Environmental- and life cycle cost impact of reused steel structures: a case study

S. Vares, P. Hradil, S. Pulakka
VTT Technical research Centre of Finland Ltd

V. Ungureanu
Politehnica University of Timişoara

M. Sansom
Steel Construction Institute

ABSTRACT:

The European steel sector has developed LCA assessment methods over many years, methods taking into account benefits of recycling. Unlike recycling, the reuse of steel structures extends the steel life with lower impacts, because steel recovery through melting process is not needed. Benefits based on the savings in natural/virgin resources seem to be obvious by re-using materials, structures or buildings and giving them second, third or even fourth life. However, to show the benefits with the using a well justified methodological framework is not easy or straightforward as assumptions about the future reuse should be made. End of life processes, further processing, material identification and possible modification, and re-construction are the processes should be evaluated for the reuse case.

Earlier studies have shown difficulties in the analysis of realistic economic impacts of reuse concepts. The number of possible alternatives is high and in worst cases, the reuse could lower the benefits compared to steel recycling.

This theoretical case study is a part of PROGRESS project (Provisions for greater reuse of steel structures). The goal is to show the greenhouse gas impacts (as GWP) and life cycle costing (LCC) of the steel framed industrial building for the first life cycle and for the case of steel frame and envelope reuse. The study pointing out benefits and loads and by discussing the meaning of methodological differences when using building Life Cycle Assessment methods (LCA).

1 INTRODUCTION

The study describes an LCA model of a single-story industrial hall in Finland, which is made of steel portal frames, secondary structure (purlins, side rails and bracing), and envelope from steel sandwich panels with mineral wool insulation.

Although, the most common single-storey steel structure in the Nordic countries has roof truss girders on columns, portal frames offer a competitive alternative to this construction system, especially for shorter spans. Moreover, portal frames are more easily reusable because they are more resistant to damage caused during the deconstruction process.

In this study, the main principle for assessing the profitability of a case or project is to compare the economic benefits of reuse to the economical inputs required by the new construction in use of steel structures.

The market of second hand elements is relatively small. In addition, the clients may reconsider using old elements from the demolished building or salvage yard if it is more costly than the traditional sources. The lack of recovery facilities (salvage yards) for reused elements and the lack of information about available components from planned and on-going demolitions inhibit mainstream reuse. Therefore, it is essential to identify a framework of cost optimal reuse cases like industrial buildings and warehouses with similar steel sandwich panels and load-bearing structures with standardized dimensions, connections, joints and steel structures as modular elements.

The assessment of profitability is based on the literature and the outcomes of recent relevant research and demonstration projects.

Environmental impact assessment is based on life cycle assessment method (LCA), considering the system boundaries as presented in Section 3.

2 STRUCTURAL OPTIMIZATION

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 RFCS project PRECASTEEL was a database of optimized constructional steelwork for industrial buildings (Precasteel web 2.0 application, 2011) that is 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 (PGA) up to 0.32 g.

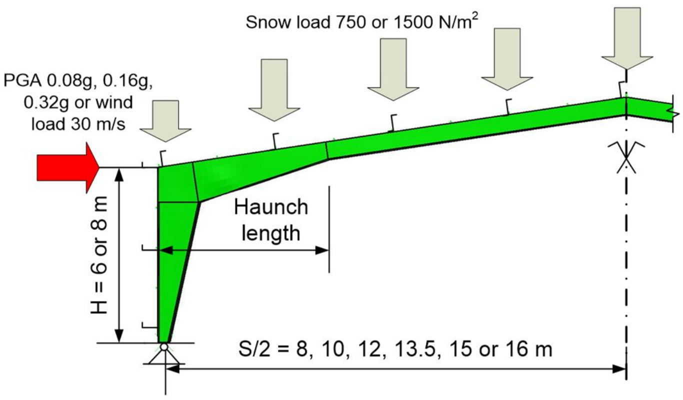

Figure 1. Loads and basic dimensions of the optimized frames

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 (Figures 1 and 2).

One of the optimized solutions with welded-tapered frames was selected for the purpose of this study. Since the building shall be erected in Finland, heavy snow load (1500 N/m^2) was assumed, but no seismic loading. The span of the frame is 16 m and eaves height is 6 m, which leads to steel consumption of the primary structure under 20 kg/m^2 (Figure 3). The total length of the building is 30 m with six identical frames at 5 m spacing.

This theoretical study takes into account optimized steel structures.

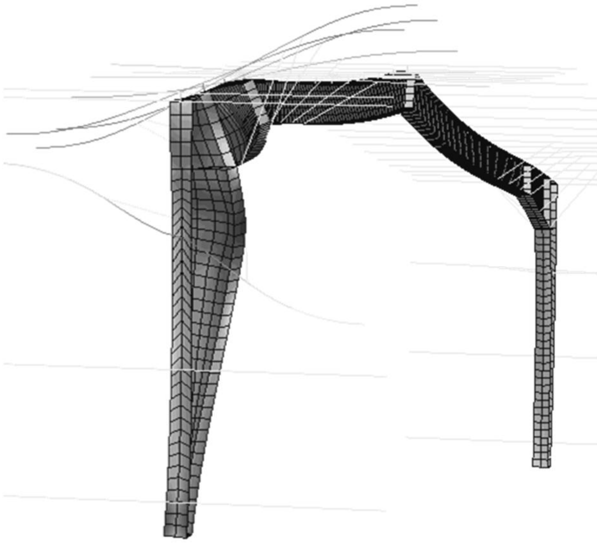

Figure 2. Example of lateral-torsional buckling failure of 3D FEM model used for optimization of the structural shape.

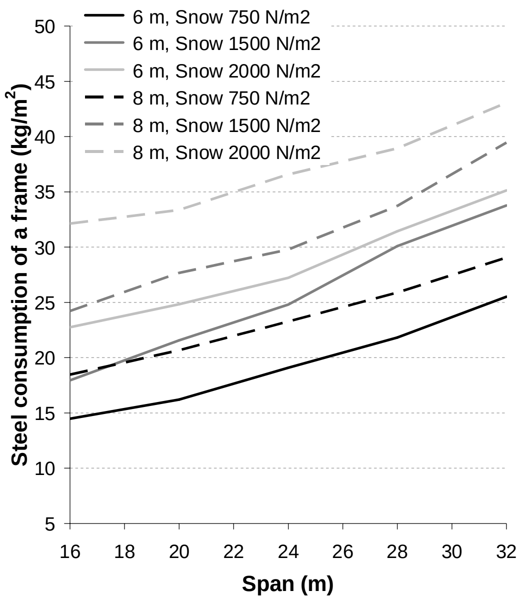

Figure 3. Steel consumption of welded-tapered frames with different heights and snow loads

3 LIFE-CYCLE ASSESSMENT

Life cycle assessment method (LCA) was chosen for the evaluation of the environmental- (SFS-EN ISO 14044:2006, EN 15978:2011) of the industrial building.

The main goal is to show the potential of environmental performance and improvements through comparison of new hall construction (‘New building’) and steelwork with reused steel components (‘Reused steel’). The assessment considers greenhouse gases (GWP) as the indicator of environmental performance and euros (€’s) for lifetime costing.

System boundaries:

- Functional unit for the industrial building hall is the heated floor area 480 m^2;
- External walls and ground floor slab has U-value 0.16 W/m^{2}K, roof elements 0.09

W/m^{2}K and windows + entrance-door 1.0 W/m^{2}K;

- The area of windows and door is 44 m^2 (20 + 24 m^2);
- The assessment takes into account the main following building structures: foundation (concrete), ground floor slab (concrete and EPS insulation), steel frame, sandwich panels (steel cassettes with mineral wool), triple glazing windows and entrance door;
- The building assessment includes the following life cycle stages: 'Product stage' (A1 - raw materials, A2 - transportation, A3 - production), 'Construction stage' (A4 - transportation, A5 - building construction), 'Use stage' (B6 - operational energy use), 'End of life' (C1 - demolition/deconstruction and C2 - transportation to the salvage yard, in case of reused steel) and impact beyond the system boundary (D - recycling and future reuse);
- GWP's for building materials based on Environmental Product Declarations (EPD's) by Ruukki Construction Oy (Ruukki Construction, 2015), ELCD database (Joint Research Centre, 2006) and literature data (Haney, 2011, Rossi et al., 2011).

4 LIFE-CYCLE COSTING

Life Cycle Cost (LCC) calculations are also made for the theoretical industrial steel hall ('New building') and for the steel reuse building case ('Reused steel'). This follows ISO 15686-5 standard. LCC assessment contains:

- 'Product stage' includes inventory in reuse case, structural planning, use of BIM model, HVAC planning, steel panels and steel frame in new buildings case, concrete + EPS, new windows and doors in both cases and transport;
- Construction stage includes transport, additional testing, cutting, drilling, installing, paintings etc., works on site;
- Use stage contains only operational energy use (no maintenance).

Critical points of cost optimization are: simple assessment of reusability, relatively low disposal cost, no or minor prefabrication needs, no needs for storage costs, relatively cheap construction actions.

4.1 *Product stage (A1-3)*

This simplified assessment takes into account primary structure (Figure 4), secondary structure, foundations, floor slab and envelope. In the "reuse" scenario, it is considered that the building is completely re-assembled or all of its parts are reused with no steel waste materials generated. Use of the building materials for the primary construction is shown in Table 1.

Product stage for the reused structures include sand blasting and cutting welds (if required) 10 kgCO_2e per tonne of steel (Rossi et al., 2011) and repainting from 260 to 280 kgCO_2e per tonne of steel as in Table 1.

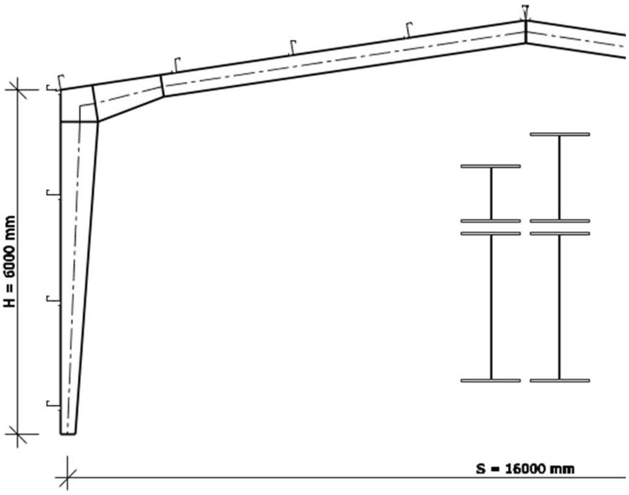

Figure 4. Selected portal frame shape

Table 1. Total amount of products (mass, area, volume) and unit GWP (kg CO_2e) for material production (A1-A3).

Product	total units	unit impact kgCO_2e
Welded-tapered frames [1)]	8.52 t	2.71 / kg
Purlins, rails & bracing [1)]	5.18 t	2.75 / kg
Sandwich panels[1)]	1068 m^2	53.5 / m^2
Concrete [2)]	565.5 t	290 / m^3
EPS [2)]	3.9 t	3.38 / kg
Windows [3)]	20 m^2	20.5 /m^2
Door [3)]	24 m^2	21.5 / m^2
Frame reconditioning [4)]	8.52 t	0.27 / kg
Purlins etc. reconditioning [4)]	5.18 t	0.29 / kg
Panels reconditioning [4)]	1068 m^2	0.32 / m^2

[1)] Environmental Product Declarations (Ruukki Construction, 2015)
[2)] ELCD database (Joint Research Centre, 2006)
[3)] VTT tool, Ilmari (VTT, version 2017)
[4)] Communication from Ruukki (Ruukki Construction, 2018)

4.2 *Construction stage (A4-5)*

The finished products should be transported to the building site from the factory in Raahe (frame) and Hämeenlinna (purlins, rails and panels). The distances of 469 km and 107 km used in this study are the weighted average distances to the major cities in Finland from Raahe and Hämeenlinna respectively. Articulated lorry transport (40t) was assigned to each product from the ELCD database (Joint Research Centre, 2006), and 0.1638 kgCO_2e/km was used for the return journey of an empty truck.

The construction work included excavation of soil for the floor slab and foundations from the ELCD database, concreting and erection of constructional steelwork using 100-tonne crane, forklifts and man-lifts (Haney, 2011). Their respective workloads are presented in the following tables (Table 2 -4).

Table 2. Crane workload.

Process	per piece	total
Columns preparation	3 min	36 min
Columns placing and temp. conn.	10 min	120 min
Rafters preparation	2.5 min	30 min
Rafters placing and temp. conn.	7.5 min	90 min
Purlins and rails placing	5 min	250 min
Sandwich panels placing	5 min	490 min
Total load		**1016 min**

Table 3. Forklift workload.

Process	per piece	total
Columns unloading	7 min	84 min
Columns placing	5 min	60 min
Rafters unloading	7 min	84 min
Purlins and rails unloading	3 min	270 min
Sandwich panels unloading	3 min	447 min
Total load		**945 min**

Table 4. Man-lift workload.

Process	per piece	total
Rafters placing and temp. conn.	7.5 min	90 min
Purlins and rails placing	5 min	250 min
Sandwich panels placing	5 min	490 min
Total load		**830 min**

Additional diesel consumption of 2400 kg was estimated for equipment transportation (1 x crane, 2 x forklift and 2 x man-lift) and workers transportation (15 workers, 14 working days).

4.3 *Use stage (B6)*

The use stage covers the building lifetime from the completion of building construction to the point of time when the building is deconstructed/demolished.

Lifetime for this assessed building is 27 year (it is the building service time according to lognormal calculation for the existence of Finnish industrial halls). During this lifetime, no maintenance, repair and material replacements and refurbishment are considered.

Operational energy consumption based on energy simulation made by E-pass tool (NewBee). Assessment considers building location Helsinki and climate condition based on weather data 'Helsinki 1979'. Default value used for the heating of industrial hall was 15^{o} C degree. No mechanical cooling was considered. Building hall was connected to the district heating network. GWP's for the energy consumption based on Finnish average district heat mix (Finnish District heating, Energy year 2016) and average electricity mix (Finnish Electricity, Energy year 2017) both including delivery losses and in case of electricity, also electricity imports. No heat recovery is considered.

Operational energy consumptions and unit GWP values for industrial hall is given in Table 5.

Table 5. Operational energy consumption and unit GWP.

Product	kWh/ m^2, yr	unit impact $kgCO_2$
Space heating	161	0.173 /kWh
Hot water	14	0.173 /kWh
Space cooling	0	0.152 /kWh
Electricity	45	0.152 /kWh

4.4 *Demolition/deconstruction stage (C1, C2)*

It is assumed that the deconstruction of the steel frame is the same process as its erection with an additional effort to maintain the integrity of the disconnected components. Such additional effort is in this study modelled as workload multiplier between 1 and 2 depending on the amount of reused steel. Moreover, the transportation (C2) of the recovered building elements to the nearest salvage yard was added to the model.

4.5 *Impacts beyond the system boundary (D)*

It is possible to calculate loads and benefits beyond the system boundary of the structure with components designed to be reused (Table 6).

Table 6. Life cycle stage D, GWP-values for steel structures (Environmental Product Declarations (Ruukki Construction, 2015).

Process	total units	unit impact kgCO2e
Welded-tapered frames	8.52 t	-1.31 / kg
Purlins, rails & bracing	5.18 t	-1.32 / kg
Sandwich panels	1068 m^2	-12.4 / m^2

The World Steel Association LCA methodology (World Steel Association, 2011) assumes that approximately 0.4602 $kgCO_2e/kg$ of steel is the saving allocated already in the product stage due to the recycling. In the sandwich panel with two 0.6 mm thick sheets it means to 4.335 $kgCO_2e/m^2$. This amount has to be subtracted from the potential saving (difference between allocated saving in Module A of the current and future buildings) in the product stage of the building to show correctly the net-impact beyond the system boundary.

5 RESULTS

LCA and LCC results are calculated for two scenarios: the first use ('New building') and 100% reuse of the steel structure of industrial building hall ('Reuse steel'). The reuse case is re-assembled from the recovered steel from the first scenario (Tables 7 and 10).

This assessment takes use environmental benefits as (GWP-savings). Result for the steel reuse case shows about 12 % lower GWP than when steel structures used in 'New building' first time (Table 7 and Figure 5).

Components for reuse and materials for recycling are considered as potential resources for future use (Modul D) and normally considered as beyond of system boundaries. This is taken use as net benefit and shown in Table 8 and Figure 9.

Table 9 and Figure 10 show correspondingly LCC results of the two alternatives studied ('New building' and 'Reused steel'). Result for steel reuse case shows 25 % lower investment cost, but when total life cycle is considered (27 year and life cycle stages A - C) the saving is only 5 %.

Both, the investment cost and life cycle cost difference, is about 40 €/floor-m^2.

Table 7. LCA results.

Product	New building tCO_2e/27yr	Reused steel tCO_2e/27yr
Product stage (A1-3)	**180.1**	**90.7**
Frame	*23.0*	*2.3*
Purlins and rails	*14.3*	*1.5*
Bracing	*3.1*	*3.1*
Envelope	*57.1*	*0.3*
Concrete and EPS	*81.6*	*81.6*
Reconditioning	*0.0*	*0.4*
Windows	*0.4*	*0.4*
Doors	*0.5*	*0.5*
Construction (A4-5)	**14.3**	**14.4**
Transport	*2.5*	*2.6*
On-site energy	*0.9*	*0.9*
Crane	*6.5*	*6.5*
Forklifts	*1.4*	*1.4*
Man-lifts	*2.0*	*2.0*
Excavator	*0.9*	*0.9*
Use stage (B6)	**481.0**	**481.0**
Demolition (C1, C2)	**10.8**	**19.3**
Transport	*0.0*	*0.4*
On-site energy	*0.9*	*0.9*
Crane	*6.5*	*13.1*
Forklifts	*2.0*	*2.0*
Man-lifts	*1.4*	*2.8*
Total (A-C)	**686.2**	**605.3**

The impact beyond system boundary (Module D) calculation is based on the net-savings of the future building's scenario compared to the current building. Therefore it is negative whenever the future recovery is superior to the current one (today's recycled content vs. future recycling or today's recycled content vs. future reuse), it is zero when the scenarios are identical (today's reused content vs. future reuse), and it is positive when the future end-of-life (EoL) scenario is less efficient (today's reuse vs. future recycling). The results are presented in Table 8 and Figures 5 and 9.

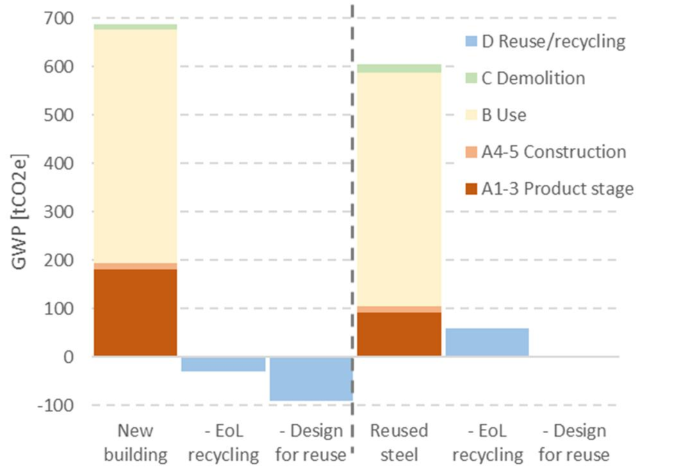

Figure 5. Total GWP (LCA method) of a new building (left) and reused building (right) including possible EoL scenarios.

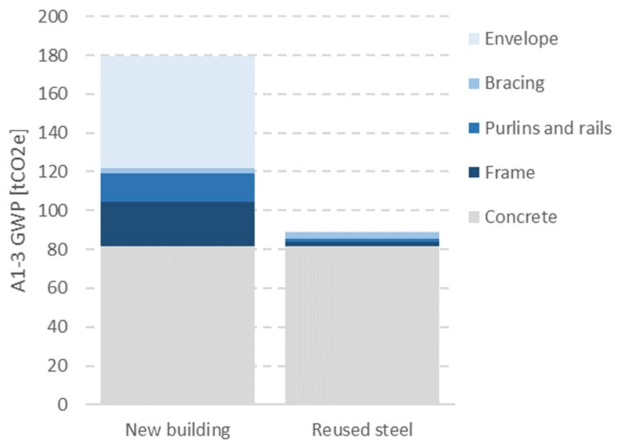

Figure 6. Product stage (Module A1-A3).

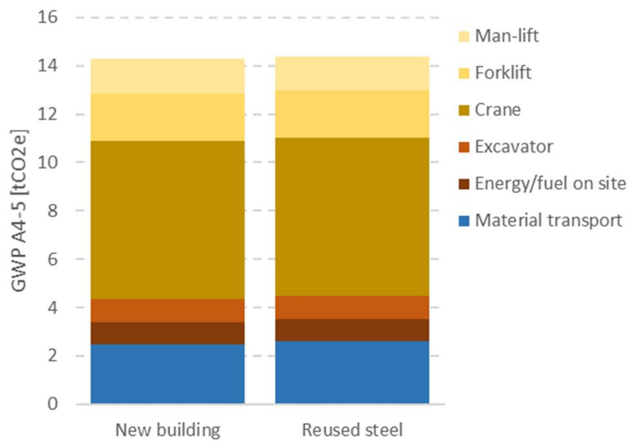

Figure 7. Construction stage (Module A4-A5)

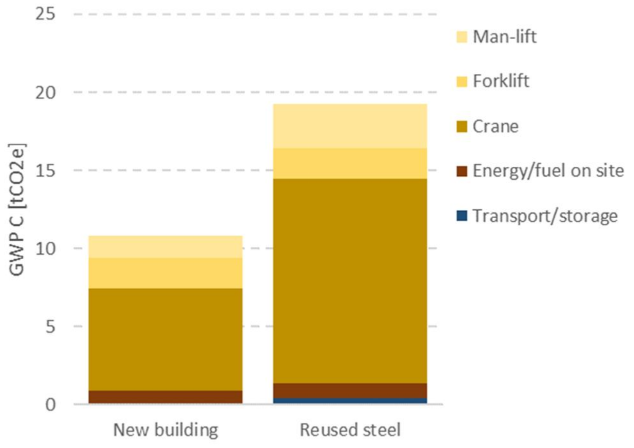

Figure 8. Demolition stage (Module C1 and C2)

Table 8. LCA potential savings.

Product	New building tCO_2e	Reused steel tCO_2e
Loads/benefits (D) with EoL recycling	**-31.2**	**59.1**
Frame	*-11.1*	*9.6*
Purlins and rails	*-6.8*	*5.9*
Envelope	*-13.2*	*43.6*
Loads/benefits (D) with EoL reuse	**-90.3**	**0.0**
Frame	*-20.7*	*0.0*
Purlins and rails	*-12.8*	*0.0*
Envelope	*-56.8*	*0.0*

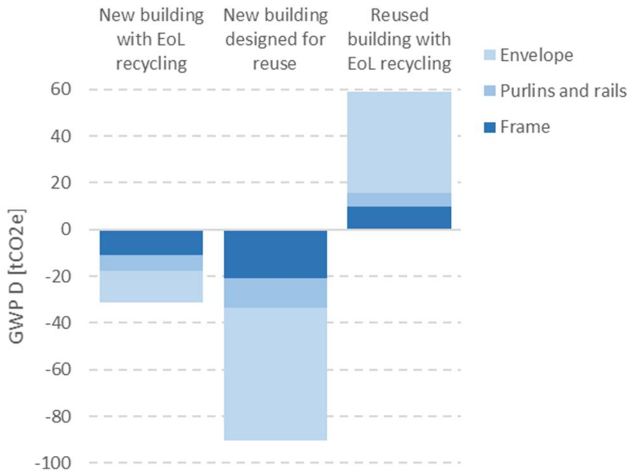

Figure 9. Loads and benefits beyond the system boundary (Module D)

Table 9. LCC results (Cost level is 1/2018, VAT 24%).

Product	New building € / 27 yr	Reused steel € / 27 yr
Product stage (A1-3)	**99 000**	**75 000**
Inventory		*6 000*
Planning	*9 000*	*10 000*
Demolition		*9 000*
Steel panels	*51 000*	*0*
Steel frame	*16 000*	*0*
Concrete + EPS	*8 000*	*8 000*
Windows + door	*15 000*	*15 000*
Reuse price	*0*	*27 000*
Construction (A4-5)	**24 000**	**31 000**
Use stage (B6)	**205 000**	**205 000**
Demolition (C1, C2)	**9 000**	**9 000**
Total (A-C)	**337 000**	**320 000**

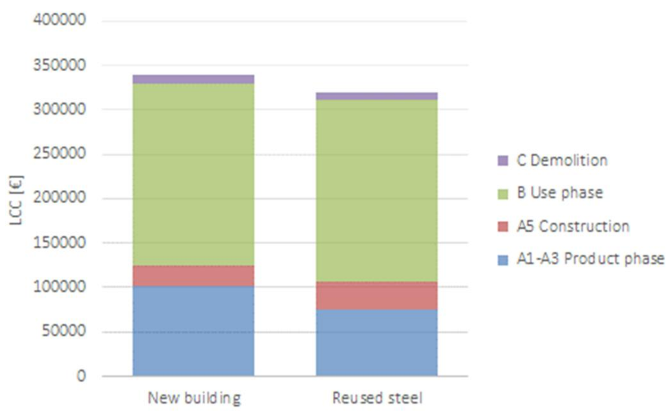

Figure 10. Total Life Cycle Costs (LCC method)

6 CONCLUSIONS

LCA and LCC are the tools for assessment of environmental and economic impacts and benefits of building construction. This study presents results, which are calculated for two scenarios: the first use ('New building') and reuse of the steel structure of a single-storey industrial building ('Reuse steel'). LCA result show that GWP emissions for steel reuse case is about 170 kg CO_2/m^2 less (in total 80.9 tCO_2) than in case when the steel structure is used in the first time (and for the whole building life cycle). The difference is not big (12 %) because steel industry uses recycled steel in new steel production.

When the study takes into account also Module D (load and benefits beyond system boundaries) the net benefit in case of reused steel structures (reused frame, purlins, rails and envelope) is -188 $kgCO_2/m^2$ (in total -90.3 tCO_2). In case of new construction, the benefits achieved also, but not because of the reuse but because of the steel production processes which using recycled steel. This, 'New building' case resulting to the benefit - 65 $kgCO_2/m^2$ (in total -31.2 tCO_2). The study shows that industrial steel hall has potential GWP savings (difference) -59.1 tCO_2 when steel structures reused instead of the case 'New building', when part of the steel is coming from recycled route.

Building construction uses substantial amount of materials and material manufacturing causes environmental impacts to the air, land and water. Efficient way to improve impacts from construction is to replace virgin material with the materials disassembled from demolished buildings. However, this is not always possible, but when the steel structures designed for the reuse, like in assessed case, the GWP benefits was achieved.

It is essential to identify the framework of cost optimal reuse cases like structure-fixed storages with similar kind of steel sandwich panels and loading structures. In this case, investment cost for 100% steel reuse is 17 000 € lower (which is around 10 %) than in case of new construction without reused steel structures. The costs for the 'Use stage' are equals for the 'New building' and 'Reuse steel'. Cost optimization possibilities achieved by planning of construction to reusability concern inventory cost, demolition cost and construction cost.

As essential reuse target is to maximise product lifetime and minimize new purchase.

7 ACKNOWLEDGEMENTS

The research presented in this paper received funding from European Commission's Research Fund for Coal and Steel project under grant agreement No 747847. We would like to acknowledge the active contribution of Ruukki Construction, and additional support from the Swedish steel producers' association Jernkontoret, Ramboll Finland and Peikko Group Corporation.

REFERENCES

Dowling, P.J., Mears, T., Owens, G. & Raven K. (1982), A development in the automated design and fabrication of portal framed industrial buildings, *The Structural Engineer*, vol. 60A, Oct. 1982, pp. 311-319.

Finnish energy statistics. Energy year 2016 - District heat, 29.3.2017, assessed online at https://energia.fi/en/news_and_publications/publications/energy_year_2016_-_district_heat.html#material-view, 30.1.2018

Finnish energy statistics. Energy year 2017 - Electricity. 25.1.2018, assessed online at https://energia.fi/en/news_and_publications/publications/energy_year_2017_-_electricity.html, 30.1.2018

EN ISO 14044:2006. Environmental management. Life cycle assessment. Requirements and guidelines.

EN 15978:2011 Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method.

Haney, J.H. (2011), *Environmental emissions and energy use from the structural steel erection process: a case study*, Master's thesis, Colorado State University, Fort Collins, Colorado.

ISO 15686-5:2017. Buildings and constructed assets. Service life planning. Part 5: Life cycle costing.

Joint Research Centre (2006), European Life Cycle Database, accessed online at http://eplca.jrc.ec.europa.eu/ELCD3/, 20.1.2018.

NewBee E-pass tool (2015), NewBEE project 2012 - 2015. EeB.NMP.2012-3 Programme.

Precasteel web 2.0 application (2011), accessed online at http://www.unav.es/Precasteel/, 20.1.2018.

Rossi, B., Lukic, I., Iqbal, N., Du, G., Cregg, D., Borg, R.P. & Haller, P. (2011), Life cycle impacts assessment of steel, composite, concrete and wooden columns, Proc. of the *International Conference on Sustainability of Constructions - Towards a better built environment*, Innsbruck.

Ruukki Construction (2015), Environmental Product Declarations, accessed online at https://www.ruukki.com/, 20.1.2018.

Ruukki Construction (2015), Unit cost information 22.1.2018.

Ruukki Construction (2018), personal communication with Terhi Leiviskä, 24.1.2018.

VTT (2017), ILMARI - arviontipalvelu, Life-cycle assessment tool for buildings, accessed online at http://cic.vtt.fi/ilmari_DEV/, 20.1.2018.

World Steel Association (2011), Life cycle assessment methodology report, accessed online at worldsteel.org, 20.1.2018.