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Reusability indicator for steel-framed buildings and application for an industrial hall

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ABSTRACT

This paper introduces a new method for the assessment of reusability of components and structures of steel-framed buildings. It enables classification of various building parts and products through a procedure to calculate, weight and aggregate recyclability indicators and thus it helps to explore their potential to a second life. In connection with life cycle analysis (LCA), such an indicator provides valuable information for the Module D of the European standard EN 15804 and the Environmental Product Declarations.

The method is applied on an existing typical industrial hall structure. Five different end-of-life scenarios were investigated for selected components, including recycling of the material as scrap, but also the careful deconstruction with components prepared for future reuse after cleaning, sorting, inspection and packaging. As an example, both cost and environmental burdens are compared in the life-cycle study of a selected girder.

The results clearly show the significant reduction of environmental impacts achieved with reuse. However, we conclude that the reuse processes could be made more competitive with further reduction of life cycle costs. The higher reuse costs originate from the quality checks, manual work during deconstruction, storage and long transport distances. Adoption of cost effective deconstruction, sorting and inspection technologies can significantly improve the economic benefits in the studied reuse scenarios.

Keywords: steel structures, circular economy, reuse of building components, sustainability

1 INTRODUCTION

Reusing components from existing steel-framed buildings as well as designing new ones in view of deconstruction and reuse create a great opportunity to retain the economic, environmental and in some cases also cultural value of the building stock [1, 2]. Spontaneous attempts to trade reusable components are emerging in online trading platforms and engineered examples are plentiful [3]. The benefits to include the recycling and reuse potential in accordance with Module D of EN 15804 and Environmental Product Declarations (EPDs) have also been recognized in procedures of life cycle assessment of buildings and products [4]. However, a common method to systematically assess the degree of reusability of building components and structures is still missing. Such method will directly support the priorities of the European Waste Directive [5].

The paper introduces a new approach to assess the reusability of components and structures of steel-framed buildings. It is a procedure for an expert team capable of selecting relevant parameters and calculating, weighting and aggregating the reusability indicator. Based on the reusability indicator, the components and structures can be classified regarding their potential reusability. At this stage, the method is a proposal for discussion.

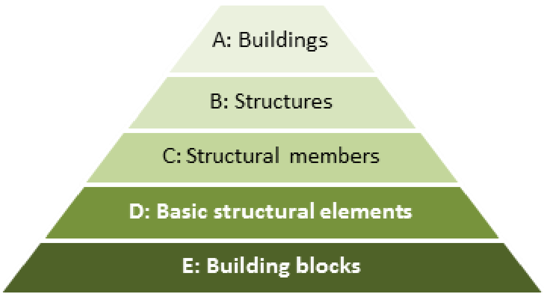
In essence, the reusability indicator gives information about impacts of various deconstruction, demolition and reuse scenarios of components and structures of steel-framed buildings. The reusability indicators can also be aggregated into an overall reusability index of a whole building. In this way, it helps the facility owners to select the most suitable end-of-life scenario for their buildings.

2 REUSABILITY ASSESSMENT PROCEDURE

A building comprises both off-site and on-site produced components, connected and joined together through various techniques and materials. This complexity naturally influences the reuse potential of a building and its components. Based on a literature survey, it can be concluded that design and technical factors easing disassembly and thus improve reusability are related to greater visibility, accessibility, simplicity and separability of materials as well as similarity of solutions and resistance to damages [6, 7]. Concerning reuse potential, quality of materials and available information about their use history is also of importance.
The reusability assessment method presented in this paper was originally developed in the ReUSE project financed by Finnish Ministry of the Environment, Finnish Wood Research and Ekokem [8, 9]. It is based on the literature survey, stakeholder interviews and expert evaluations. The authors of this paper have complemented the method in particular with descriptions of weighting factor selection and applied the method to a case building with five different end-of-life scenarios.

2.1 Component classification

The load-bearing structures and components of a steel-framed building can be classified according to their primary function, size and consistency as presented in *Fig.1*. This classification can be seen as extension of the "building - component system - element" concept presented in [10]. For instance in steel structures, class A is the whole load-bearing frame or one of its standalone parts, class B can be portal frame or truss girder, class C can be façade panel, beam or column, class D can be hot-rolled/cold-formed section or steel corrugated sheet, and the smaller parts such as bars, rods and plates belong to class E.



Component class	A	B	C	D	E
resists all loads and transfers them to the foundations	x				
has a single defined purpose	x	x			
has 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 parts 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

Fig. 1. a) Functional classification of building parts; b) descriptions of various classes [5]

2.2 Reusability indicator of the components

This section describes a simple reusability indicator r for each component or structure. The indicator r is a weighted average value of reusability performance assessment results ρ_i for eight different operations such as deconstruction, transport, cleaning, redesigning, quality and geometry verification. It can be calculated using *Eq.* (1):

$$r = \sum \rho_i w_i \tag{1}$$

The processes and the estimated component's reusability ρ_i related to them are presented in *Table 1*. The weights w_i in *Table 1* are estimated to be from 5% (geometry check) to 35% (disassembly).

Table 1. Components' reusability categories, based on [8] and modified by the authors

Category	ρ_i = 20% (very difficult)	ρ_i = 40% (difficult)	ρ_i = 60% (moderate)	ρ_i = 80% (easy)	ρ_i = 100% (very easy)
Deconstruction Disassembly[1] w_i = 35%	Welded connections, high risk of damage during deconstruction	Welded connections between components with difficult access	Mostly welded connections between components	Bolted connections between components with difficult access	Easily accessible bolted connections between components
Handling Manipulation[2] w_i = 10%	Exceeding standard transport dimensions, prone to damage, requires special protection	Standard transport, prone to damage, requires special protection	Manipulation by crane, not damage sensitive	Small lifting devices	Manipulation by hand
Separation Cleaning[3] w_i = 10%	Machine cleaning/cutting needed to separate other materials	Hand tools for cleaning/cutting can be used to separate other materials	Bolted connections with difficult access for separation	Bolted connections need to be removed for separation	Free-standing components requiring no cleaning
Redesigning[4] w_i = 10%	No documentation, components would not fulfil the standard design requirements without modification	No documentation available, new design is required	Design documentation available	Detailed documentation available incl. loading and maintenance history	Designed to be reused, documentation and maintenance records in digital format
Another purpose[5] w_i = 10%	Unique sizes and shapes, no other application possible	Possible to reuse for another purpose with some re-manufacturing	Limited possibility to use for another purpose	Possible to use for another purpose even outside the construction sector	There is a larger demand for another application than the original purpose
Modification[6] w_i = 10%	Sizes are unique, reuse would require complete remanufacturing	Requires removal of welded parts	Requires addition and adjustment of bolt-holes	Requires only addition of new components	Requires no modification
Quality check[7] w_i = 10%	No documentation, demanding environment, loading history is difficult to estimate, laboratory tests are needed	Laboratory tests are needed to check material properties	Documentation available, loading history known, on-site test needed to check material properties	Material documentation available incl. loading and maintenance history	Material documentation available Exploited in less demanding environment
Geometry check[8] w_i = 5%	Components would not pass geometry requirements without modification	Complex geometry 3D scanning required	Need to confirm positions of bolt-holes, etc.	Straightness and distortion check needed (lasers)	Straightness enough to confirm usability (wire, visual, etc.)

[1] Deconstruction or disassembly is a site operation resulting in transportable parts that will be further handled;
[2] Handling or manipulation means lifting, transporting, storage and protection of the reusable components after the deconstruction process;
[3] Separation and cleaning is a workshop process leading to a reusable component acceptable by the salvage yard or material dealer. It is the pre-process of modification;
[4] Re-design is an office process governed by the new life target, the availability of components and the result of checks. The purpose of re-design is to modify the components or verify that they can sustain loads in the new life scenario;
[6] Modification is an optional workshop process leading to a modified product;
[5] Another purpose category indicates the freedom to use the component in a wider scope, different purpose (e.g. column as a beam), and even different industry;
[7] Quality check is a process supporting re-design by confirming the quality of the materials in the component;
[8] Geometry check is a process supporting re-design by showing that the geometry of components conforms to the tolerances in execution standards;

2.3 Reusability indicator of a building

The results obtained for a single component or substructures can be generalized as a single reusability indicator *R* of the whole building. This indicator is the weighted average of the particular components or substructures (see *Eq.* (2))

$$R = \frac{\sum m_i r_i}{\sum m_i}, \tag{2}$$

where m_i is the weight of all components or substructures in a given group. The sum of all components' weights has to be equal to the total weight of structural steelwork, and therefore all non-reusable parts form a special group with the reusability index $r = 0\%$.

3 CASE STUDY

The method based on recyclability indicator was applied on a case study building in Romania. The goal is to explore different options that the facility owner has at its end-of-life starting from the complete building relocation up to selling individual sections to the salvage yard. The studied building consists of the production facility plus office combo that is a fairly popular configuration with SME companies or local production facilities. The plant and office buildings share foundations, but have independent superstructure (*Fig. 2*).

Fig. 2. Case-study steel building in Arad, Romania

The single-story part of the building (4.1 m height) has a width of 2×20 = 40 m from two-span frames with an overall length of 9×5 = 45 m. The regularity of the steel structures in this area is high, only disrupted by the presence of longitudinal purlins and bracing in the roof and walls. The gable ends of the hall are identical to the ordinary frames, with only the connection of the gable-end columns distinguishing these frames. While probably not the most optimal design choice from material consumption point of view, this further contributes to the regularity in case of a potential reuse.

The office part of the building is higher (6.1 m), having a width of 40 m and length of 3×5 = 15 m (*Fig. 3*). There are independent columns at the interface of the two structures, making it possible that the two sections are demolished and reused separately. One part of the office area is divided by an intermediate floor. The floor was designed as steel grid with secondary beam and corrugated sheet. A layer of concrete was casted on top of the corrugated sheet. In the design phase, the use of a composite floor would have resulted in lower material consumption. However, in that case the separation of the welded studs from the composite structure would have been impractical making the reuse of the floor beams difficult.

The column-base connections of the frame structure were fixed in order to fulfil the drift requirements on the higher part of the structure. Since base fixing leads to double curvature bending in columns, it is economical to use constant cross-sections as columns. This resulted in the use of hot-rolled sections for the columns and beams of the building. In order to preserve a consistent construction system, the choices concerning base fixing and the use of hot-rolled sections has been propagated to the lower hall even if a pinned-tapered configuration may have been also fitting for the low height part of the building. Fixed base leads to larger anchoring assemblies than if the base was pinned. Fixed base anchors may contribute as much as 10-15% to the weight of the structure, while pinned base anchors are in the range of 4-8%. Since anchor elements are embedded in the foundations, they are not recoverable in a reuse scenario. On the other hand, the choice for hot-rolled sections facilitates reuse at structural member level (Class C see later). Due to their compactness, hot-rolled members are also easier to handle during deconstruction, being less prone to torsional deformations during the deconstruction and transport compared to welded sections.

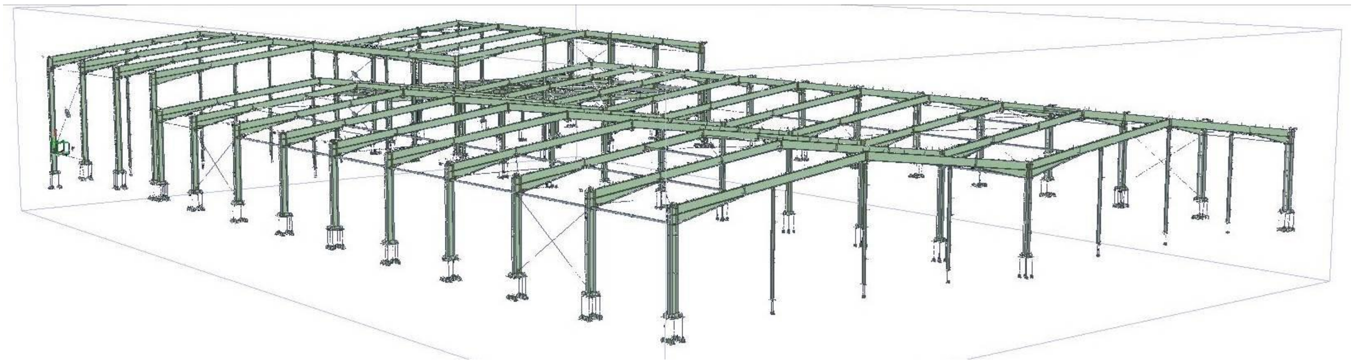
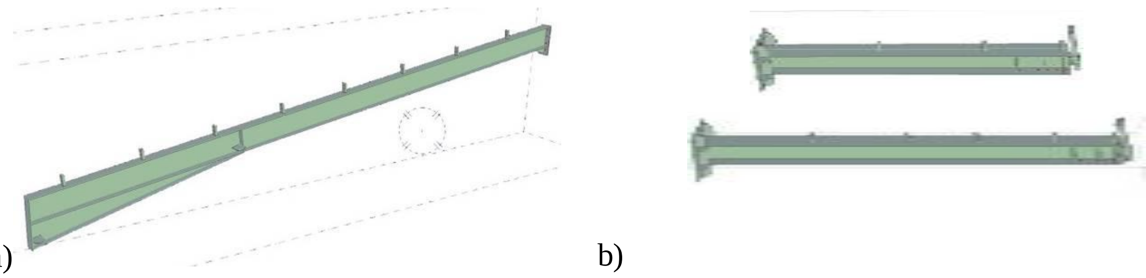


Fig. 3. Load-bearing structure

3.1 Structural decomposition

In order to create different reuse scenarios, the building has to be divided into individual components or substructures, from which the scenarios may be developed. Separation into reusable components and substructures can be handled at different levels of complexity, ranging from reuse of the entire building to reuse of standard steel sections. The classification below is performed according to *Fig. 1*.

<u>Buildings (class A)</u>: As mentioned earlier, the complete load-bearing frame can be separated into two independent units in this case. Hence, building level reuse can take place for the entire building or as two separate units.
<u>Substructures (class B)</u>: Portal frames can be reused as independent structural units belonging to class B. The office part consists of four frames and the industrial one of ten frames. These frames can be integrated in the fabric of a new structure, e.g. by supplementing them with additional components.
<u>Structural members (class C)</u>: Columns and rafters are typically representing class C (see *Fig. 4*). Especially the rafters can be considered for a reuse option, because they consist of two groups of 28 identical parts and may offer complete roofing solution for a new project. Six groups of components with different lengths and cross-sections, on the other hand, represent columns. It should be noted that several columns and beams of individual dimensions or configuration were not considered for reuse as class C.



a) b)

Fig. 4. Structural members a) Rafters b) Columns

<u>Basic elements (class D)</u>: The structural members can be further reduced to steel sections of various lengths (up to 9.9 m). The steel hall consists of 755 m of IPE360, 191 m of IPE300, 27 m of IPE160, 133 m of HEA300, 42 m of HEA200, 42 m of HEA160 and 70 m of HEB220. Unlike the parts of class C and above, it is assumed that the sections will be sold to various material dealers and the original design documentation and quality certificates might not be available to the final user.

The reuse of the high-strength bolts (class E) may also be allowed under certain circumstances [11], but this effect is not assessed in our study.

3.2 Reusability indicators of components or structures

We have applied the proposed methodology on the components classified as A to D and assessed the reusability from *Table 1* for this particular case. *Table 2* presents the results of the evaluation. The value of reusability index *r* for the particular components and substructures is then according to *Eq.* (1): 60% for complete hall (class A), frames (class B) and rafters (class C), 62% for columns (class C) and 64% for steel sections (class D). The numbers indicate that the ease of deconstruction and separation/cleaning at frame level (class B) is balanced by more versatility of reusing at section level (class D).

Table 2. Reusability assessment of the components and structures from the case study

Category		Score ρ_i	Note
Disassembly	All parts	80% (easy)	Bolted connections with difficult access
Handling Manipulation	Complete structure, frames, columns or rafters	40% (difficult)	300-800 kg parts (up to 10 m) with end-plates that may need protection from the damage during manipulation
	Steel sections	60% (moderate)	300-700 kg parts (up to 9.9 m) without connections
Separation Cleaning	Complete structure, frames, columns or rafters	80% (easy)	Bolted connections between the parts, easy access
	Steel sections	20% (very difficult)	Welded end-plates, long welds and other attachments have to be removed
Redesigning	Complete structure	80% (easy)	Verification/update of the original design documentation
	Frames	60% (moderate)	In-plane resistance and stability check can be adapted from the original documentation
	Columns or rafters	40% (difficult)	The design of connected components will have to fit the geometry of the reused member
	Steel sections	20% (very difficult)	Simplification of the new design is not possible
Another purpose	Complete structure, frames or rafters	20% (very difficult)	The structure or structural member can be used only for the original purpose
	Columns	40% (difficult)	Limited use also as horizontal beams
	Steel sections	80% (easy)	Can be used anywhere else, limited by length
Modification	Complete structure, or frames	20% (very difficult)	Size modifications are very limited
	Columns or rafters	40% (difficult)	Removing welded plates necessary
	Steel sections	80% (easy)	Cutting or extending is possible
Quality check	Complete structure, frames, columns or rafters	80% (easy)	It is assumed that the original design documentation is available, possible degradation has to be checked
	Steel sections	40% (difficult)	Some material tests may be required
Geometry check	Complete structure,	40% (difficult)	Complex geometry
	Frames, columns or rafters	60% (moderate)	Tolerances, straightness and connections
	Steel sections	100% (very easy)	Tolerances and straightness (no connections)

The remaining material not classified as reusable parts have automatically reusability score of 0%. This category also contains the steel parts removed in order to prepare steel sections (Class D) to be reused as standard section without any restrictions. The estimated loss of the material due to the cutting of end plates is 10%.

3.3 Reusability indicator of the building

For the demonstration of the various choices at the end-of-life of the building, we have introduced and evaluated five different scenarios. *Scenario 1* involves the reuse of the entire building. The higher and lower halls are considered to be reused separately in *Scenario 2*. Then in *Scenario 3* the building will be dismantled into individual frames and in *Scenario 4* into individual components. The last option, *Scenario 5*, considers that the steel sections are extracted from the components by cutting off the end-plates and other intermediate welded parts. The inventory of reusable components and structures in each scenario is listed in *Table 3* as well as the overall reusability index R calculated according to *Eq.* (2).

Table 3. Structural decomposition of selected cases

Reuse case	Structure/Component	Class	Reusability r	Weight m	% of total weight
Scenario 1 R = 60%	Complete hall	A	60%	94,3 t	100 %
Scenario 2 R = 51%	Higher hall	A	60%	25,2 t	27 %
	Lower hall	A	60%	47,0 t	50 %
	Steel sections	D	64%	7,2 t	8 %
	Other steel	-	0%	14,9 t	16 %
Scenario 3 R = 51%	4 Higher frames	B	60%	21,0 t	22 %
	10 Lower frames	B	60%	46,5 t	49 %
	4 Columns HEA200/6.5 m	C	62%	1,5 t	2 %
	6 Columns HEA200/3.0 m	C	62%	1,4 t	1 %
	Steel sections	D	64%	8,8 t	9 %
	Other steel	-	0%	15,2 t	16 %
Scenario 4 R = 51%	28 Beams IPE360/9.98 m	C	60%	22,9 t	24 %
	28 Beams IPE360/9.94 m	C	60%	22,7 t	24 %
	3 Columns HEB220/6.1 m	C	62%	1,6 t	2 %
	10 Columns HEB220/4.1 m	C	62%	3,8 t	4 %
	6 Columns HEA300/6.1 m	C	62%	4,3 t	5 %
	19 Columns HEA300/4.1 m	C	62%	9,7 t	10 %
	4 Columns HEA200/6.5 m	C	62%	1,5 t	2 %
	6 Columns HEA200/3.0 m	C	62%	1,4 t	1 %
	Steel sections	D	64%	10,6 t	11 %
	Other steel	-	0%	15,9 t	17 %
Scenario 5 R = 43%	Steel sections	D	64%	63,9 t	68 %
	Other steel	-	0%	30,4 t	32 %

It can be observed than despite the higher reusability index r of steel sections, the overall score for *Scenario 5* is the lowest (see *Fig. 5*). This is caused by the loss of material due to cutting. It is calculated that 320 sections need to be cut in *Scenario 5* while only less than 112 sections in all the other scenarios. The structure contains also 489 bolted joints that have to be dismantled in any case.

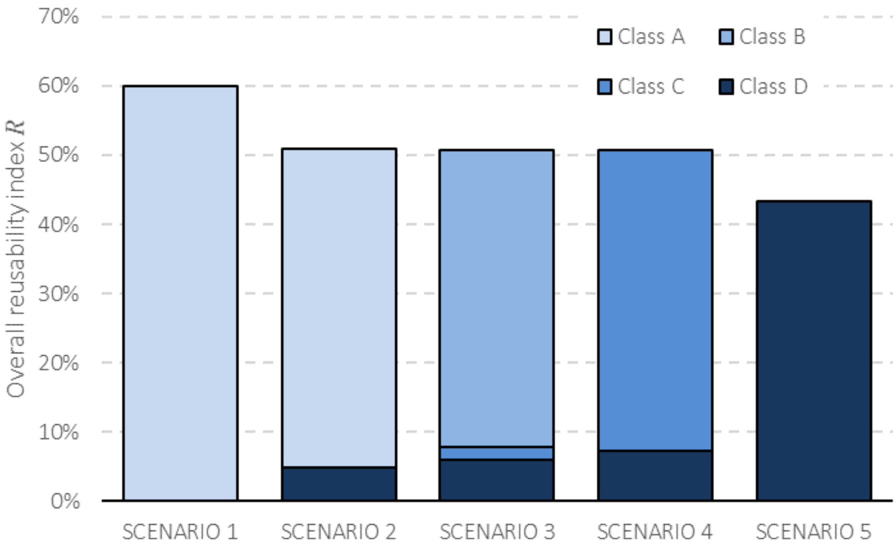


Fig. 5. Contribution of different component classes to the overall reusability index for the selected scenarios

4 LIFE-CYCLE ANALYSIS OF A SELECTED COMPONENT

The following case study compares the life-cycle environmental impacts and cost of a re-used rafter to the traditional "recycling" practice where the scrap is collected after demolition and melted in to produce new material. It is based on the LCA and LCCA calculation presented in [8], where the results were reported for 1 to 3 reuse cycles. Considering that the reusability index is 60% for the rafters, we can calculate that the average number of service lives is 2.49 if 60% of the rafters are always reused.

The calculation was carried out in OpenLCA software together with ELCD database for steel production, transport and waste processing. The components of steel rafter (see *Fig. 6*) are transported from different locations. 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 assembled in the workshop in Bocşa, Romania and transported to the building site in Arad. The same workshop is used for the cleaning and remanufacturing of reused beams.

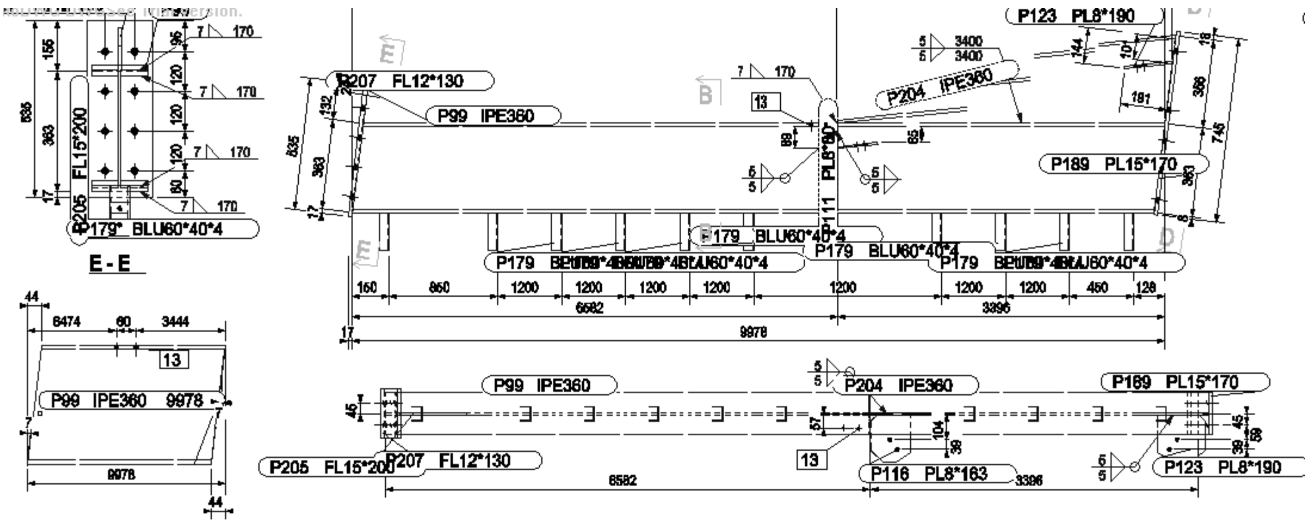


Fig. 6. Drawings of the selected steel component

Due to the comparative nature of the results presented, the environmental impacts of construction and use stages were not calculated, and only production, manufacturing, deconstruction and end-of-life stages are included in the results. The processes that are not present in ELCD database are based on the literature study [12]. *Table 5* shows selected life-cycle impacts and costs of the manufacturing, construction, demolition (or deconstruction) and recycling (or reuse) stages. More details of the inventories and processes can be found in [9].

Table 5. Results of LCA and LCCA calculations

LCIA category	units	no reuse	1x reuse	2x reuse	1.49x reuse
Global warming potential (GWP100)	kg CO_2 eq.	1075	901	642	774
Stratospheric ozone depletion (ODP10)	kg CFC11 eq. x 10^{-8}	4.27	4.44	3.52	3.99
Acidification potential (AP generic)	kg SO_2 eq.	3.33	2.90	2.11	2.51
Eutrophication potential (EP generic)	kg $(PO_4)^{3-}$ eq.	0.293	0.278	0.212	0.25
Photochemical oxidation (POCP high NOx)	kg ethylene eq.	0.089	0.046	0.032	0.039
Cost (designed for re-use)	€	1149	1131	1048	1090

The recycling scenario, where all the material is turned into scrap, can sometimes be more cost-effective because the cost of deconstruction can be higher compared to construction or demolition, due to the additional processes such as cleaning, sorting and quality check [8, 9].

We assumed that the cost of deconstruction could be 20% higher than construction (2.4 times the cost of demolition) in the building properly designed for reuse, because the building documentation and material certificates are available at the time of deconstruction. As it can be seen in the *Fig. 7*, the predicted final cost is lower than in the case of demolition/recycling (despite of higher deconstruction cost) and the environmental impacts are reduced as well.

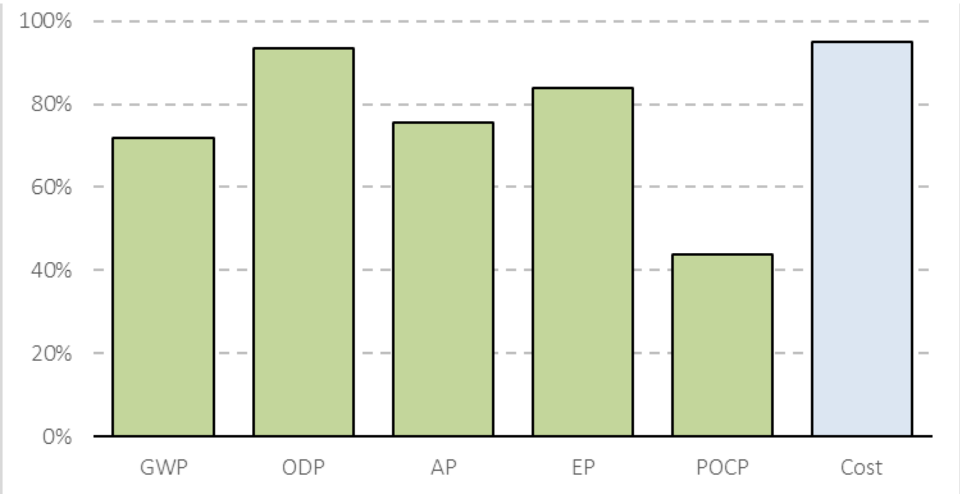


Fig. 7. Reduction of selected life-cycle impacts of the rafter reused 1.49x in average in comparison to the scenario without reuse

5 SUMMARY AND ACKNOWLEDGEMENTS

The method for the estimation of reusability of a single element, structure or the whole building was presented in this paper and applied on the existing case study of single storey steel structure. Comparison of different reuse scenarios showed that even separation to the most easily reusable parts (steel sections) might not be the best solution for the whole structure. The LCA/LCCA study demonstrated the use of the reusability index in the prediction of life-cycle impacts.

We would like to acknowledge the support of the partners of ReUSE project who provided a valuable feedback to the original version of the presented methodology.

REFERENCES

[1] Fujita M, Iwata M. “Reuse system of building steel structures”. *Structure and Infrastructure Engineering* 06/01;4(3), pp. 207-220, 2008

[2] Ngo T.D, Crawford R.H., Gammampila, R., Mendis, P. “Embodied energy analysis of prefabricated reusable building modules for a multi- residential building”. Proc. of Solar09: 47th ANZSES Annual Conference, Townsville, 2009

[3] Pongiglione, M., Calderini C. “Material savings through structural steel reuse: A case study in Genoa”. *Resources, Conservation and Recycling* 86, pp. 87–92, 2004

[4] Wastiels L., Van Dessel J., Delem L. “Relevance of the recycling potential (module D) in building LCA: A case study on the retrofitting of a house in Seraing”. Proc. of the Conf. on Sustainable Building SB14, Barcelona, pp. 650-659, 2014

[5] “Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives”, Brussels, 2008

[6] Sassi P. “Defining closed-loop material cycle construction”. *Building Research & Information* 36, pp. 509-519, 2008

[7] Webster M.D., Costello D.T. “Designing Structural Systems for Deconstruction: How to Extend a New Building’s Useful Life and Prevent it from Going to Waste When the End Finally Comes.” Proc. of Greenbuild Conference, Atlanta, GA.,14 p., 2005

[8] Hradil P., Talja A., Wahlström M., Huuhka S., Lahdensivu J., Pikkuvirta J. ”Re-use of structural elements: Environmentally efficient recovery of building components”. *VTT Technology* No. 200, VTT Technical Research Centre of Finland, 2014

[9] Hradil P. “Barriers and opportunities of structural elements re-use”. Research report VTT R-01364-14, VTT Technical Research Centre of Finland, 2014

[10] Densley Tingley D., Cooper S., Cullen J. “Understanding and overcoming the barriers to structural steel reuse, a UK perspective”. *Journal of Cleaner Production* (in press), 2017

[11] RCSC, “Specification for Structural Joints Using High-Strength Bolts”, Research Council on Structural Connections, December 2009

[12] Haney, H., “Environmental emissions and energy use from the structural steel erection process: A case study”, Master’s thesis, Colorado State University, 2011