Assessment of reusability of components from single-storey steel buildings

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ABSTRACT: This paper presents the development of the method for prediction of reusability of building components and whole structures. The method was developed especially for single-storey steel buildings, but can be applied with some modifications for any component (or cluster of components) reclaimed from a demolished or refurbished building. It enables classification of various building parts and products through a procedure to calculate their reusability index. These values can be further used to produce a single reusability indicator of the whole end-of-life scenario (e.g. the complete or partial building reuse). The aggregated result of the whole building may be very useful in planning of demolition or reconstruction works as well as for the assessment of the environmental impact of the new buildings. The main novelty explored in this paper is the possibility of integrating the economical prospect of the recovered components in the reusability assessment. Indeed, the earlier developed reusability index was purely based on the technical requirements of recovering, remanufacturing and reusing component. Hence, it was a technical reusability indicator. The added element here is the possibility to include information on the prospective marketability of the recovered component. The methodology is benchmarked on a suite of single-storey hall type structures of different structural configuration.

1 INTRODUCTION

Reusing components of building, with minimal remanufacturing, presents considerable environmental benefits instead of crushing and recycling the base materials. Furthermore, spontaneous attempts to trade reusable construction elements in online trading platforms also demonstrate the economic viability of the reuse concept (Purkutori, 2018, Portal Power, 2018). Companies using similar building configurations (e.g. retail chains, petrol stations etc.) also discovered that it makes sense to pay attention to the assets locked in the building stock they use. In a rapid business cycle, these assets may become available sooner than the traditional fifty or hundred years design life used by engineers.

To improve the technical reusability of components further standardization and design for reuse should be introduced already in the planning phase. In parallel with these efforts, it is also important to develop conceptual level hierarchy to compare the effect on reusability of the different design solutions. Such hierarchical methodology, leading to technical reusability index of individual components and entire buildings was proposed to support the priorities of the European Waste Directive (European Commission, 2008).

The study here extends the initially developed technical reusability index (Hradil et al., 2017) with elements related to the market potential of the recovered components. This technical-economical assessment is applied for three framed-building configurations in the present paper.

2 ASSESSMENT OF REUSABILITY

World Steel Association (2015) highlighted, in the context of circular economy, the significant advantages that steel industry has over competing materials, identifying the main four attributes to define these advantages, i.e. *Reduce*, *Reuse*, *Remanufacture* and *Recycle*.

Kibert (2008) presented some basic steps needed to obtain a closed-loop material usage and material recovery and to reduce waste at the end of the life of a building, i.e. (a) the building must be designed for demountability; (b) the materials used in construction process must be recyclable; (c) the production and use of materials must be harmless; (d) the recycled materials must be harmless.

Steel structures are, in general, highly demountable and the reuse process can offer great environmental and economic advantage. It is also very well known the second-hand market for reuse of steel structures is still small, but there is a great potential for increasing it. The reuse refers either to the structures as a whole or to components (frames, beams, columns, purlins) and cladding system.

Densley Tingley and Allwood (2014) identified a number of existing barriers to structural steel reuse, highlighting three of main concern: (1) sourcing and procurement of reused steel, (2) cost implications for structural steel reuse and (3) steel re-certification.

From this point of view a degree of standardization is needed, both in the design for deconstruction and evaluation of reused structures/components.

The aim of design for deconstruction is to eliminate demolition process as an end-of-life building option. Design for deconstruction should be implemented on three levels, i.e. building level, product level, and materials level.

In the second case, it is needed a clear procedure to evaluate the performance of the existing steel elements for reuse by non-destructive tests, if possible.

Reuse of building materials and components replaces the efforts arising from acquisition and preprocessing of the primary material or recycling from the cradle to the point of their functional equivalence. This point, however, depends on the complexity of the component or component cluster to be reused. Therefore, a classification system was developed in ReUSE project (Hradil et al., 2014) to distinguish between different reusable components and structures (see Figure 1). This classification corresponds to the common definitions for structural steel (CEN, 2008) with steel constituent product (Class D and E), fabricated components (Class B and C) and structural kit (Class A).

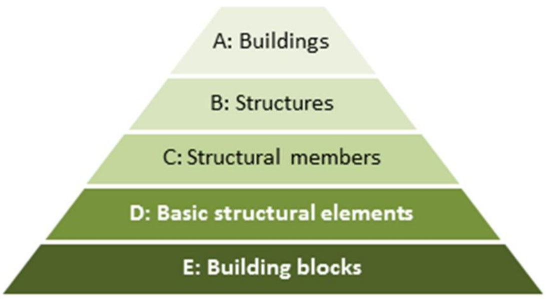

Figure 1. Functional classification of the building parts

This classification system was then used to develop a methodology for the assessment of the technical reusability of components r and whole building R (Hradil et al., 2017). Such indicator describes the technical readiness of the structure to be deconstructed and reused either as whole or part-by-part. However, the real reuse potential depends also on the market demand at the time of deconstruction. This aspect is introduced in the present study.

2.1 *Technical reusability*

The reusability r of a single component or component cluster is calculated according to Hradil et al. (2017) using Equation (1).

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

where ρ_i are the results of assessment of individual performance categories (Deconstruction, Handling, Separation and cleaning, Redesigning, Repurposing, Alterations, Quality checking and Geometry checking) from 0% (impossible) to 100% (very easy) and w_i are weighting factors of those performance categories in order to obtain reusability index r between 0 and 1. For the whole building, an aggregated result R can be calculated according to Equation (2).

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

where m_i denotes the mass of individual components.

2.2 *Economic prospect*

Similarly, as in case of technical reusability, the market demand for the recovered components can be described as a number ranging from 0 to 1. This number can be, in fact related to so-called “allocation factor for burdens and credits between supplier and user of recycled materials” in PEF CFF formula (European Commission, 2017). An example of such factor calculated for single-storey steel buildings and their components in Finland is given in this section.

According to the data from the Finnish Population Register (2015), 2587 single storey steel buildings were erected in Finland between 2013 and 2014. Typical spans of those buildings were estimated from their floor areas (assuming 2:3 aspect ratio) and approximated with the lognormal distribution with geometric mean 7.77 m and standard deviation 2.51 m (Figure 2). Similarly, the lognormal distribution of building heights was obtained with the geometric mean 4.15 m and standard deviation 1.71 m (see Figure 3). The geometric properties of their floor areas log-normal distribution are then 221 m^2 and 3.03 m^2 as in Figure 4.

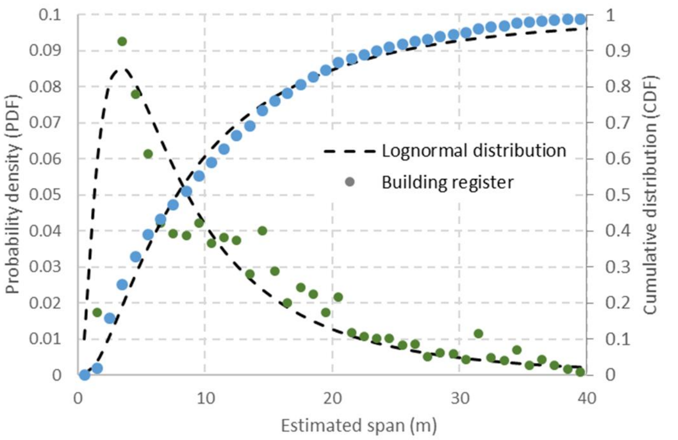

Figure 2. Statistical model of spans of single storey steel buildings built in Finland between 2013 and 2014 (Population Register Centre of Finland, 2015).

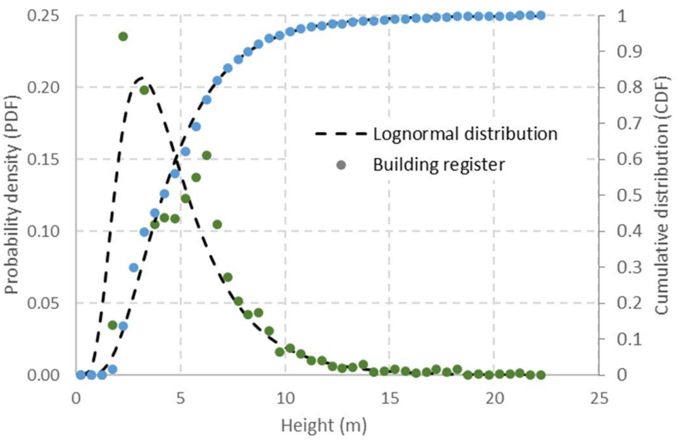

Figure 3. Statistical model of heights of single storey steel buildings built in Finland between 2013 and 2014 (Population Register Centre of Finland, 2015).

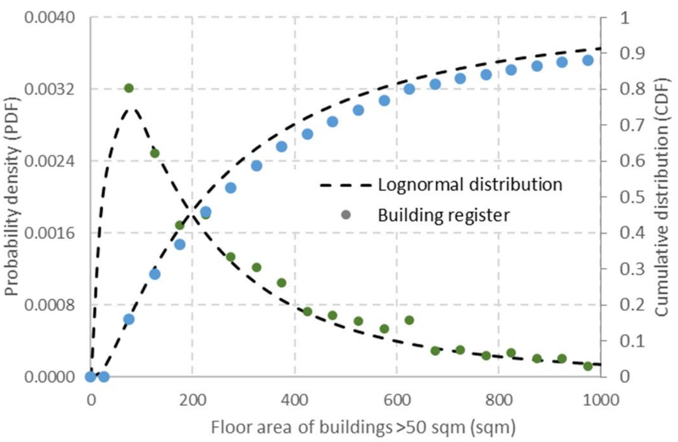

Figure 4. Statistical model of floor areas of single storey steel buildings built in Finland between 2013 and 2014 (Population Register Centre of Finland, 2015).

The absolute likelihood of having the same building available for demolition as the new design at a certain time is, of course, zero. However, with some flexibility in main dimensions, the models indicate for instance that the probability that a single building has span 32 ± 1 m is 0.83%, probability that its height is 6 ± 0.25 m is 4.9% or probability that its floor area is 960 m^2 ± 10% is 3.03%.

Such probabilistic models can be used to predict the economic index e_i of the individual building components with the given ranges of timing and main building dimensions. Then the overall economic prospect E can be calculated according to the Equation (3).

$$E = \frac{\sum m_i e_i}{\sum m_i} \tag{3}$$

3 REUSABILITY OF INDUSTRIAL BUILDING

Portal frames for industrial buildings have been extensively studied because of their widespread use. The improvement of the design methods for portal frames is one of the recurring topics in the field of steel structures. Due to the large number of similar framed structures, the desire to “automate” the design and manufacturing process was popular from the very early stage. As Dowling et al. (1982) noted, there are two design tendencies when trying to achieve more economical solutions: (a) to use compact hot-rolled sections and exploit the advantages of plastic design and (b) to use slender built-up sections with the most advantageous distribution of the material but keep the design in the elastic range. The second option usually leads to slender structures, and therefore stability becomes the main concern of the designer.

One of the outcomes of the earlier research project PRECASTEEL was a database of optimized constructional steelwork for industrial buildings (University of Navarra, 2010) that are able to resist up to 1500 N/m^2 of vertical snow load and appropriate horizontal wind load or seismic load with the peak ground acceleration up to 0.32 g. In this project, the frames (welded-tapered, hot-rolled and truss girders) were optimized to minimize the steel consumption with sufficient structural resistance and stability using advanced 3D finite element models and genetic algorithms as optimization and simulation methods.

3.1 *Selected building types*

Three of the optimized solutions with welded-tapered, hot-rolled and truss frames were chosen for comparison in this study (Figures 5 to 7). Configurations were taken from outcomes of PRECASTEEL project dedicated to optimizing industrial buildings for different climatic and earthquake regions in Europe (University of Navarra, 2010).

The dimension range for the building was deliberately selected, for which several of these typologies are competitive. Heavy snow load (1500 N/m^2) was assumed and minimum seismic loading to reflect the typical configurations in Finland. The span of the frame is 32 m and eaves height is 6 m. The total length of the building is 30 m with six identical frames at 5 m spacing.

Comparative advantages and disadvantages of the three typologies are well documented, for instance in terms of manufacturing demand, strength, deflection limitations, ductility etc. This study, however, focused on the assessment of the reusability of such buildings from the technical and economical point of view. Figures 5 to 7 show the cost breakdown provided by the project web application (University of Navarra, 2010).

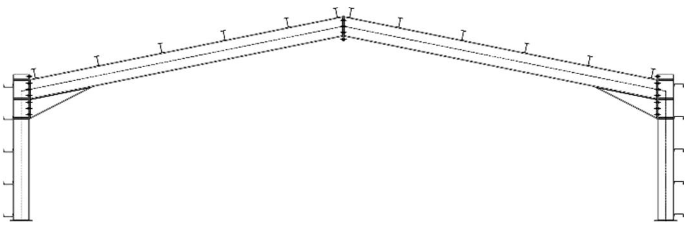

Figure 5. Geometry of the selected hot-rolled frames (University of Navarra, 2010).

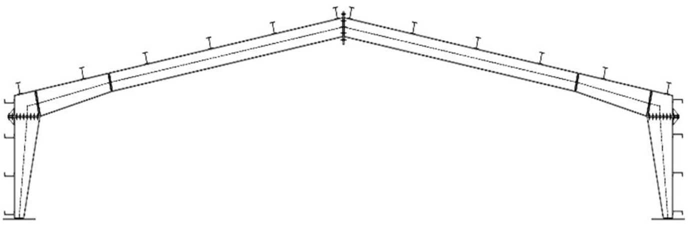

Figure 6. Geometry of the selected welded-tapered frames (University of Navarra, 2010).

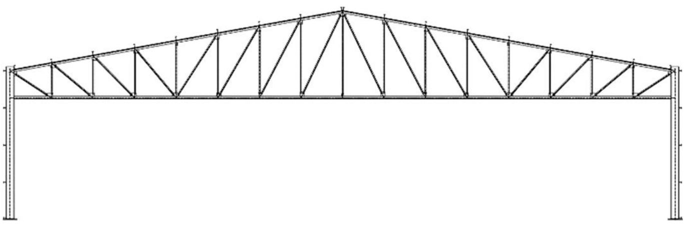

Figure 7. Geometry of the selected truss-girders on columns (University of Navarra, 2010).

Table 1. Materials and costs of different solutions

	Hot-rolled	Welded	Truss
Steelwork	50.9 t	49.1 t	34.0 t
Frames	*32.5 t*	*30.7 t*	*15.8 t*
Purlins & rails	*17.7 t*	*17.7 t*	*17.6 t*
Bracing	*0.44 t*	*0.44 t*	*0.39 t*
Abutments	*0.24 t*	*0.24 t*	*0.24 t*
Envelope	1792 m^2	1792 m^2	1792 m^2
Estimated cost	242 k€	242 k€	203 k€

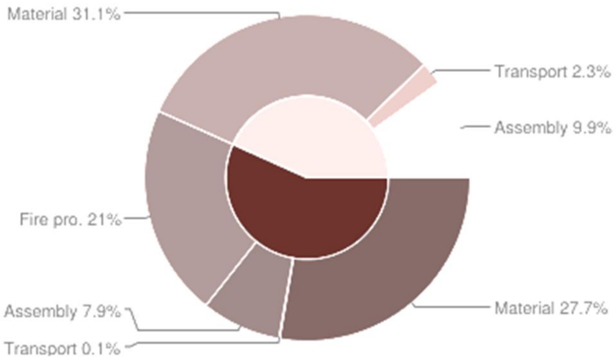

Figure 8. Cost breakdown of the structure with hot-rolled frames (University of Navarra, 2010); structure 56.7% (dark) and cladding 43.3% (light).

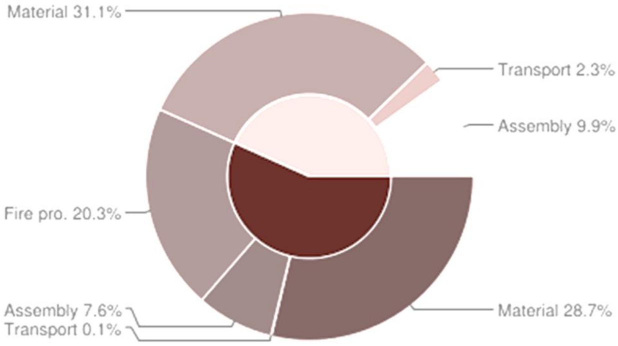

Figure 9. Cost breakdown of the structure with welded-tapered frames (University of Navarra, 2010); structure 56.7% (dark) and cladding 43.3% (light).

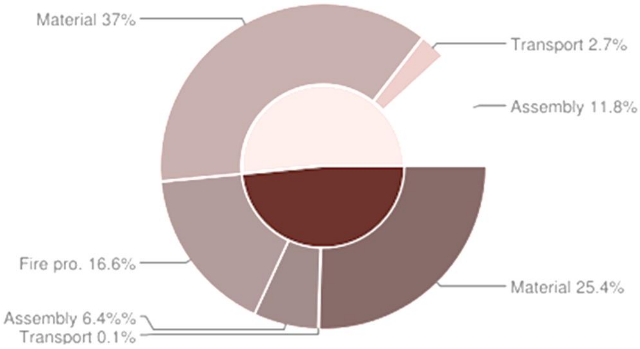

Figure 10. Cost breakdown of the structure with truss girders (University of Navarra, 2010); structure 48.5% (dark) and cladding 51.5% (light).

As can be seen from Table 1, hot-rolled and welded-tapered frames have almost identical weight that results in an overall steel consumption between 51 and 53 kg/m^2 of floor area and similar cost estimation in Table 1. Obviously, the truss girder is more suitable solution for such a long span and its steel consumption is considerably lower (about 35 kg/m^2). It should be noted that this difference does not affect the assessment of reusability because both technical and economic indicators are normalized to the total mass of the structural steelwork as described in Equations (2) and (3).

3.2 *Reuse scenarios*

Three basic situations are considered in the present study.

Scenario 1: Deconstruction and re-assembly of the whole structure is the scenario where most of the structural steel can be recovered. It is also economically competitive especially when the original building's design documentation and material certificates are available.

Scenario 2: Reuse of the primary structure (frames) in a new building design can be considered for instance if the new building's span is the same as the original one, but its length or frame spacing needs to be different. It is assumed that the steel sections recovered from the secondary structure (purlins and rails) are offered for reuse to the material dealers with 5% weight loss due to the removed end-joints.

Scenario 3: The last scenario considers the situation, when there is no possibility to reuse directly the whole structure or frames. Then the building owner or demolition contractor may decide to extract from the salvaged structural steel as many hot-rolled sections as possible by removing old paint and welded plates. It is assumed that 95% of purlins weight can be recovered (as in Scenario 2), 90% of hinged columns, 80% of fixed columns and 50% of tapered hot-rolled rafters. Short sections from truss girders are not considered as viable material for reuse, and therefore are not included in the list of recovered sections.

The total mass of reclaimed steel in each scenario is presented in Table 2. It is clear that the difference between Scenario 1 (Whole structure) and Scenario 2 is very small and the final choice will depend mostly on the actual demand from the new building plan.

Table 2. Reused steel

	Hot-rolled	Welded	Truss
Whole structure	50.9 t	49.1 t	34.0 t
Frames, sections	49.3 t	47.6 t	32.5 t
Sections	37.2 t	16.9 t	20.2 t

It is assumed that the fabricated elements will retain their value (1.3 €/kg) when reused, but steel sections can be only sold for the price of steel scrap (0.2 €/kg) together with the remaining material.

Calculation of the present value *PV* of reused steel is based on the mean service life of single-storey steel buildings in Finland $t = 27$ years (Population Register Centre of Finland, 2015), unit cost of fabricated components $u = 1.3$ €/kg, steel sections and scrap $u = 0.2$ €/kg and discount interest rate $r = 5\%$ in Equation (4).

$$PV = \sum m_i u_i / (1 + r)^t \tag{4}$$

where m_i is the mass of reused steel components, sections and scrap.

Figure 11. Present value of the industrial hall with 5% discount interest rate of reused components.

As can be seen from Figure 11, the most valuable scenario is the relocation of the whole building. However, it is typically the least feasible scenario as well due to very limited market prospects to re-assemble the structure in a different location. These aspects will be discussed in the following sections.

3.3 *Technical reusability*

Several types of components (or component clusters) are assessed in this study according to the methodology presented in Hradil et al. (2017). The weighting factors used in this study are presented in Table 3.

Class A: Whole structure disassembled and prepared to be re-assembled in the future.

Class B: Primary structure, frames, removed from the building in order to be erected in another building project.

Class C: This class is not considered in the present scenarios, although it might include for instance sandwich panels, fabricated columns and rafters.

Class D: Steel sections recovered from purlins, rails and hot-rolled frames and columns by removing welded end-plates and cleats.

Table 3. Performance weighting factors *w*

Performance category	*w*
Deconstruction	30%
Separation and cleaning	10%
Handling and manipulation	15%
Quality control	15%
Geometry checking	5%
Redesigning (reuse of design documentation)	10%
Repurposing	5%
Modification	10%

Then the evaluation of technical performance of the building components and structures is described in the following overview and Table 4. Its results calculated by Equation (1) are then presented Table 5.

Table 4. Performance assessment of reuse *r*

Assessment		*r*
Deconstruction		
Any component	*easy*	0.8
Separation and cleaning		
Whole structure	*easy*	0.8
Primary structure, frames	*difficult*	0.4
Hot-rolled sections	*very difficult*	0.2
Handling and manipulation		
Whole structure, frames	*very difficult*	0.2
Hot-rolled sections	*moderate*	0.6
Quality control		
Whole structure, frames	*easy*	0.8
Hot-rolled sections	*difficult*	0.4
Geometry checking		
Whole structure	*difficult*	0.4
Primary structure, frames	*moderate*	0.6
Hot-rolled sections	*very easy*	1.0
Redesigning (reuse of design documentation)		
Whole structure	*easy*	0.8
Primary structure, frames	*difficult*	0.4
Hot-rolled sections	*impossible*	0.0
Repurposing		
Whole structure	*impossible*	0.0
Primary structure, frames	*very difficult*	0.2
Hot-rolled sections	*very easy*	0.8
Modification		
Whole structure, frames	*very difficult*	0.2
Hot-rolled sections	*very easy*	0.8

Deconstruction
This performance is assessed as easy because all parts are connected by bolts that are accessible from the ground or man-lift.

Separation and cleaning
The bolted connections are easily accessible in the studied structures, and therefore separation and cleaning of components for the whole structure re-assembly is assessed as easy. On the other hand, it is assumed that the intumescent paint has to be shot blasted from frames in order to reuse them in a different type of building. Separation of sections is then very difficult because their welded end-plates and cleats have to be additionally removed.

Handling and manipulation
Since several components are exceeding standard transport lengths and are prone to damage, the hall and frame handling is assessed as very difficult. However, manipulation with already separated steel sections is a moderate task according to the assessment methodology.

Quality checking
It is assumed that the design documentation of the hall and its frames is available at the building's end of life. Therefore, the quality of the materials can be very easily verified. On the other hand, the sections are typically distributed via material dealers and their quality needs to be verified again to comply with the requirements of EN 1090, which tends to be a difficult task.

Geometry checking
All relevant dimensions and tolerances have to be verified, in order to properly re-assemble the whole structural steelwork or its parts including connections (the complete structure is assessed as difficult and the frame as moderate). The verification of straightness and tolerances of the sections is then very simple.

Redesigning (reuse of design documentation)
The re-assembled structure needs typically very little additional design input (redesigning is easy). However, the isolated frames contribute only partly to the new building design (moderate redesign). Finally, the separated sections are assessed as impossible, because the new building has to be completely designed from the scratch.

Repurposing
The complete hall has practically no chance to be repurposed into something else, and therefore its performance score is zero in this category. It is also very difficult to give another purpose to its primary structure (frames). On the other hand, steel sections can be used in a wide range of applications (also as non-structural components), and therefore are evaluated as easy.

Modification
It is possible to extend or reduce the hall by adding or removing its bays, but other changes would be very difficult. Similar assumption is made for the separated frames. Steel sections are, however, easy to cut to smaller sizes or combine to build up more complex components.

Table 5. Component reusability index *r*

	Class	*r*
Whole structure	A	0.61
Primary structure, frames	B	0.53
Hot-rolled sections	D	0.58

The aggregated results for the whole building subjected to one of reuse scenarios were calculated according to Equation (2) and are presented in Figure 12.

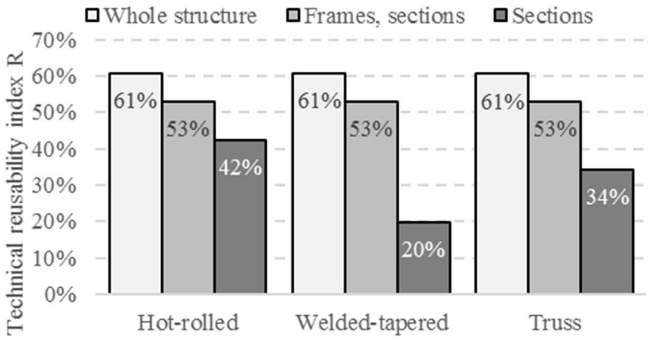

Figure 12. Reusability index of the structural steelwork

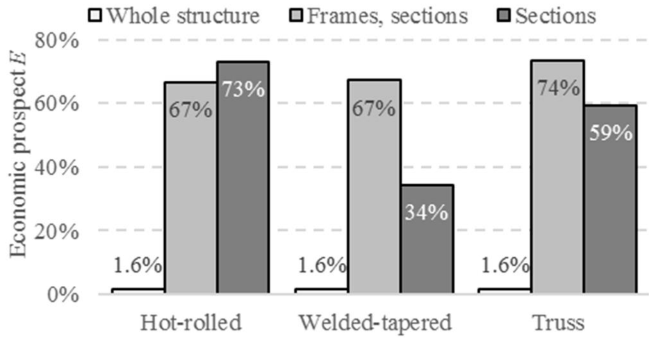

Figure 13. Economic prospects of the structural steelwork

3.4 *Economic prospects*

Form the evaluation of the single-storey steel buildings market in Finland presented in Section 2.2 of this paper, individual indexes can be obtained for the time span of 1 year and geometric limits given in Table 6. It is assumed that in the case of the whole structure reuse, all three criteria have to be satisfied (span, height and floor area), and therefore the index *e* is calculated as number of buildings per given period *n* multiplied by the probability *P* that all the criteria will be satisfied. With 1294 buildings erected per year (Population Register Centre of Finland, 2015), the chance that one of them will satisfy all criteria is only 1.59% according to Equation (5).

$$e = P(span \cap height \cap area) \cdot n = 1.59\% \qquad (5)$$

On the other hand, the reuse potential of separated frames is significantly higher, because only span and height are considered. It results in 52.6% chance that a similar building will be erected (see Table 6).

Table 6. Component economic prospect *e*

	Class	*e*
Whole structure [1), 2)]	A	0.016
Primary structure, frames [2)]	B	0.526
Hot-rolled sections [3)]	D	1.000

[1)] Floor area should be 960 m^2 ± 10%
[2)] Frame span should be 32 ± 1 m and height 6 ± 0.25 m
[3)] It is assumed that the sections can be always reused

Similarly, as for the reusability index *R*, the overall economic prospect *E* is the weighted average of the individual coefficients related to the particular scenario according to Equation (3). The results are presented in Figure 13.

The evaluation of the market potential of the reusable components indicates that the most viable scenario would be to reuse sections from the structure with hot-rolled frames, and frames in the other two cases. This market potential strongly depends on the selection of geometrical and time ranges. Generally, if the possibility of having reused structure or some of its components is considered in earlier stages of building planning, the geometric constrains can be less strict. Moreover, the possibility to store the disassembled structure for longer time increases the chance that it will meet the requirements of some investors. In combination with the superior technical reusability of the whole structure, the companies such as Portal Power (2018) are able to sell successfully pre-used steel structures.

4 SUMMARY AND CONCLUSIONS

The technical-economic assessment of the reusability of single component or the complete constructional steelwork presented in this paper can become a useful tool for the decision making process before the deconstruction and processing of the deconstructed steelwork. It can be also used to evaluate the reusability of the new building's design for instance in the framework of the sustainable building certification system.

The pilot study of three similar frames revealed the importance of the clear definitions of the performance limits and proper calibration of the weighting factors *w* in the technical assessment part, and of the ranges of acceptable parameters for reuse in the economic assessment part. The further calibration and benchmarking and "reality checks" of this assessment method will be performed in the framework of the ongoing RFCS project PROGRESS (Provisions for Greater Reuse of Steel Structures).

5 ACKNOWLEDGEMENTS

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