system	Country Launched	Localized versions in other countries	Applicable in Finland
BREEAM	UK 1990	Sweden, Norway, Germany, Netherlands, Spain, Austria	BREEAM International Bespoke BREEAM Europe Commercial
LEED	USA 2000	Canada, India, Cuba, Italy	via USGBC (US standards)
DGNB	Germany 2009	Denmark, Switzerland, Austria, Bulgaria, Thailand	DGNB International (EN/ISO standards)
GreenStar	Australia 2002	New Zealand, South Africa	-
Miljöbyggnad	Sweden 2009	-	-
HQE	France 2004	Brazil, Lebanon	HQE International (EN/ISO standards)
CASBEE	Japan 2002	-	-
IGBC	India 2007	Nepal, Bangladesh	-

It is very likely that the common European certification system will be developed in the near future because of the strong need to measure the progress towards the strategies for sustainable Europe [3]. It may be based on the existing schemes that are already applied to thousands of buildings (see Figure 6) and are following the European and international standards (see Table 4). However, it would be very difficult to harmonize certification procedures in Europe because the current methods are strongly depending on the local building practices and the climate.

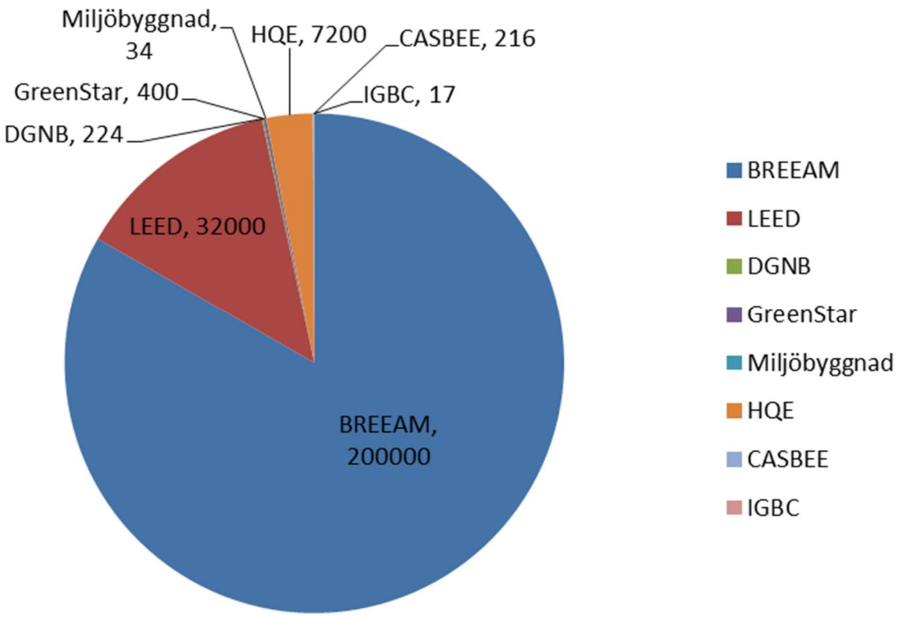

Figure 6. Number of certified buildings in 2012.

The focus of certification on various environmental categories is different in each system. Some emphasize indoor air quality; others are more energy or process oriented. Building resource efficiency can be represented by “materials” and “waste” categories that occupy altogether less than 20% in all of the selected systems [10] as demonstrated on Figure 7. The findings of FORCE [11] criticized that less that 5% of credits are attributed directly to life-cycle performance of building products and materials in the four major schemes (BREEAM, LEED, DGNB and HQE) and LEED does not utilize LCA results at all. The situation has slightly improved nowadays, since of the schemes (also LEED v4, GreenStar since 2013) can use quantitative measures of environmental impact (such as CO_2e originating from LCA calculations).However, only DGNB and HQE are fully harmonized with international standards (EN 15804, EN 15978 and ISO 14044). It is out of scope of this report to evaluate whether such low significance of materials reflects the real environmental performance of the building, but it is clear that it won’t significantly encourage the designers to consider re-using or recycling of materials and building components. This situation may change in the future since the new versions of the certificates are constantly being developed.

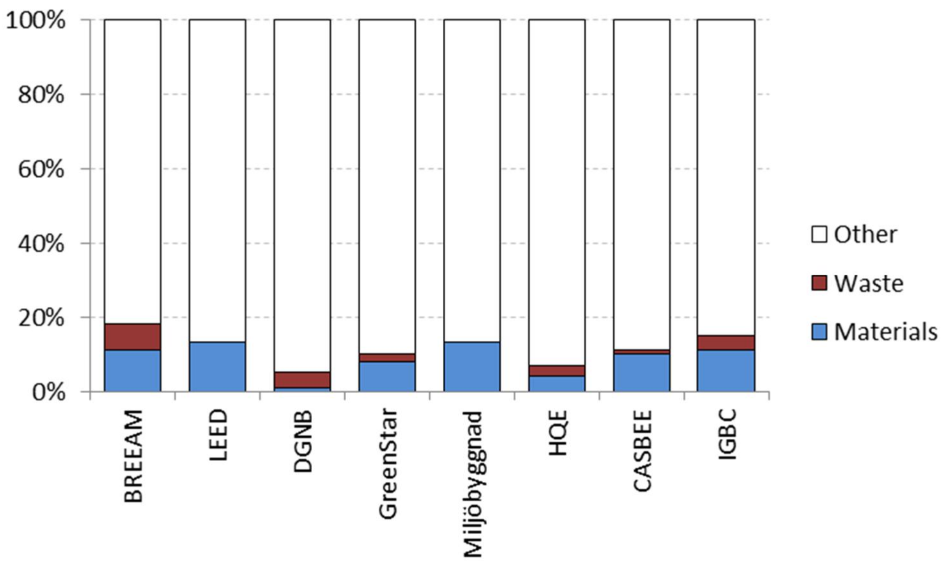

Figure 7. The proportions of "materials" and "waste" categories.

Another important issue is that the building stock is not equally covered by the certifications because many of the systems are strongly oriented to the certain types of buildings and some building categories cannot be assessed at all by several certification systems.

The largest environmental certification systems are presented in more detail in the following sections. The focus is on four major categories:

(a) Materials selection - the source and environmental impact of materials in the project
(b) Waste management - material separation, diverting from landfill and preparing for re-use
(c) Building re-use - the re-use of building elements or the whole structure
(d) Design - design for reuse or deconstruction and other design considerations contributing to the resource efficiency.

3.1 BREEAM

BREEAM was introduced in UK in 1990 by Building Research Establishment (BRE). In the BREEAM certification, the quantitative values of environmental impacts are combined with qualitative values resulting in a certain number of credits. The percentage of achieved credits is then multiplied by a weighting factor to contribute to the overall score. The sum of weighting factors is 1, and therefore the overall score is also expressed in % (see Table 5).

In practice, a building product receives the Environmental Profile Certificate that is based on BRE's own "Ecopoint" evaluation of the life cycle results (see Figure 8). Then the rating (from A+ to E) is allocated to this product during the BREEAM assessment. This rating scale may change dynamically based on the range of similar products on the market.

Materials selection - Materials with low environmental impact such as embodied CO_2e are preferred. Green Guide specifications, Environmental Product Declaration or LCA software can be used. Elements re-used in-situ obtain automatically the highest rating (A+) for LC impact, but are excluded from responsible sourcing assessment. This focuses on recycling and material re-use of new materials with the appropriate 3rd party certification (e.g. at least 80% of materials in building elements have to be responsible sourced).

Building re-use - Re-use of the structure (e.g. at least 80% by volume) and façade (e.g. at least 50% by vertical area) is assessed at the end of building life.

Waste management - Credits are awarded based on the volume (or tonnage) of waste diverted from landfill. Pre-demolition audit and site waste management planning is encouraged. Demolition and excavation waste is excluded from resource efficiency benchmark.

Design - Robustness of materials and building envelopes is assessed (protection from pedestrian and vehicular traffic) as well as the material optimization.

Table 5. BREEAM rating.

Percent	Rating
30%	Pass
45%	Good
55%	Very good
70%	Excellent
85%	Outstanding

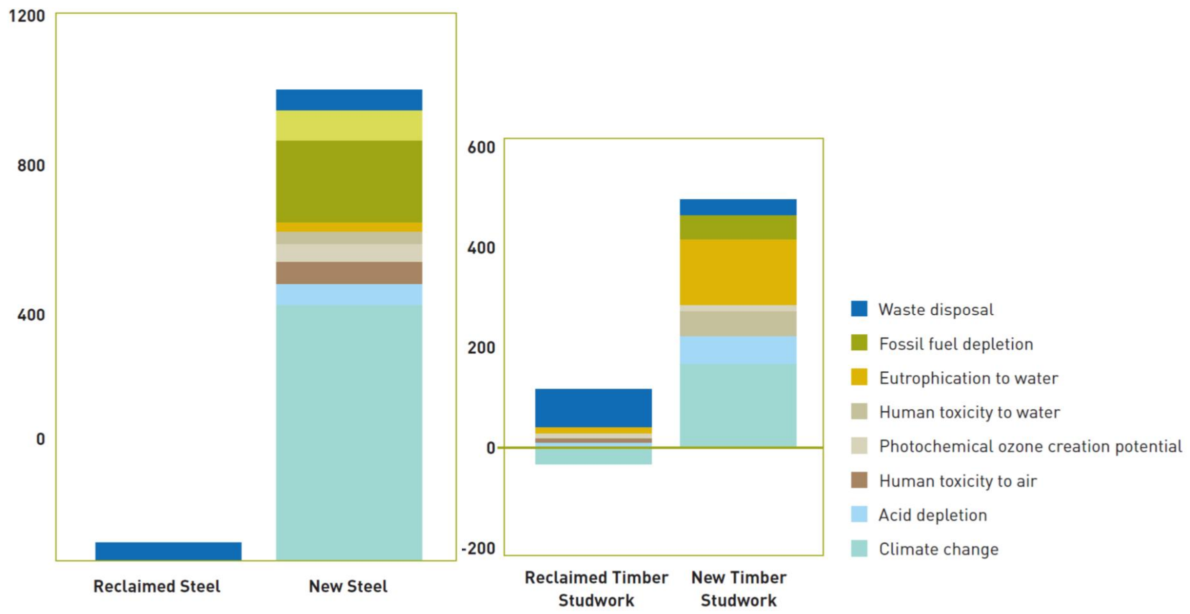

Figure 8. BRE environmental profile of reclaimed steel (99 t) and timber studwork (54000 m) expressed in Ecopoints (www.bioregional.com).

3.2 LEED

The Leadership in Energy and Environmental Design (LEED) certification is managed by the US Green Building Council (USGBC) since March 2000. Total 110 certification points (100 + 10 bonus points) can be achieved in this system and the rating scale follows the Table 6.

Table 6. LEED rating.

Points (LEED for homes)	Rating
40-49 (45-59)	Certified
50-59 (60-74)	Silver
60-79 (75-89)	Gold
80 (90)	Platinum

Materials selection - Reporting of raw materials consumption is one of the assessment criteria. Then the responsible sourcing is encouraged (by cost of the permanently installed materials). Re-using as well as recycling is regarded as 100% reduction of the cost. Moreover, if at least 25% of surface area is from re-used elements and materials, life-cycle impact criteria of LEED certification may be used. In some of the BD+C schemes, all wood is required to be non-tropical, reclaimed, re-used or USGBC approved.

Waste management - Points can be earned by diverting at least 50% of materials weight to at least 2 different streams or by total waste reduction to 12.2 kg/m^2.

Design - Waste management plans can increase the score in LEED certification. Material efficient framing (dematerialization) is for instance part of LEED BD+C Homes.

3.3 GreenStar

Materials selection - Recycling and material re-use is encouraged (at least 50% of recycled content in 1% or 2% of materials, at least 2% of project value should be re-used materials). Specific rules exist for concrete (at least 20% of substituted aggregate in structural elements), steel (at least 50% re-used or recycled) and timber (at least 95% re-used, recycled or FSC certified).

Building re-use - Re-use of the structure (by volume) and façade (by vertical area) is assessed at the end of building life. This idea is similar to BREEAM assessment.

Design - Points are awarded for design for disassembly (at least 50% of the area or 95% of the façade has to be designed for disassembly) and high material utilization (significant reduction of building materials when the function and integrity is maintained).

Table 7. GreenStar rating.

Points	Rating	
10-19 p	☆	
20-29 p	☆☆	
30-44 p	☆☆☆	
45-59 p	☆☆☆☆	Best practice
60-74 p	☆☆☆☆☆	Australian Excellence
75+ p	☆☆☆☆☆☆	World Leadership

3.4 DGNB

The German Sustainable Building Certificate DGNB was established by German Sustainable Building Council in 2009 and it is considered as the second generation certification system. Even though only small number of buildings has been certified since its introduction, it is compatible with the new European legislation, and therefore it can be easily adopted for use in EU member countries.

Table 8. DGNB rating.

Percent	Rating
50%	Bronze
65%	Silver
80%	Gold

The assessment criteria are based on the ecological, economical, socio-cultural, technical and process quality. The quantitative life-cycle results are based on the German Ökobau.dat database or DNGB's own database called ESUCO that has the ambition to serve as the European reference database. Those results are multiplied by EGNB's own weighting factors to contribute to the overall score for the ecological quality assessment.

The quantitative impacts of material production and disposal are usually less that 25% of total impact. They contribute to 7 out of 11 categories in environmental quality assessment of DGNB which occupies 22.5% of the total rating. Therefore the changes of environmental impact due to material sourcing and waste treatment of a building component have almost no contribution (less than 0.1%) to the overall results of DGNB certification [11].

4. Business concepts

The following scenarios demonstrate the basic concepts of transferring the ownership and responsibility of re-used elements in relation to their physical flow from producer to contractor, owner, contractor and eventually the new owner.

(a) Re-using via salvage yards - The most common way of re-using especially smaller elements is by selling them after sorting and cleaning to the salvage yard where they are stored and offered for another use (Figure 9). The role of salvage yard can be also taken by the recycling companies. This approach is suitable for basic elements such as wood framing, steel sections, boards and some common types of structural panels.

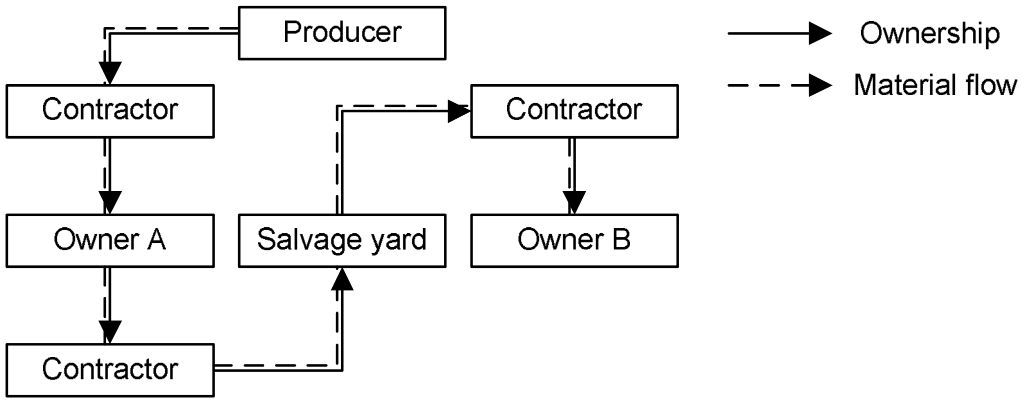

Figure 9. Re-using via salvage yards.

(b) Direct re-selling - When handling more complex or unique building elements, or the whole structural systems, the building owner may decide to find the suitable application directly. In that situation the storing and transport costs are usually lower; however, such cases are very rare due to many limitations (Figure 10). This approach is suitable for the structural systems such as industrial hall frames or roof trusses.

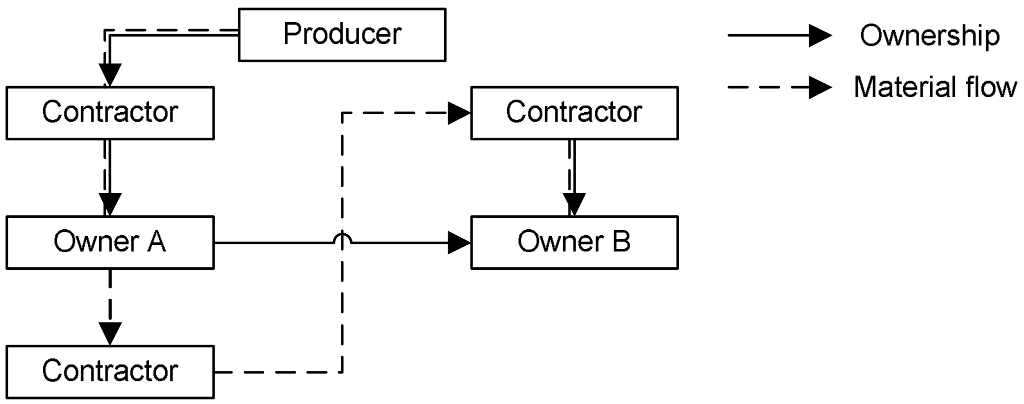

Figure 10. Direct re-selling.

(c) Producer takes the responsibility - The manufacturers are usually best equipped to disassemble the product and the European legislation is moving in the direction of shifting the end-of-life responsibility to them [2]. The limitation is obviously the extremely long service life of the building, and therefore some alternative ways should exist in the case of non-existing producer at the time of deconstruction (Figure 11). This approach is suitable for the commonly used building elements that are, however, unique for each producer such as cladding panels. Shorter service life of the building is an advantage.

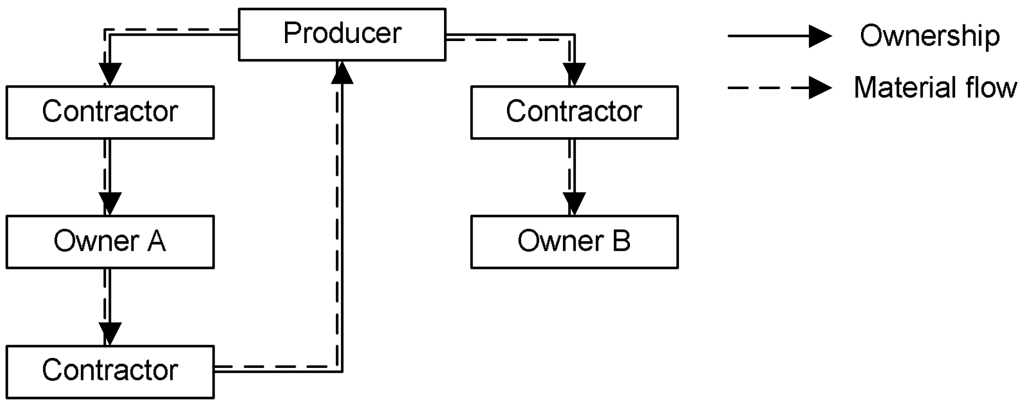

Figure 11. Producer takes responsibility for collecting used elements.

(d) Product lease - The idea of renting products instead of selling them is promoted in the EU. However, its application to the building structural elements seems to be very limited due to the relatively low value of building materials and long building service life. This approach is suitable for temporary structures such as expo buildings and stalls. Another example may be the structural provisions such as foldable bridges for the areas affected by natural disasters. Here also high quality materials are utilized for a short service time, and therefore re-using is preferred.

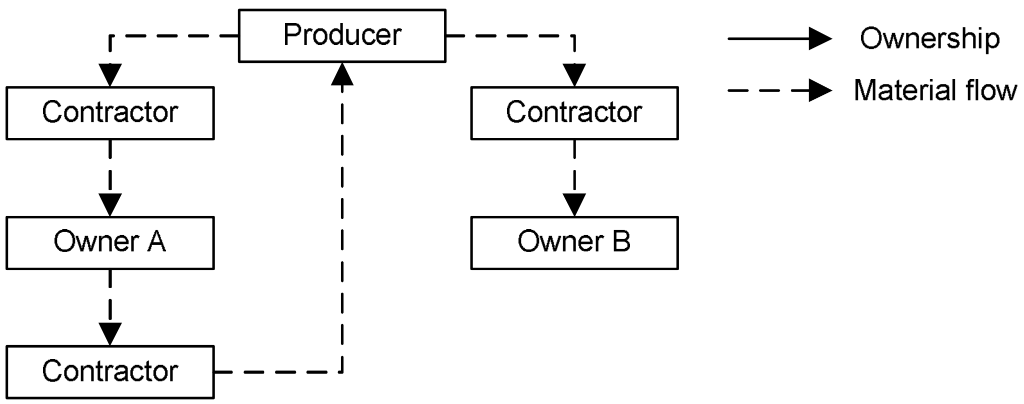

Figure 12. Rented product.

5. Re-using opportunities

Building components re-using affects the whole sustainable environment (see Figure 13), and therefore it requires active cooperation of people from different business areas, administration, research and education.

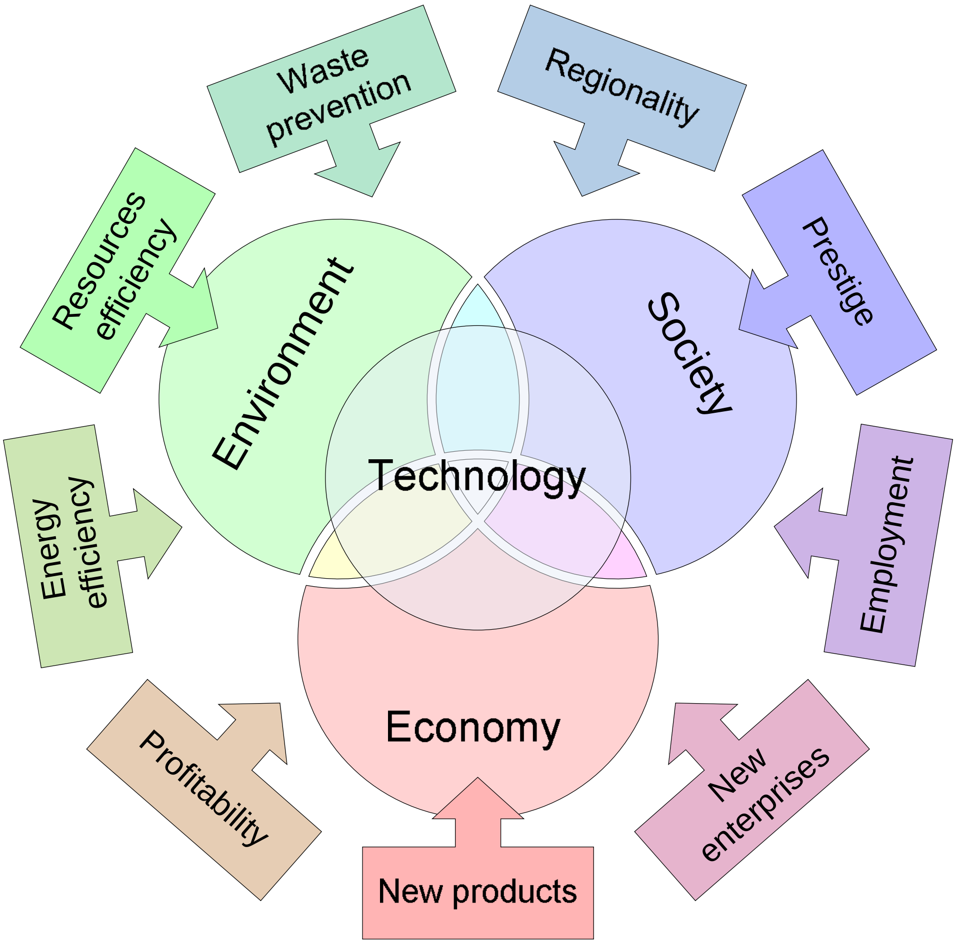

Figure 13. Potential areas affected by implementing re-using strategies.

The following sections explain in more detail the expected benefits from re-using in economy, society, environment and technologies.

5.1 Economic opportunities

(a) **Profitablitiy** - Re-using can be a cheaper option only if the prices of new components or materials are higher than the difference between the cost of deconstruction (including transport, storing, re-distribution) and demolition (including sorting and other recovery, transport and landfilling). This simple rule is not affected by the interest rate nor the number of building life cycles before the element cannot be re-used anymore. Moreover, the profitability of re-using will be always growing in the future because (a) prices of raw materials will grow (b) costs of landfilling will grow and (c) costs of deconstruction will decrease due to new technologies and smarter building design.

(b) **New products and technologies** - The modern technologies help assessing the potential economic benefits of re-using. Most of the current product development aims to reduce/optimize the waste from deconstruction and maximize the profit from the material recovery.

(c) **New enterprises** - The need for more efficient collection, sorting and re-distribution of deconstructed materials and components will open new business opportunities. Companies specialized in deconstruction will emerge as well as the salvage yards re-selling reclaimed building components.

5.2 Social opportunities

(a) **Employment** - New employment opportunities will be emerging such as opportunity for demolition contractors to expand their business. More training prospects will open for people already involved in the construction industry.

(b) **Prestige** - The re-use of building elements can be rewarded by various Environmental Assessment Methods (such as BREEAM, LEED, GreenStar, or the Code for Sustainable Homes). New methods are proposed (Green Demolition Certificate). Moreover, the local authorities and governments may motivate material efficient building projects by grants and other incentives.

(c) **Regionality** - Low cost and good quality components and materials will be produced by deconstruction that can be used within the local community. Opportunity to trade also those salvaged components and materials. Re-using supports self-sufficient communities since the whole process usually does not involve fabrication plants and heavy machinery.

5.3 Environmental opportunities

(a) **Resource efficiency** - Re-using aims to decrease the need for new materials in buildings, but it will also significantly reduce the resources (such as fossil fuels) connected with recycling or other recovery of materials.

(b) **Waste prevention** - Salvaged components not only reduce the waste sent to the landfill, but may also avoid the whole demanding process of the waste management.

(c) **Energy efficiency** – More efficient use of materials is naturally connected with the reduction of energy demands in the whole process.

5.4 Technological opportunities

(a) **Labelling systems** – If the components are clearly labelled, it would be possible to make available the information about their usage history. New technologies in smart labelling and wireless sensing can make re-using (deconstruction, transport and new assembly) much more efficient.

(b) **BIM** - Building information modelling is particularly suitable for handling the component information during its life cycle even if it is several times re-used. Its modularity and extendibility allows for storing all essential information and its easy modification in the future.

(c) **Online marketing** - Salvaged elements can be offered for sale online. Such databases of components may be extended with the pre-demolition inspection inventory of elements suitable for re-use. Designers and building contractors may be able to pre-order such elements from the future demolitions.

6. Re-using barriers

6.1 Economic barriers

Usually it is difficult and costly to start business with re-using building components.

(a) **A1: Cost -** The overall cost of re-using is often higher than building traditionally from new or recycled materials. Introducing product to the market may require expensive certification including material tests. The design cost is increased by the additional adjustments during the construction from old elements and the deconstruction planning for the new buildings. This applies to short-term up-front costs, and not social, economic, or environmental externalized costs that may be long term.

(b) **A2: Market -** There is small market of second-hand elements. The lack of recovery facilities (salvage yards) for re-used element and the lack of information about available components from planned and on-going demolitions prevent re-using in a larger scale.

(c) **A3: Coordination -** Clients may reconsider using old elements in their building because the coordination of collecting elements from the demolished building or salvage yard is more costly than the traditional sources. Moreover, it is difficult to find companies specialized in deconstruction, designers willing to design from used elements and construction companies willing to build from used elements.

(d) **A4: Diversion to the other streams -** It is often cheaper to landfill materials or to refabricate the whole components. Accessibility to landfills which have low tipping fees prevents investing into waste recovery.

(e) **A5: Insurance -** The price of insurance policy for reclaimed building elements may be higher, even if the safety of the building is usually guaranteed following the same design codes as for new buildings.

6.2 Social barriers

Designers, contractors and property owners do not have enough information and rules for planning and execution of re-using project.

(a) **B1: Legislation -** The legislation is new (not tested in practice), scarce or missing. Some legislation is discouraging re-using by very high requirements on documentation and certification of building elements. It may be difficult to get building approval from local authorities if the second-hand elements are used. There is not a clear goal in EU policies for implementation of component re-using.

(b) **B2: Standards -** There are inadequate rules for design, deconstruction or product certification. The design standards do not recognize the difference between new and re-used component. There are not enough rules for deconstruction design. The certification of re-used components is difficult.

(c) **B3: Awareness -** The re-use concept is not widespread and may be difficult to accept by the industry. The ways of re-using should be more explained in specialized seminars/courses. There is not enough public information about re-using in media (internet, journals …). The building industry is conservative and new concepts and practices are adapted slowly.

(d) **B4: Perception -** People have generally negative opinion towards second-hand materials. With the exception of wood and some worn bricks and tiles, it is believed that the new component is much more valuable that the used one.

(e) **B5: Health & Safety -** Salvaged building elements may contain hazardous substances and should be tested. This surprisingly applies more to modern hybrid elements and materials. Deconstruction requires more manual labour than demolition, and therefore it is associated with higher safety concerns. Carrying and lifting old elements on the building site may be more risky than the new elements.

6.3 Environmental barriers

It is not clear if the environmental benefits are not overridden by storing, additional transport, new technologies and practices.

(a) **C1: Impacts –** Re-using is not always superior to recycling or other waste treatment considering the whole material and product life cycle. The life cycle performance of the building is sometimes not studied at all.

(b) **C2: Transport -** The transport and handling of components may have considerable environmental impact. The salvaged components are sometimes transported over huge distances. The site-to-site transport mostly requires trucks that are not very environmentally efficient. Some building parts are unnecessarily transported and never used since the bad quality of component is often not recognized before it arrives to the site.

6.4 Technological barriers

Technologies for re-using are mostly developed, however not used in the full scale.

(a) **D1: Products -** Current building products are often not suitable for re-using. Designing new building from existing elements is very demanding. Trusses and frames are very large and difficult for handling. Re-using of the complete building units gives little flexibility to the architects.

(b) **D2: Materials -** Structural materials are usually combined in such way that it is difficult to separate them at the end of the building service life. The durability is an issue for life expectancy of wood elements. Some joints may be problematic (glued, nailed). The market is small. It is not possible to disassemble concrete structural joints. The recycling process (collecting scrap and melting) is already well-established for metals and it would be difficult to implement any alternatives.

(c) **D3: Applications -** There is a lack of knowledge of possible alternative applications of particular element or possible alternative element for particular application. There is not much knowledge about possible lower-level applications. Sometimes it is difficult to find a planned building of the same type. Elements (even if they have sufficient strength and quality) don't have optimal shape for structural use. E.g. rotor blades are not straight; rails are not structurally efficient as beams.

6.5 Evaluation of re-using barriers

The small survey about the importance of particular barrier categories from the previous section was carried out during the second general meeting of ReUSE project in Tampere. Total 10 participants answered the survey and the results are presented in Figure 14. The answers were evaluated as the average of all participants scores that was “not important at all" (-2 points), "not important" (-1 point), "don't know" (0 points), "important" (+1 point) and "very important" (+2 points).

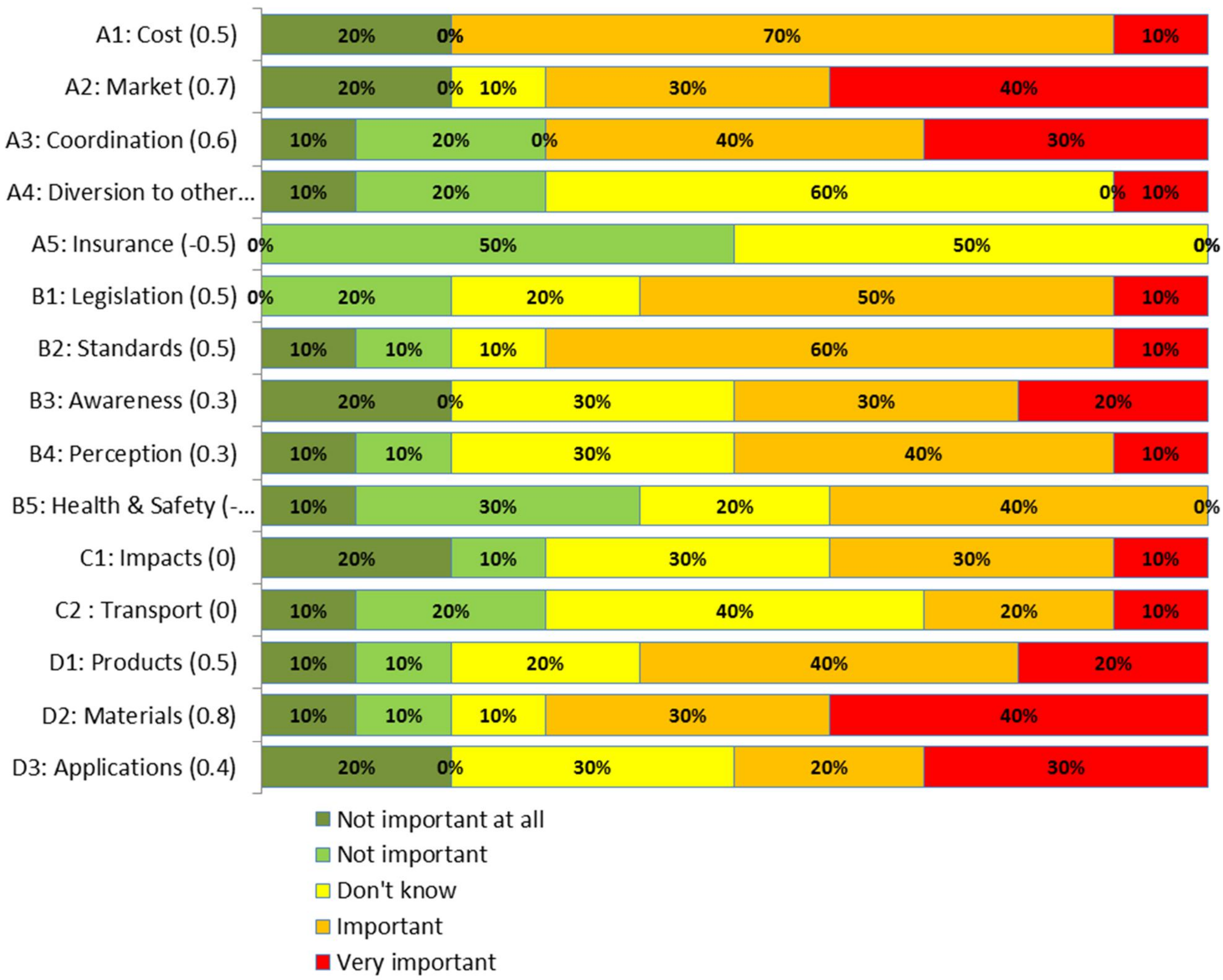

Figure 14. Results of the survey.

The survey clearly indicates that among the most important barriers are materials (+0.8 pt.), market (+0.7 pt.) and coordination (+0.6 pt.). Cost, legislation, standards and products scored also relatively high (+0.5 pt.). On the other hand participants answered that the insurance (-0.5 pt.), diversion to other streams (-0.2 pt.) and health & safety (-0.1 pt.) are not so important in Finland.

The following comments were given by the survey participants:

(a) Perception is the biggest barrier in Finland, hopefully it is going to change.
(b) Transport is not too big barrier if the project is well planned.
(c) No one knows how to coordinate re-using activities.
(d) Diversion to other streams is important especially for energy recovery (wood) and recycling to ground (concrete etc.).
(e) Problems related to impacts were not thoroughly studied.
(f) LCA shows that CO_2 is not a big problem in transport.
(g) Category D2 is important especially for composite materials.
(h) A new category is suggested: Quality.

7. Steel and timber building frames

The great advantage of structural steel and timber is that those materials can very easily form a simple load-bearing frame that serves as a platform for all other components attached to it (see Figure 15). The load-carrying function of the frame is clearly separated from the functions of connected elements (such as building envelope, flooring, services) and therefore the buildings are very easy to modify and deconstruct which is very important for the re-using process.

Figure 15. Example of a timber building frame (www.timberhart.com).

Such building frame can be re-used as a whole (as the Category A element), but it may be difficult to find a suitable application for it. Therefore it would be more efficient if the building frame can be further decomposed into smaller parts preferably of as high category as possible to maintain their high value. This is called clustering (see Figure 16). For example the steel portal frames from the industrial halls (Category B) can be re-used separately if it is not possible to re-use the whole building.

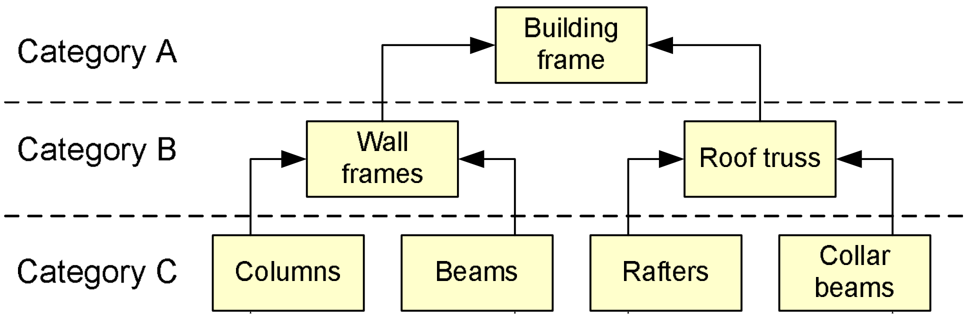

Figure 16. Example of the clustering principle.

Steel and timber building frames can be good examples of so-called “open system configuration” where all additional elements are attached directly to the basic part (the building frame in our case). This brings additional advantage for re-using. Open structures can be quickly dismantled because more deconstruction teams can work on different parts at the same time. Reduction of deconstruction time is one of the main concerns in the decision about the demolition/deconstruction process.

7.1 Steel re-using

Steel structures have very high recycling potential. It can be roughly treated (bent, torn apart, and otherwise manhandled) and still retain its value. Even if the steel is mixed with other materials, it can be magnetically separated for recycling. Most of the steel scrap from building demolition can be used in blast or electric furnaces for new material production. Melting, rolling and/or forming of recycled steel products, however, still consume considerable amount of energy and resources, and create waste and emissions. Scrap metal has to be collected and transported over relatively long distances to the steel mill. Re-using building component is, on the other hand, an alternative end-of-life scenario where most of the heavy industrial processes can be simply bypassed.

According to the World Steel Association there are over 3500 steel grades worldwide. However, over 90% of steel production contributes to the carbon steels where only few grades are used in building structures. Then the simple tension test of coupon or rod and the Charpy impact test of material extracted from the building element may be sufficient to determine the element's strength grade and fracture limits. If the designer intends to weld the recovered element, more tests may be needed to ensure the weldability and to select the suitable filler material. It should be a good practice to check all the existing welds in the element for cracks and to avoid using elements from cyclic loaded structures. The basic types of connections of steel elements are presented in Table 9.

Table 9. Steel connections.

Connections	**Suitability**	**Note**
Welds	not suitable	Cannot be separated without damaging the elements.
Rivets	sometimes suitable	Difficult separation without damaging the elements.
Standard bolts & screws	mostly suitable	Bolt hole can be already damaged.
Slip-resistant bolts	suitable [a)]	

[a)] Such connections are typically parts of structures with high cyclic loading and therefore the fatigue history of the elements may prevent their re-using.

7.2 Timber re-using

Unlike steel, the rough treatment of structural timber and mixing with the other materials during demolition vastly reduces its value. Separation from the mixed waste is very difficult and even if it is recovered, its possible applications are limited due to its broken-up state. Chipping for particleboard or fibreboard is always possible, but it means down-cycling the original high-value solid material. Re-using is therefore the only option for full recovery of the structural timber potential, and deconstruction should be the clear choice over demolition.

The assessment of reclaimed timber strength grade should be generally the same procedure as the grading of new timber. However, several new failures can be present which makes the proper grading according to the current standards impossible. Therefore the new grading rules for re-used timber have to be developed that take into account the effects of construction & demolition, maintenance and aging of wood (see Table 10). It can be particularly difficult to distinguish different types of cracks (see Figure 17). Structural connections are then summarized in Table 11.

Table 10. Timber damage.

Damage	Importance	Note
Bolt holes	mild	reduce the cross-section
Notches	severe	reduce the cross-section, cause stress concentration
Shakes (crack from overloading) and splits	severe	require a treatment
Checks (rheological cracks)	mild	reduce the stiffness, increase the risk of biotic damage
Shape distortions	mild	difficult to fit into new structure
Biotic damage	mild to severe	usually requires a treatment

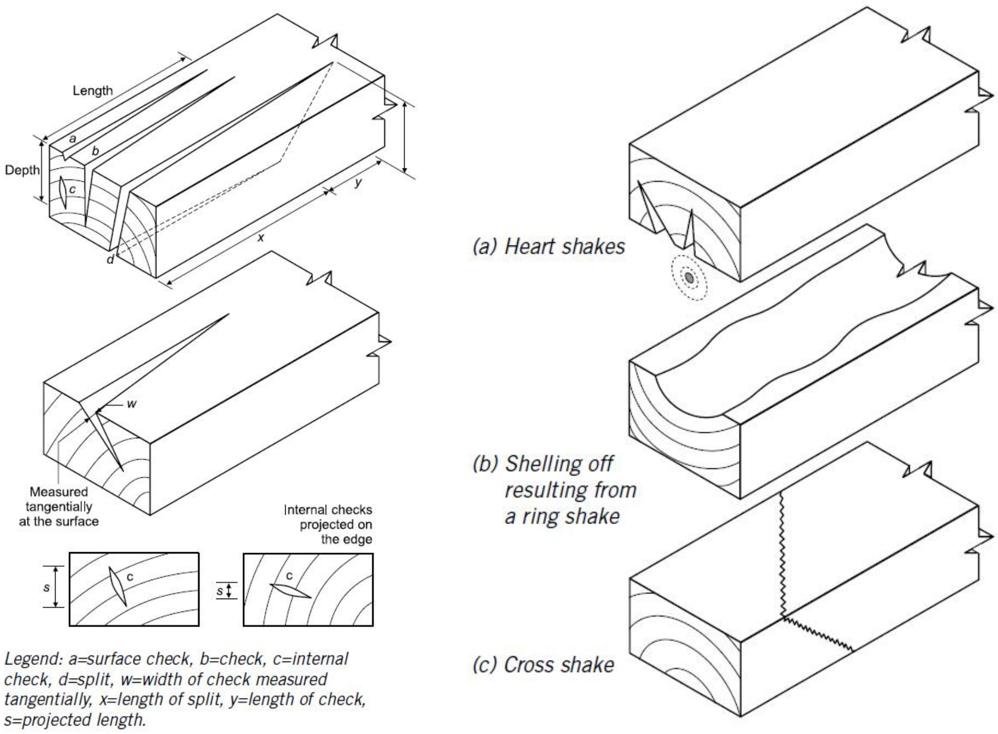

Figure 17. Shakes, checks and splits [12].

Table 11. Timber connections.

Connections	Suitability	Note
Glued connections	not suitable	Cannot be separated without damaging the elements.
Carpentry joints	sometimes suitable	Notches can cause stress concentration if the elements are used in different configuration.
Nails, staples	sometimes suitable	Fail in bending, and therefore are difficult to remove without damaging the element.
Screws	mostly suitable	The same connector is not so effective in the same hole.
Bolts, dowels	suitable	The hole and the cracks should be checked.

7.3 Case study: LCA of steel element

The following LCA study compares three cases of life-cycle environmental impact and costs of a hot-rolled steel beam with welded end-plates and bolted connections that can be easily reused in similar structure after dismantling from the original one.

In the first scenario (recycling), a beam is produced from steel sections and plates delivered from the mill, while the second case (reusing) considers reclaimed beam as an input.

OpenLCA software was used for calculation [13] together with ELCD database of European's Commission [14] that provided basic data for steel production, transport and waste processing.

7.3.1 Goal and scope

The study concentrates on declaring benefits and loads beyond the traditional system boundary in environmental product declaration (part D of EN 15804:2012 [3]). The aim is to calculate the difference of environmental impact and costs of two scenarios (recycling and reusing). Therefore, the whole life-cycle doesn't have to be calculated since the construction and use stages are the same in both cases (see Figure 21). In our example, the use stage was totally neglected.

7.3.2 Functional unit

One steel beam welded from hot-rolled profile and steel plates, and connected to the structure with preloaded bolts is a functional unit of this life-cycle study (see Figure 19). The same beam (822.2 kg) is referred as new (welded together), finished (painted), in structure (assembled) and used (disassembled) during the LCA study. It is part of the industrial building (see Figure 18) located in Arad (Romania). However, its parts are transported from different locations (see Figure 20). Bolts are manufactured in Dortmund (Germany), steel hot-rolled sections in Ostrava (Czech Republic) and steel hot-rolled coil in Galaţi (Romania). The beam is then manufactured in the workshop in Bocşa (Romania). The same place will be used also for cleaning and re-manufacturing of re-used beams. For the simplicity we assume that the new location of re-used beam will be as well in Arad.

Figure 18. Industrial building in Arad (Romania).

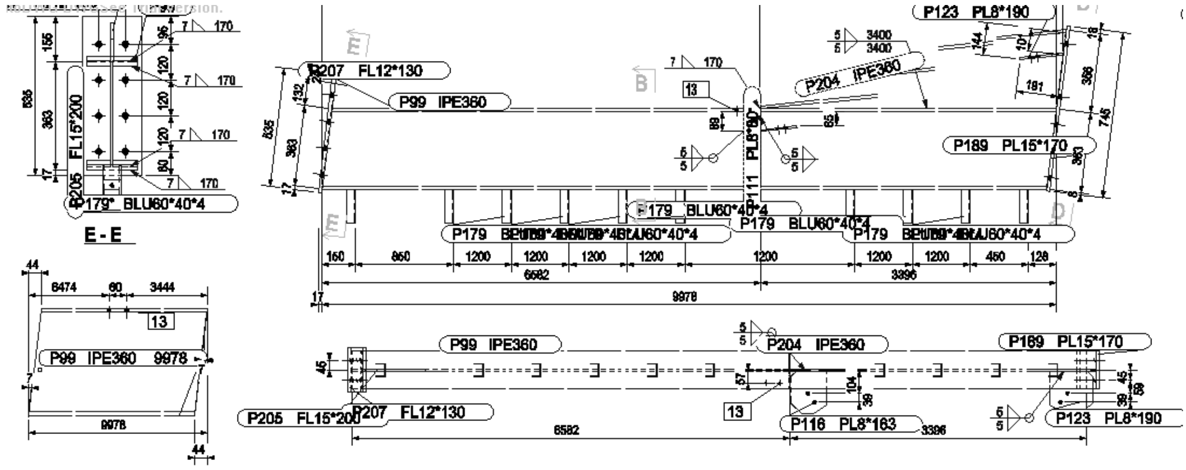

Figure 19. The studied beam drawings.

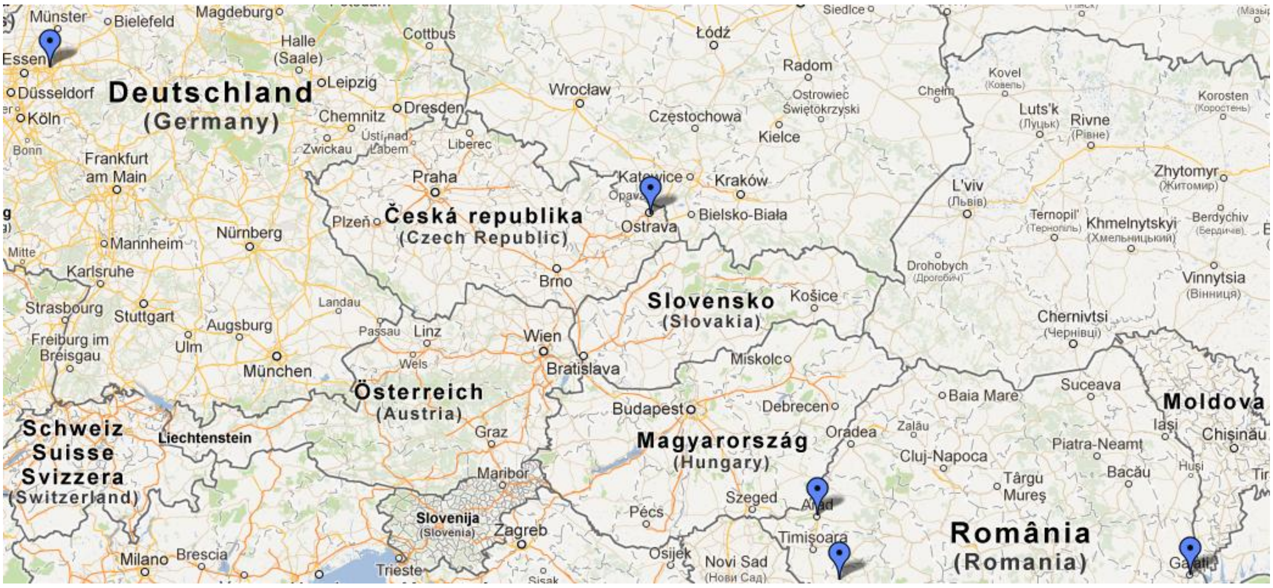

Figure 20. Location of producers, manufacturer and the building site.

7.3.3 System description

Due to the comparative nature of the presented results, the construction and use stages were not needed. Therefore only product and end-of-life stages were studied in this example (highlighted in Figure 21).

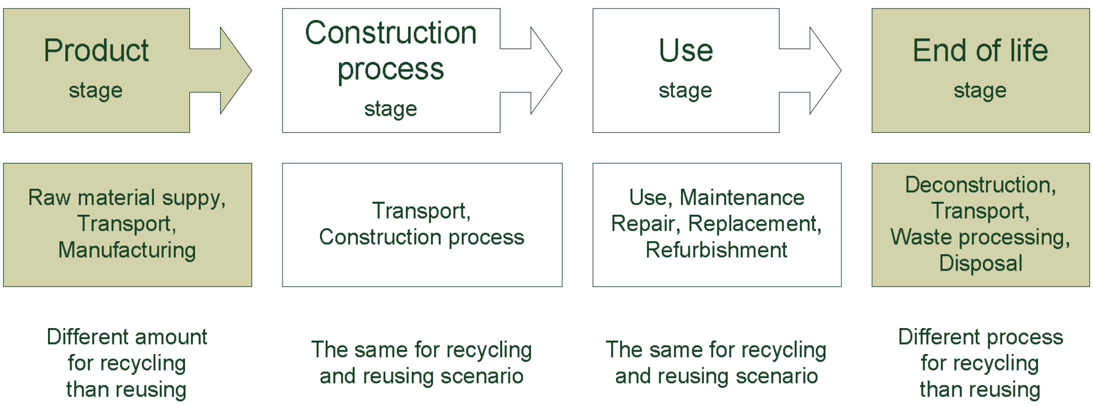

Figure 21. Life-cycle stages of building product.

It should be noted that due to lack of relevant data, some environmental impacts that would play a role in the comparative study were omitted. Part of the impact information is missing in construction, demolition and deconstruction stages.

The basic flowchart of re-using and recycling scenarios is demonstrated in Figure 22. Some of the processes were adapted from the ELCD database [14], however, the available data didn't include manufacturing processes and building deconstruction. Those processes were created for the calculation purpose and their inputs and outputs are presented in the following tables.

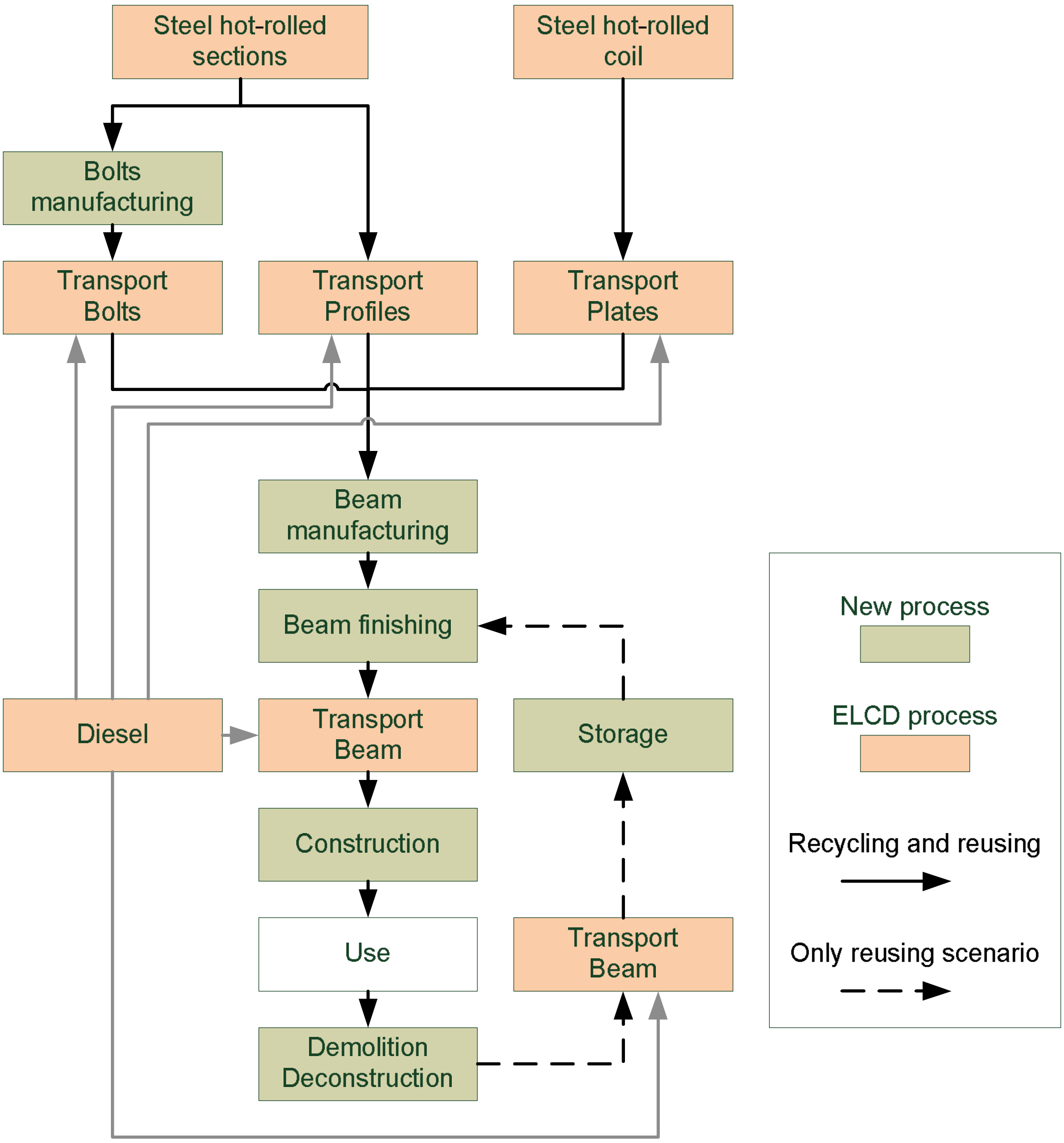

Figure 22. Flowchart of recycling and reusing scenarios.

Bolt manufacturing

The production of one M20 bolt (with nut and washers) in Dortmund consumes approximately 0.35 kg of steel.

Table 12. Bolt manufacturing inputs and outputs.

Inputs			
Steel hot rolled section	0.35	kg [a)]	Provided by: Steel hot rolled section, production mix, at plant, blast furnace and electric arc furnace route (ELCD database [14])
Cost	0.2	€	-
Outputs			
Bolt	1	item(s)	Used in: Transport, bolts supply

[a)] M20 bolts estimation of steel consumption.

Beam manufacturing (welding, cutting, drilling)

A new beam is manufactured in Bocşa from 839 kg of hot-rolled section and 61.3 kg of hot-rolled coil according to the drawings. Bolts will be assembled during construction, but they were added already at this stage for simplicity. Material supply costs are added to the cost of manufacturing.

Table 13. Beam manufacturing inputs and outputs.

Inputs			
Bolt	18	item(s) [a)]	Provided by: Transport, bolts supply
Steel hot rolled section	838.86	kg [a) b)]	Provided by: Transport, profiles supply
Steel hot rolled coil	61.295	kg [a) c)]	Provided by: Transport, plates supply
Cost	438.2	€	Material supply 0.093 €/kg, manufacturing 0.44 €/kg [4]
Outputs			
Beam (new)	1 (822.2)	item(s) (kg)	Used in: Beam finishing (sanding, painting)
Steel scrap	84.255	kg [b) c)]	-

[a)] From the design
[b)] Estimated 10% loses from hot rolled sections
[c)] Estimated 15% loses from hot rolled coil.

Beam finishing (sanding, painting)

New or re-used beam has to be cleaned (sanding) and painted before the transport to the building site. This process is also made in Bocşa, but is separated from the manufacturing step because it uses different inputs in recycling and re-using scenarios.

Table. 14 Beam finishing inputs and outputs.

Inputs			
Beam (new)	$1-0.9*(1-1/N)$ [a)]	item(s)	Provided by: Beam manufacturing, welding, cutting, drilling
Beam (used)	$0.9*(1-1/N)$ [a)]	item(s)	-
Cost	131.6	€	0.16 €/kg [16]
Outputs			
Beam (finished)	1	item(s)	Used in: Transport, beam to site

[a)] The value is calculated for N number of service lives (e.g. for 1x re-use $N = 2$).

Beam construction

Finished beam is transported to the building site in Arad, erected and assembled. It is assumed than forklift will be used 3.3 minutes for unloading and 5.37 minutes for preparation. Then the beam will be erected by 100-ton crane in approximately 6.01 minutes [5].

Table 15. Construction inputs and outputs.

Inputs			
Beam (finished)	1	item(s)	Provided by: Transport, beam to site
Cost	328.9	€	0.4 €/kg [16]
Energy	375.0	MJ	6.01 min of 100-ton crane (16.73 kg of CO_2) 10.5 min of forklift (9.81 kg of CO_2) [17]
Outputs			
Beam (in structure)	1	item(s)	Used in: Beam demolition or Beam deconstruction
CO_2	26.54	kg	6.01 min of 100-ton crane (16.73 kg of CO_2) 10.5 min of forklift (9.81 kg of CO_2) [17]
CO	53.5	g	
NO_x	132.3	g	
Particulated matter	11.2	g	
SO_x	53.9	g	

Beam demolition or deconstruction

Two different approaches are considered. Recycling scenario, where all the material is turned into scrap is more cost-effective (estimated half of the construction cost) while deconstruction of beam for future reuse needs the same technology as construction plus cleaning, sorting, inspection and packaging. The cost is estimated as double compared to construction cost (4 times higher than in case of demolition) because of the additional processes.

We can also assume that when the building is properly designed for re-use and all the material certificated are preserved until the deconstruction; the estimated cost can be significantly reduced. Especially the quality check of the material can make up to about 80% of additional costs. Therefore we included the optional scenario with the reduced cost of deconstruction that will be only 1.2 times higher than construction (2.4 times higher than demolition).

While the amounts of steel scrap and demolition waste are varying in different re-using scenarios, the costs and impacts remain the same since it is assumed that the full deconstruction will be executed regardless the life expectancy of the steel element.

Table 16. Demolition and deconstruction inputs and outputs.

Inputs			
Beam (in structure)	1	item(s)	Provided by: Beam construction
Cost (demolition)	164.4	€	0.20 €/kg
Cost (deconstruction)	657.8	€	0.80 €/kg
	394.7	€	0.48 €/kg when designed for re-use
Energy (demolition)	103.5	MJ	10 min of man-lift estimated acc. to [17]
Energy (deconstruction)	375.0	MJ	see beam construction
Outputs (demolition)			
Steel scrap	781.09	kg a)	-
Demolition waste	41.11	kg a)	-
CO_2	7.32	kg	10 min of man-lift estimated acc. to [17]
CO	64.2	g	
NO_x	60.0	g	
Particulated matter	6.0	g	
SO_x	14.8	g	
Outputs (deconstruction)			
Beam (used)	0.9*(1-1/N) c)	item(s) b)	Used in: Transport, beam from site
Steel scrap	781.09*[1-0.9*(1-1/N)] c)	kg a) b)	-
Demolition waste	41.11*[1-0.9*(1-1/N)] c)	kg a) b)	-
CO_2	26.54	kg	see beam construction
CO	53.5	g	
NO_x	132.3	g	
Particulated matter	11.2	g	
SO_x	53.9	g	

a) Estimated 5% waste from the recovered steel scrap
b) Estimated 10% scrap from the recovered beams (every 10th beam)
c) The value is calculated for N number of service lives (e.g. for 1x re-use N = 2).

Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total load, 27 t max payload

Transport was provided as a generic process with variable cargo and distance. The basic parameters are summarized in the following tables.

Table 17. Transport inputs and outputs.

Inputs			
Cargo	1	kg a)	Provided by various processes
Diesel	0.00139	kg/100 km	Provided by: Diesel, consumption mix, at refinery, from crude oil, 200 ppm sulphur (ELCD database [14])
Outputs			
Cargo	1	kg a)	Used in various processes
Ammonia, Benzene, Carbon dioxide, Carbon monoxide, Dinitrogen monoxide, Methane, Nitrogen oxides, NMVOC, Particulates < 2.5 um, Sulphur dioxide, Toluene, Xylene b)			

a) Different cargo used (Steel hot-rolled section or coil, Bolt, Beam)
b) According to ELCD database [14].

Table 18. Transport data.

Transport process	Cargo	Distance	Cost [16]
Transport, bolts supply	Bolt (2.86 item(s) per kg)	1550 km (Dortmund - Bocşa)	0.03 €/kg*100 km 2.93 €/beam
Transport, profiles supply	Steel hot rolled section	850 km (Ostrava - Bocşa)	0.01 €/kg*100 km 7.13 €/beam
Transport, plates supply	Steel hot rolled coil	750 km (Galaţi - Bocşa)	0.005 €/kg*100 km 0.23 €/beam
Transport, beam to site	Beam (0.00122 item(s) per kg)	150 km (Bocşa - Arad)	0.005 €/kg*100 km 0.62 €/beam
Transport, beam from site	Beam (0.00122 item(s) per kg)	150 km (Arad - Bocşa)	0.005 €/kg*100 km 0.62 €/beam

Other processes

Table 19. Other processes.

	Inputs [14]	Outputs
Steel hot rolled coil, production mix, at plant, blast furnace route, thickness 2 to 7 mm, width 600 to 2100 mm	elementary inputs according to ELCD	Steel hot rolled coil (+ emissions, waste)
Steel hot rolled section, production mix, at plant, blast furnace and electric arc furnace route	elementary inputs according to ELCD	Steel hot rolled section (+ emissions, waste)
Diesel, consumption mix, at refinery, from crude oil, 200 ppm sulphur	elementary inputs according to ELCD	Diesel (+ emissions, waste)

7.3.4 Results

The basic life-cycle impact categories (GWP, ODP, AP and EP) were calculated using CML 2001 methodology (see Table 20 and Figure 23). Moreover, the total cost of the processes involved in the calculation is presented in Table 20 and Figure 23. The value of the salvaged parts is not subtracted from the final results because it was already included in the manufacturing phase (no cost was allocated for the used beams).

Table 20. Results of LCA study (values expressed for one beam and one building life).

LCIA category		units	N = 1 no re-use	N = 2 1x re-use	N = 3 2x re-use	N = 4 3x re-use
GWP	Global warming potential (GWP100)	kg CO_2 eq.	1075	901	642	454
ODP	Stratospheric ozone depletion (ODP10)	kg CFC11 eq. x 10^{-8}	4.27	4.44	3.52	2.78
AP	Acidification potential (generic)	kg SO_2 eq.	3.33	2.90	2.11	1.53
EP	Eutrophication potential (generic)	kg $(PO_4)^{3-}$ eq.	0.293	0.278	0.212	0.160
POCP	Photochemical oxidation (high NOx)	kg ethylene eq.	0.089	0.046	0.032	0.025
Cost		€	1149	1394	1312	1270
Cost (designed for re-using)		€	1149	1131	1048	1007

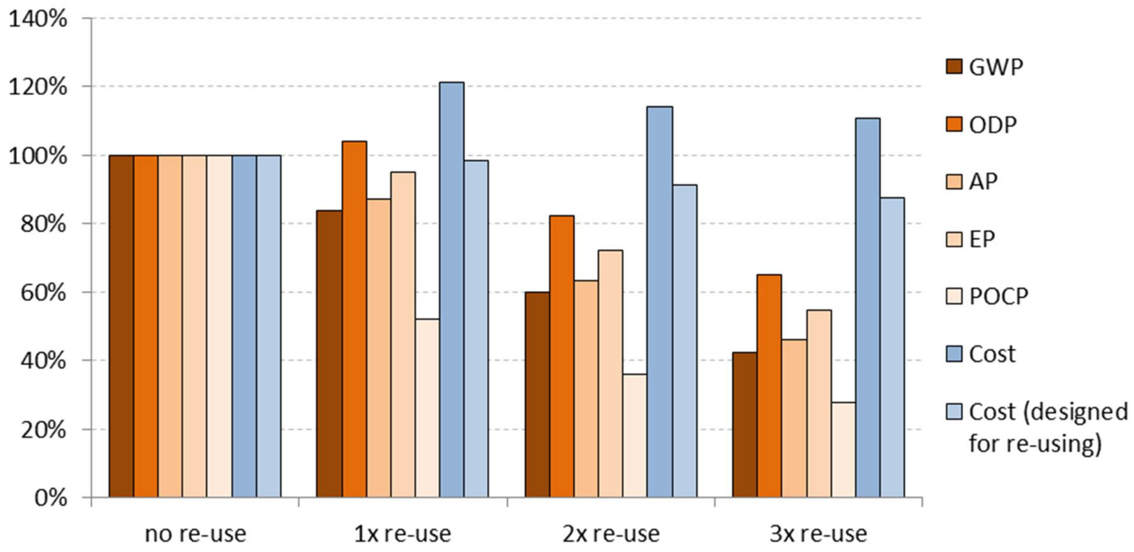

Figure 23. Results of LCA study normalized to the case without re-using.

The study showed clearly that significant advantage in environmental indicators can be achieved when re-using scenario is selected. The small increase of ODP in 1x re-use scenario is contributed to the more difficult deconstruction process; however, it decreases with more re-using cycles. The accumulated cost of re-used beam is higher in this basic study than the “no re-use” scenario, but the situation changes completely if we assume reduced costs for material quality check. Although the rough estimation of deconstruction being two times (or 1.2 times) more expensive than construction increases the uncertainty of the results presented, the potential of savings is clearly highlighted at this stage. The introduction of cheaper deconstruction, sorting and inspection technologies changes the balance between costs in both scenarios. Moreover, increasing the number of building service lives N will also reduce the life cycle cost of the element.

7.4 Case study: Dynamic simulation of wood-housing

The aim of this calculation is the demonstration of the potential of dynamic material flow (MFA) calculation in the assessment of the environmental performance of a building or the whole district. The advantage of dynamic calculation is that the inputs and outputs of the processes can be allocated in a specific time (e.g. the demolition waste is released 50 years after the building construction) or distributed in the time period (e.g. emissions and energy associated with the building use). In this artificial example houses are built from structural timber and wood-based panels. Those products are made from lumber and low-quality wood allowing for re-use and recycling when possible.

Standard LCA calculations are based on the desired outputs (demand vector f_i), technosphere matrix A_{ij} that defines internal flows of the system, biosphere matrix B_{jk} which describes emissions released and resources consumed for each of the system outputs and the characterization factors in a form of weighting matrix $C_{k,l}$ transforming the resources and emissions into environmental impact categories. Then the full life-cycle analysis of the system results in a single vector of impacts h_l and can be written as:

$$h_l = C_{kl} B_{jk} A_{ij}^{-1} f_i \quad (1)$$

Indexes i, j, k and l represent demand, supply, emissions & resources and impact categories respectively. Demand and supply flows categories are the same, and therefore A is the square matrix.

The extension of this calculation to time domain is, however, not simple. Characterization factors are generally not valid with dynamic outputs and the results have to be expressed as basic emissions and resources. Moreover, adding temporal variation to demand and supply flows may lead to negative material stocks in certain time steps and the processes are not fully reversible. For example the “positive” demand of sawn wood triggers the sawmill process, however its “negative” values - the excess of sawn wood - cannot revert back to the lumber. Therefore we adapted another approach. We have divided the system into small sub-systems with only single demand value and boundaries carefully selected in the asymmetric flows. Those systems were solved in a given order in each time step. Because of the newly emerging “stocks” of materials in the system boundaries, it would be more appropriate to classify the calculation method as MFA rather than LCA.

The particular difficulty of the example simulation is that the system has to decide about material sourcing according to pre-defined preferences and the material availability (e.g. structural timber can originate from the demolished buildings or sawmill production, low-quality wood as an input for wood-based panels production can be recycled from the demolition waste, by-product of lumber production or it has to be harvested in the forest if no previous option is available). Then the accumulation of unused materials has to be handled in the model. For instance structural timber suitable for re-using can be downgraded to low-quality wood if there is no suitable application for it. The low-quality wood can be similarly incinerated together with the wood waste. Both problems could be easily solved by the sub-system approach. The asymmetric flows are shown as dashed lines in Figure 25, Figure 26 and Figure 27.

7.4.1 Goal and scope

The simulation aims to estimate the impact of different policies/strategies to implement re-using of structural timber and wood panels in residential buildings. The target is 30% of sorted deconstructed wood elements. This means that approximately 40% of the deconstructed elements cannot be used in the same application (e.g. due to the damage) and 50% of the rest is reaching their durability limit (based on the assumed 100 years service life that equals to two building life cycles). The study will demonstrate the effect of implementing this policy gradually until 2020, 2050 and 2100 in the selected area.

Solid timber elements (framing) and wood-based panels (cladding and roofing) are studied including their production, material recovery, extraction landfill and incineration. The structural components are supplied from sawmill and panel production plant where the lumber and low-quality wood is either salvaged from the demolitions in the same area or extracted from the forest.

The system is therefore divided into the following sub-systems:

(1) Building use & waste recovery
(2) Structural timber production & disposal
(3) Wood panels production & disposal
(4) Low-quality wood management
(5) Wood waste management.

7.4.2 Functional unit

The neighbourhood of 80 wooden houses forms the functional unit where 2% of the buildings are renewed each year corresponding to building rotation length is 50 years [18].

7.4.3 System description and boundaries

The effect of transport between the material source and production unit is included in the product inventory. However, the transport between the producer and building site and between the building site and incineration plant or landfill is not considered in the study. Because of the comparative nature of the calculation, these stages will have negligible effect on the overall results. For the simplicity it is assumed that the removed components will be either instantly re-used in the same neighbourhood, downgraded to low-quality wood or incinerated without storing.

No LCIA methodology is used because the lack of characterization factors for dynamic LCA. The results are expressed as cumulative or yearly CO_2 balance. Part of the energy consumption and production of NO_X and SO_2 is also calculated but not used in the result interpretation.

Sub-system 1: Building use & waste recovery

The basic assumption is that the total volume of wooden family house wooden structure consists of 57% solid timber (framing) and 43% wood-based panels (cladding and roofing) as demonstrated in Figure 24 [22]. The design life of the building structure is 50 years according to the Eurocode [18] which is assumed to be equal to the building service life. Therefore, all the materials are released after 50 years in the following order:

(1) 70% of wood is sorted W_{SOR} for recycling or re-use [4] from the total volume W_{TOT} of structural timber S_{TOT} and panels P_{TOT}.

$$W_{SOR} = 0.7 W_{TOT} = 0.7\left(S_{TOT} + P_{TOT}\right) = 0.7\left(7 + 5.3\right) = 8.61\,t \qquad (2)$$

(2) 0 to 30% of the sorted wood (0 to 21% of total volume) is reclaimed as structural timber S_{REU} or panels P_{REU}. The value of re-using rate r_{REU} is dynamically changing in the study.

$$S_{REU} = r_{REU}\, 0.7\, S_{TOT} \text{ and } P_{REU} = r_{REU}\, 0.7\, P_{TOT} \qquad (3)$$

(3) Additional 14% of the total volume is recovered from the mixed waste [4]. Therefore the amount of recovered wood W_{REC} (that is not reclaimed) is 63 to 84% of the total volume. The remaining 16% of the total volume is landfilled as mixed waste.

$$W_{REC} = 0.14 W_{TOT} + \left(W_{SOR} - S_{REU} - P_{REU}\right) \qquad (4)$$

(4) The recovered wood is then sent for recycling in panel factory (23% of W_{REC}) or to incineration (77% of W_{REC}).

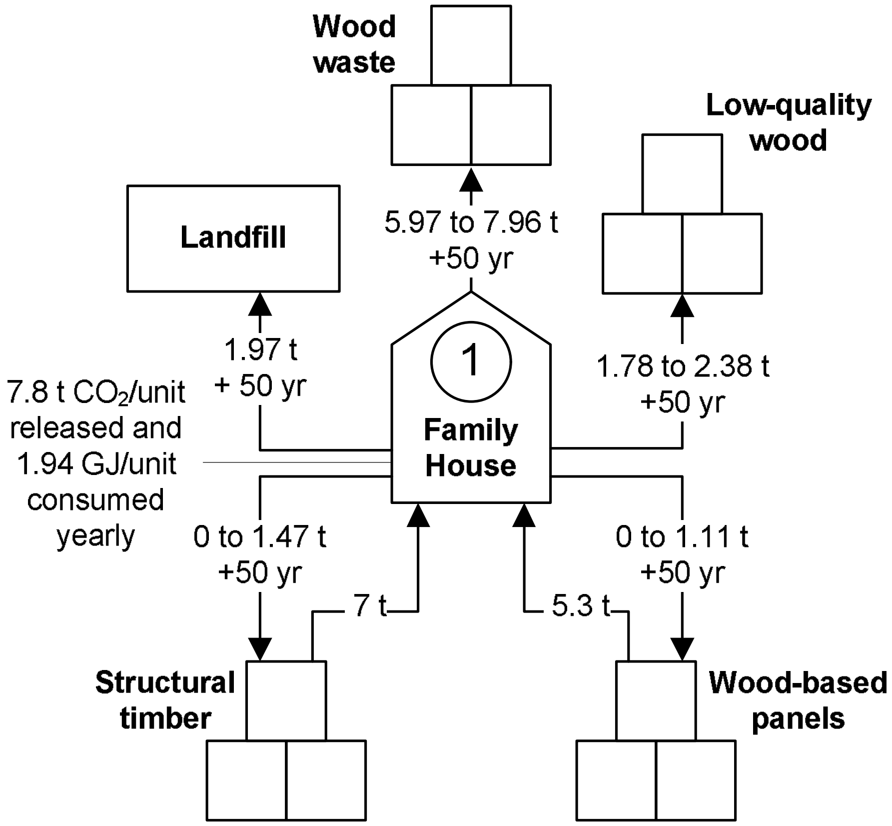

Figure 24. Building use & waste recovery sub-system.

Small family house (100 m^2) that consists of 7 t of structural timber and 5.3 t of wood-based panels forms a functional unit in this sub-system. Each unit produces 7.8 t CO_2 per year as shown in Figure 24. These operational emissions don't, however, play any role in the final comparison because they are subtracted from the overall results. All the inputs and outputs related to the other sub-systems are calculated in tons.

The only demand & supply category in this sub-system is one house at time 0 (the matrix A would be a single number). Then the remaining flows (structural timber, wood-based panels, landfill, wood-waste, low-quality wood, energy and CO_2) are regarded as resources & emissions at a given time and the matrix B collapsed into the vector with 107 values (50 of them are energy and 50 are CO_2 emissions at different time steps).

Sub-system 2: Structural timber production & disposal

The behaviour of this system depends on the amount of structural timber in the stock (the value is calculated in the Step 1: Building use & waste recovery). If there is a need for new timber (the structural timber stock value is negative), the appropriate volume of material is produced. On the other hand, the surplus of structural timber (positive value) has to be handled as well. Since no storage is simulated in the model, the stock volume has to be zero at the end of the year. Therefore all unused structural timber is treated as low-quality wood and managed in the following steps. The functional unit is 1 t of structural (dried) timber.

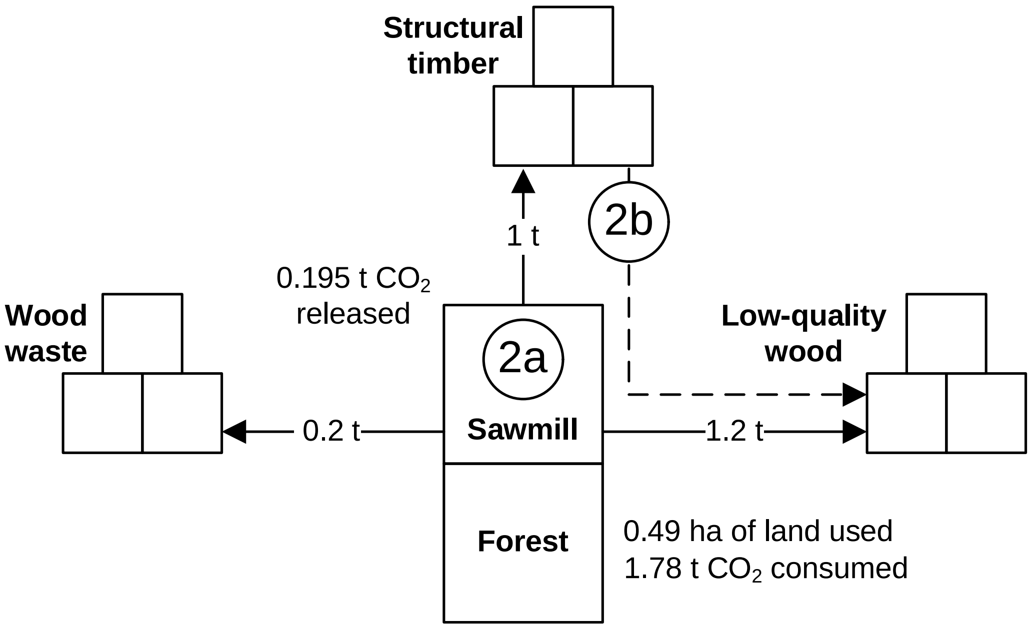

Figure 25. Structural timber production & disposal sub-system.

(1) The production in sawmill assumes that for 1 t of structural timber, another 1.2 t of low-quality wood and 0.2 t of wood-waste is generated [20] (8.3% of the total volume). The yearly forest productivity f_{PR} is estimated as 14 $m^3 ha^{-1}$ [19], and therefore the land use coefficient l_S is 0.204 ha/t. This leads to 0.49 ha of land use L_S for 1 t of structural timber produced.

$$L_S = 2.4 l_S = 2.4 \frac{1}{f_{PR}\sigma} = \frac{2.4}{14 \cdot 0.35} = 0.49\, ha/t \qquad (5)$$

(2) The CO_2 content in harvested wood is calculated from the assumption that the wood mass is composed of 45% carbon, 19% nitrogen, 10% oxygen, 8% sulphur and 18% hydrogen [22]. The resulting W_{C+} is then 0.74 tonnes of CO_2 per t of harvested wood. That means 1.78 tonnes of CO_2 per t of the final product.

$$W_{C+} = 2.4 \cdot w_{C+} = 2.4 \cdot 0.45 \left(\frac{44}{12}\right)\left(\frac{0.9}{2}\right) \cdot = 1.782\, tCO_2/t \qquad (6)$$

(3) The CO_2 released by solid timber production s_{C-} is assumed as 108 g/kg [21] and by shipping and distribution 87 g/kg [21]. Then we get 0.195 tonnes of CO_2 per t of structural timber.

$$S_{C-} = (108 + 87) \cdot 10^{-3} = 0.195\, tCO_2/t \qquad (7)$$

(4) In the case of structural timber disposal no production is activated, but the whole volume is moved to the low-quality wood stock for further processing as demonstrated in Figure 25.

Sub-system 3: Wood panels production & disposal

This sub-system is similar to the structural timber production. The source of material is, however, low-quality wood stock instead of direct forest production. The CO_2 released by wood panels production p_{C-} is 208 g/kg [21] and by shipping and distribution 87 g/kg [21]. Then we get 0.295 tonnes of CO_2 per t of wood panels.

$$P_{C-} = (208 + 87) \cdot 10^{-3} = 0.295\, tCO_2 / t \quad (8)$$

It is assumed that 1 t of low-quality wood produces 1 t of wood-based panels (see Figure 26) and the generated waste wood and consumed CO_2 is already accounted for in the forest production.

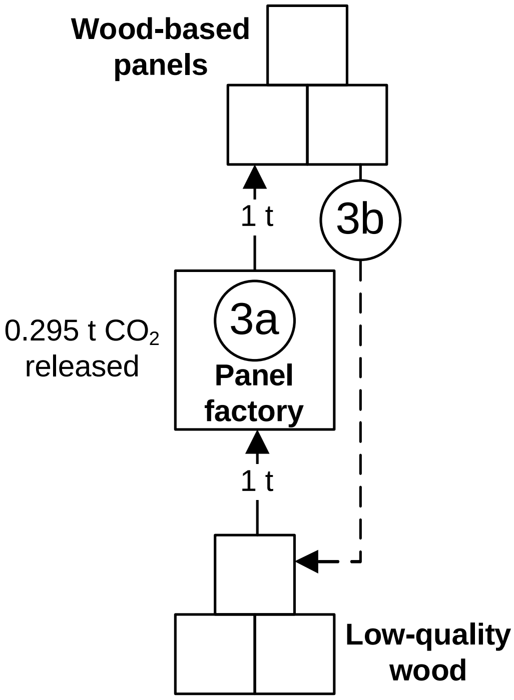

Figure 26. Wood panels production & disposal sub-system.

Sub-system 4: Low-quality wood management

Since all previous sub-processes were contributing to the low-quality wood stock, it has to be balanced in this step. If its value is negative, wood must be supplied from the forest. Here, the same amount of waste (8.3% of the total volume) is generated, the same land area (0.204 ha/t) is used, and the same amount of CO_2 (0.74 tonnes per t) is consumed as in the solid sub-system (see Figure 27).

$$L_S = 1.09 l_S = 1.09 \frac{1}{f_{PR}\sigma} = \frac{1.09}{14 \cdot 0.35} = 0.222\, ha / t \quad (9)$$

$$W_{C+} = 1.09 \cdot w_{C+} = 1.09 \cdot 0.45 \left(\frac{44}{12}\right)\left(\frac{0.9}{2}\right) \cdot = 0.809\, tCO_2 / t \quad (10)$$

If the value of low-quality wood stock is positive, it is moved to the wood-waste stock for further processing.

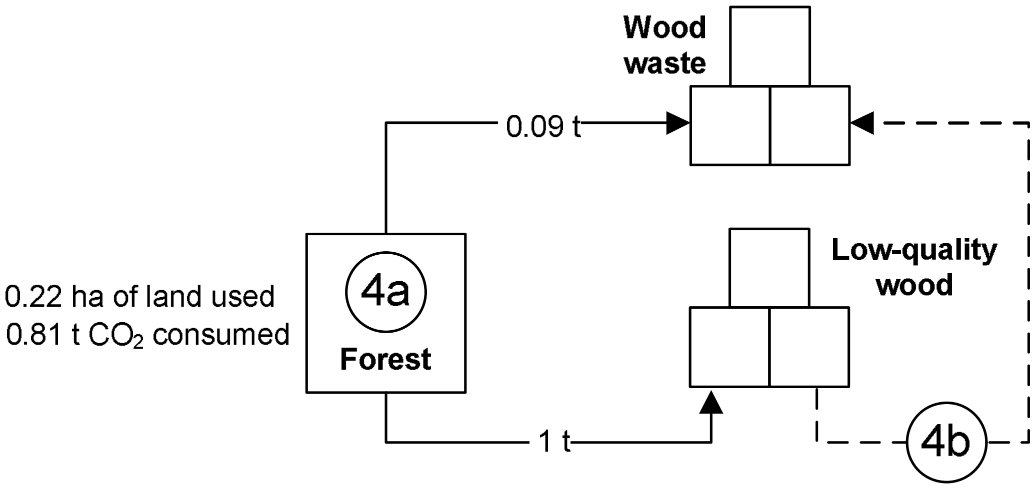

Figure 27. Low-quality wood management sub-system.

Sub-system 5: Wood-waste management

The remaining wood waste is incinerated in the last step. The energy released is 13 MJ/kg (3.61 MWh/t) of wood. The same amount of CO_2 is released as was captured in the wood production phase (w_C). The additional outputs include NO_X and SO_2 release (w_N and w_S respectively) [22].

$$W_C = 0.45\left(\frac{44}{12}\right)\left(\frac{0.9}{2}\right) = 0.743\, tCO_2 / t \quad (11)$$

$$W_N = 0.19\left(\frac{46}{14}\right)\left(\frac{0.9}{2}\right) = 0.281\, tNO_X / t \quad (12)$$

$$W_S = 0.08\left(\frac{64}{32}\right)\left(\frac{0.9 \cdot 0.8}{2}\right) = 0.058\, tSO_2 / t \quad (13)$$

7.4.4 Results

The example calculation demonstrated the method to calculate complex dynamic systems with asymmetric flows and priorities in process sourcing. Three scenarios with different re-using strategies were tested in the calculation and the results in the form of cumulative CO_2 emissions were compared to the basic calculation with no re-use. The temporal variation of composition of demolition waste is demonstrated in Figure 28.

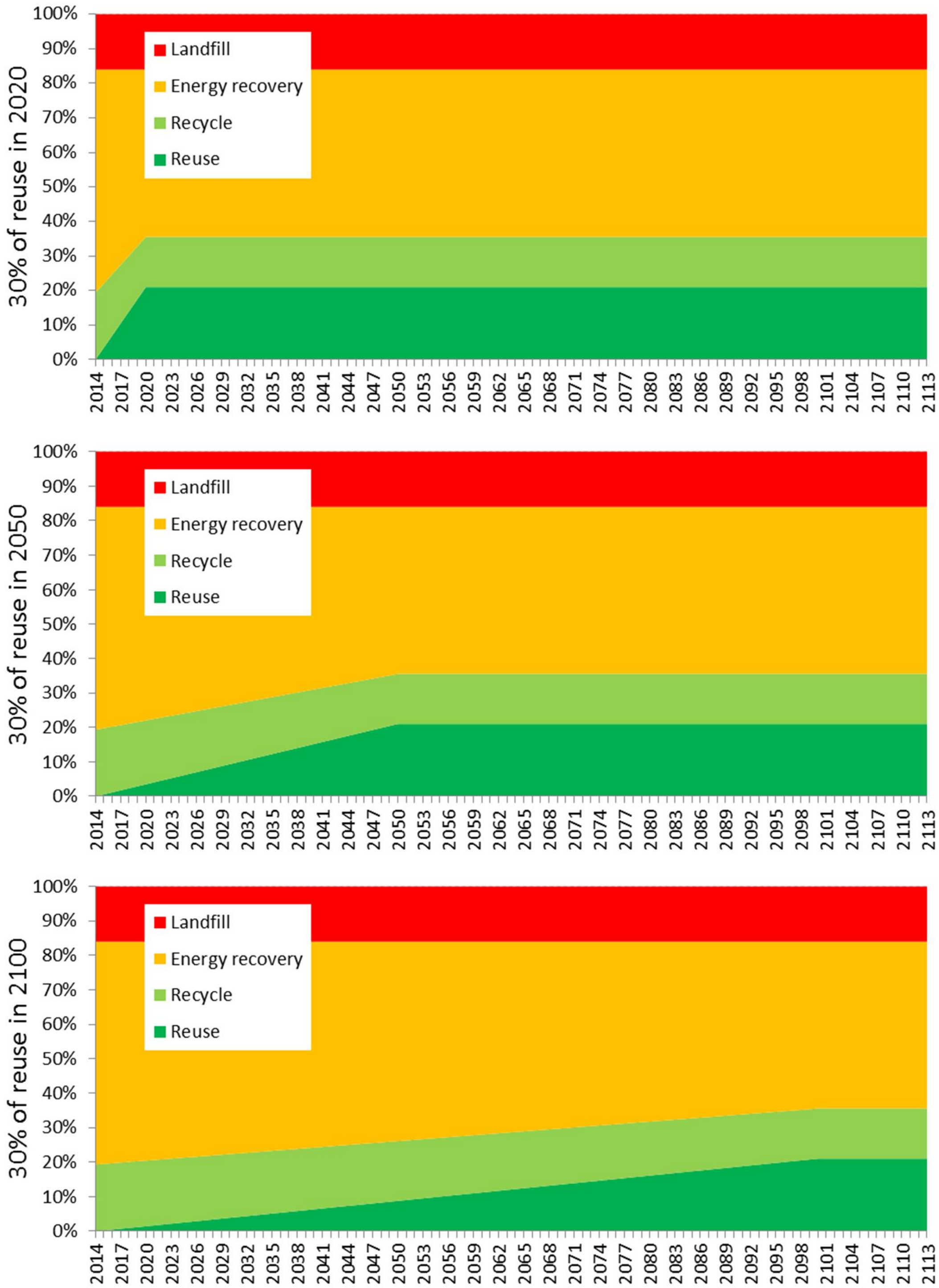

Figure 28. Demolition waste in three studied scenarios.

As can be seen from the Figure 29, significant savings of CO_2 can be achieved when the re-using strategy is applied early. However, it should be noted that the savings are only a very small fraction of the total CO_2 produced in the area (thousands of tonnes of CO_2) mostly due to the building use. Addressing the savings in operational emissions is out of the scope of this report, but the reduction of these impacts is also expected in the future.

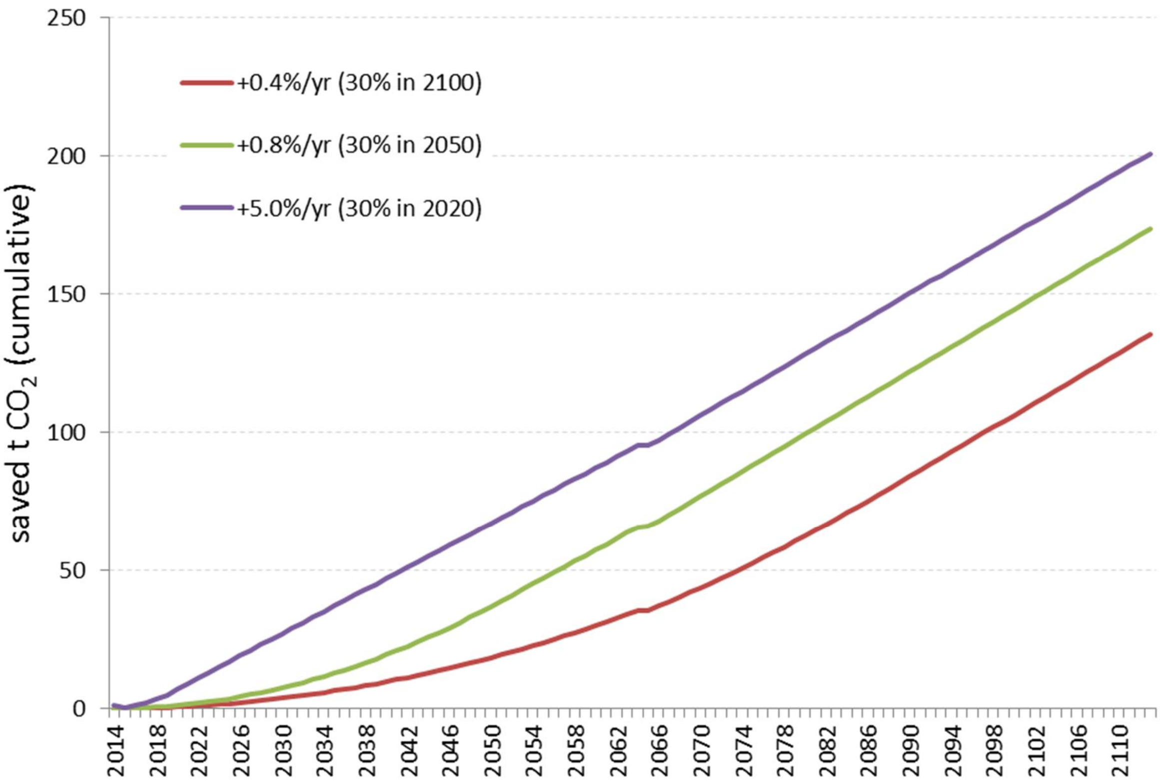

Figure 29. Comparison of three studied scenarios to the basic case without re-using.

8. Conclusions

The building element re-use practices differ with the size and complexity of the reclaimed parts. Therefore we have established 5 categories of building structural elements that can be re-used. The smaller ones (Categories D and E) tend to be re-used in more organized way, collected in the salvage yards and re-sold as basic material in the local community. On the other hand, larger and complex structural systems (Categories B and C) have higher value, but lower applicability, and therefore a different approach should be selected for their re-use. The online marketing, component labelling and BIMs are the technologies that are feasible for increasing the efficiency of such components re-using. The special category is Category A (the whole building structures). Since the re-using of the whole building should be rather called “building relocation”, the quality control of each element and the whole re-designing procedure is usually not required.

Re-using of building components is generally one of the most environmentally friendly end-of-life scenarios of the building provided that the durability of the components extends the life of the building and there is a suitable application for it. Re-suing benefits can be nowadays declared in a standardized way [15]. Many environmental certification systems recognize re-using in their assessment process, however, the contribution of material and resource efficiency to the overall score is usually very low.

There are many other practical barriers to the building components re-using that should be addressed. One is the lack of strength grading rules for materials in re-used elements. This means that re-usable load-bearing components are forced to be applied for non-structural purpose unless they are thoroughly tested in one of few certified laboratories in Finland.

Another barrier is the difficult deconstruction of existing buildings. The extended time and high demands on manual labour is usually increasing the cost of the whole process. This can be partly improved by applying standardized deconstruction practices, proper staff training and using selected technologies for deconstruction. However, the greatest impact on the building re-usability is in its design stage. Therefore we recommend addressing this issue in the planning of future steps towards resource efficiency.

The standardization process and the recent changes in the environmental certification systems indicate that the importance of life-cycle assessment of buildings and components will rise in the near future. However, the LCA study of the steel element showed that there is a lack of reliable LCA data for the most critical stages in re-use such as deconstruction, sorting, quality check and re-distribution of materials and components. These gaps in life-cycle inventory databases have to be addressed in the future.

We also recommend the amendment to the waste directive [2] (a) to include waste prevention in the 70% of (at least) recovered waste goal by 2020 in article 11, paragraph 2 and (b) to include objects that are re-used for different purpose without becoming waste in article 3, definition of “re-use”.

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