Nordic Steel Construction Conference 2012
Hotel Bristol, Oslo, Norway
5-7 September 2012

ENVIRONMENTAL ADVANTAGES OF USING ADVANCED HIGH STRENGTH STEEL IN STEEL CONSTRUCTIONS

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Abstract:

Life Cycle Assessment on the production of different grades of carbon steel and stainless steel has been performed and relationships between environmental impact, steel type and steel strength have been evaluated. High strength steel often has a larger environmental impact compared to ordinary steel when just considering the results per tonne steel. On the other hand, less material is normally required to fulfil a specific function. This means that the environmental impacts of structures in high strength steel is lower than for structures in ordinary steels and the results show that substantial environmental life time savings can be achieved.

1 Introduction

Understanding, quantifying and estimating the steel flow through its life is the best way to manage their impacts and their benefits. Application examples have demonstrated that there is a potential for weight savings and environmental savings by using advanced high strength steel instead of conventional steel. This has been further studied in the project "The environmental value of high strength steel structures" which is part of the "Steel Eco-Cycle" research program hosted by Jernkontoret, Swedish Steel Producers' Association and funded by MISTRA. The research has been carried out with input from SSAB EMEA, Outokumpu Stainless, Sandvik Materials Technology, IKEA and IVL, which have contributed by collecting data on upgrading cases and compiled a cradle-to-gate database on environmental data for different steel grades. Information has also been collected within the network of steel using companies consisting of Sweco, Volvo Car Corporation, Volvo Truck, Volvo CE, Scania, HIAB, Metso Minerals, Bombardier Transportation and Green Cargo.

2 Goal and Scope

The goal with this research is to reduce the environmental impact by developing and validate methods for Life Cycle Assessment (LCA) when using advanced high strength steel. Further the result shall be by more widely available by developing an engineering software tool.

Cradle-to-gate Life Cycle Inventory (LCI) has been performed for conventional steel and high strength steel from SSAB EMEA, Outokumpu Stainless and Sandvik Materials Technology. Life cycle analysis has been carried out in different case studies on active structures like cars, trucks, trailers, earth moving equipment, trains, ships and passive structures like cisterns, tanks, shelves, arenas and furniture.

3 Models and materials

LCI on the production of different steel grades is performed and relationships between environmental impact, steel type and steel strength have been evaluated. Models for LCA of high strength steel structures have been developed and the potential for environmental savings is exemplified by case studies.

A large number of real life upgrading cases have been compiled to investigate how well the higher yield strength of the high strength steel can be transformed into lower weight.

The steel grades included are carbon steel and stainless steel as hot rolled and cold reduced sheet material. The high strength carbon steels are micro-alloyed cold forming steels, dual phase steels and martensitic steels. Some grades of micro alloyed and dual phase steels are hot dip galvanized. The high strength stainless steels are duplex steels and steels that are temper rolled. Furthermore, structural carbon steel and abrasion resistant steel as heavy plate are included. These steels are quenched and tempered steels with fairly low alloying content. The high strength steels have yield strengths between 350 to 1400 MPa.

4 Life Cycle Assessment

When considering the environmental value of high strength steel, it is important to analyse the whole life cycle. The life cycle phases are production of raw materials, alloys, fuels and electricity (upstream), production of steel products (Gate to Gate in the steelwork) as well as downstream phases as production of steel structures, use of steel structures, dismantling/scrapping and recycling, Figure 1. The LCA also includes all related transports.

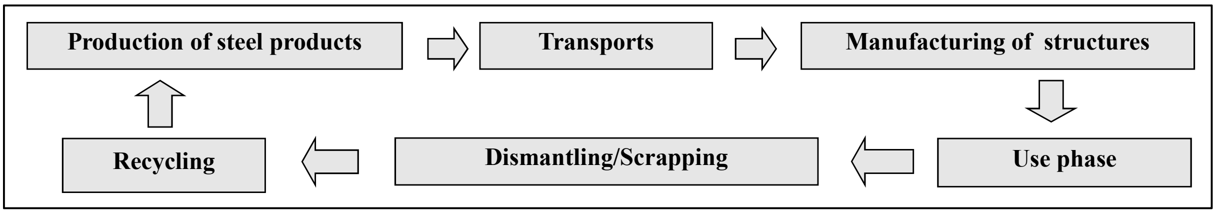

Fig.1: The life cycle phases of the full LCA of steel structures

The life cycle assessment is mainly performed as a differential analysis, in which structures of advanced high strength steel are compared with structures of conventional steel.

The cradle-to-gate analysis of steel production is performed in co-operation with the Swedish Environmental Research Institute, IVL. Most of the raw materials, the fuels and electricity, are traced back to the cradle. General data, mainly from the Gabi database [1], have been used for raw materials, alloying elements, and transportation.

The LCI-study is based on one kg of steel as weight reference unit. This is, of course, not the relevant basis for comparing the environmental impact from structures of high strength steel with structures in conventional steel, since a smaller amount of high strength steel is used for a specific function. However, the total results are expressed per functional unit e.g. “production and use of one construction during its life time”.

When assessing the environmental value of high strength steel in structural applications, it is appropriate to differentiate between passive and active structures. For passive structures, it is the production of steels, manufacture of structures and related transports, together with the service life and end of life features that contribute in the LCA. For active structures, the environmental impact during the use phase also has a substantial influence on the LCA result. It is then important to find out, especially for vehicles in the transport sector, whether the transport is weight critical or volume critical. If the transport is weight critical, a weight reduction could be directly converted into an increased payload, with corresponding decreases in environmental impact.
For volume critical transport, it is normally not possible in to convert all weight reduction into reduction in energy, since some of the energy supplied is utilized to overcome air resistance (drag), losses in transmissions and to operate auxiliary systems [2].

5 Results from the cradle-to-gate analysis of steels

Figure 2 shows environmental data on steel production including upstream environmental impact as a function of yield strength for SSAB EMEA sheet and strip steel. The results are presented in terms of Global Warming Potentials (GWP as kg CO_2-equivalents) as a function of the yield strength. The GWP-value mainly consists of CO_2-emissions but emissions such as methane and nitrous oxide also contributes. More detailed results are reported in [2 and 3] which also include the results on stainless steel. Since one of the case studies which are included in this report is the Swedbank arena, environmental data for tubes and profiles from Ruukki [3] is also included, figure 3. Data on the general level of CO_2 emissions are given by Rukki while the influence of increasing yield strength has been evaluated from data sources at SSAB EMEA in Oxelösund. The recalculation of data from [1] has been in accordance with the procedure described in wordsteel methodology report [4].

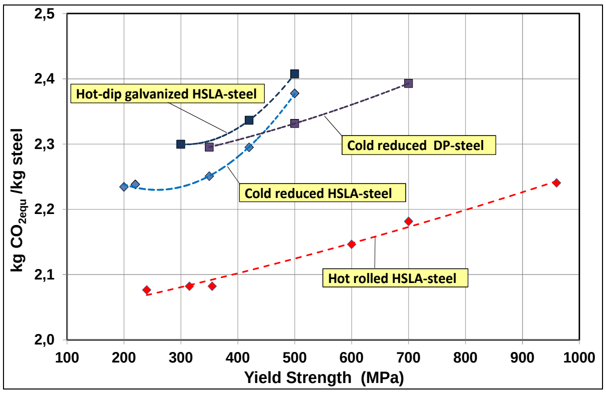

Fig. 2: GWP [kg CO_{2equ}/kg steel] as a function of yield strength for steel production at SSAB EMEA Luleå-Borlänge.

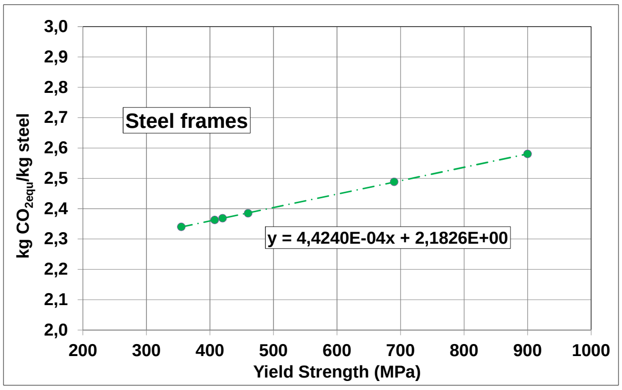

Fig. 3: GWP [kg CO_{2equ}/kg steel] as a function of yield strength for steel production at Rukki corrected for influence of yield strength with data from SSAB EMEA Oxelösund.

6 Potential for reduced weight

In order to obtain a background for further analysis of the influence of increased steel strength on possible weight reduction, a large number of real life upgrading cases have been collected. For these the relative weight and relative steel strength after upgrading from conventional steel to advanced high strength steel is shown in Figure 4. The results seem to fit an earlier found relation, the Root formula.

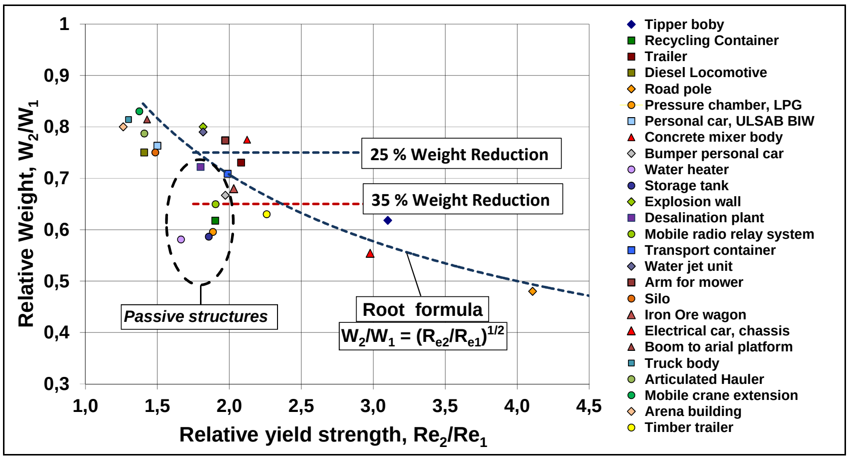

Fig. 4: Relative weight vs. relative yield strength for upgrading cases.

The slight increase in environmental load per ton steel with increasing yield strength, which is seen in figures 2 and 3, is more than outweighed by the light weighting benefits shown in figure 4.

7 Case studies

In order to show a full life cycle analysis of environmental savings when using advanced high strength steel instead of conventional steel, two case studies, Swedbank Arena and Trailer for timber transports are reported here in more detail. The life cycle assessments follow the life cycle shown in Figure 1.

7.1 Swedbank Arena

The Swedbank arena, Figure 6 and 7, has been built with 32 % steel with higher strengths than the conventional S355 steel with 355 MPa yield strength. In order to calculate the environmental savings of using high strength steel the actual arena has been recalculated by Sweco to a hypothetical reference arena in steel grade S355 only [4]. The environmental savings with the upgraded roof can then be evaluated as the difference in weight and environmental value of the actual construction and the reference structure entirely manufactured of conventional steel.

Weights and steel supplies for the tube and profile elements to the fixed roof which was *modified* when upgrading as well as the environmental value of the steels from figure 3 are shown in Table 1. The supplies of tubes and profiles are estimated to be 5 % higher than the weight of the final elements.

Fig. 6: Swedbank Arena, model overview

Fig. 7: Swedbank Arena, roof framework

Table 1: Grades and steel quantities for tubes and profiles before and after upgrading divided in steel grade classes and the environmental value for steel tubes and profiles

Before upgrading				After upgrading						Environmental value GWP, tubes and profles [kg CO_2/kg steel]
Grade	Yield strength [MPa]	Weight of final elements [kg]	Steel consumption tubes and profiles [kg]	Grade	Yield strength [MPa]	Weight of final elements [kg]	Steel consumption tubes and profiles [kg]	Weight reduction in final elements [kg]	Reduction inSteel consumption tubes and profiles [kg]	
S355	355	1 111 505	1 167 080	S355	355	1 118 362	1 174 280	-6 857	-7 200	2,410
S355	355	1 149 226	1 206 687	S460	460	919 571	965 550	229 655	241 138	2,452
S355	355	599 730	629 717	S690	690	307 027	322 378	292 703	307 338	2,554
S355	355	107 340	112 707	S900	900	43 181	45 340	64 159	67 367	2,646
Total		2 967 801	3 116 191	Total		2 388 141	2 507 548	579 660	608 643	

As can be seen some parts remaining in steel S355 after upgrading have also been modified, the design as a whole being optimized at the upgrading. This means that although the mass of these parts increases, the end result is an optimized design.

The total weight of the fixed roof was 4579 tons before and 4000 tons after upgrading, i.e. a total weight reduction of 13 % and of 20 % on the elements involved in the upgrading only.

7.1.1 Calculation of environmental gains in steel production

The environmental values, cradle to gate, for structural steels produced by Ruukki and recalculated for differ steel grades with data from SSAB Oxelösund were chosen for the analysis. Note that the amounts of steel required producing the various structural elements from tubes plates and profiles is assumed to be 5% greater than those of the finished structure. The total environmental value can be calculated by Eq (1).

$$M_{steel} = \Sigma(M_{steel,x} * W_{steel,x})_n \tag{1}$$

M_{steel} = Total environmental value of the upgraded parts of the structure
$M_{steel,x}$ = Environmental value (cradle to gate) for grade x [per kg steel]
$W_{steel,x}$ = Weight of steel x [kg]
n = Number of grades

The environmental value $M_{steel,x}$ can be found in figure 3.

According to Eq. 1 the total environmental *savings* (ΔM_{steel}) in steel production including upstream impact expressed as GWP is:

ΔM_{steel} = [2.41 * 3116191] - [2.41 * 1174280 + 2.452 *965550 + 2,554 * 322378 + 2,646 *45340] = 1369154 kg CO_{2equ}

7.1.2 Calculation of environmental benefits in transports

Profiles, tubes and rods to the roof construction are manufactured at the factory near the port 85 km from the steel mill. These transports are performed by 40 ton trucks.

After production of profiles and tubes the finished structural elements are transported by boat 275 km and then another 616 km by truck. The total environmental value of the transports can be calculated with eq. (2).

$$M_{trsp} = \Sigma(M_{trsp,y} * W_{steel,y} * TD_y)_n \qquad (2)$$

M_{trsp} = Total environmental value for transport of upgraded parts of the structure
$M_{trsp,y}$ = Environmental value (cradle to gate) for y-type of transport vehicle [per tonkm]
$W_{steel,y}$ = Total amount of steel transported with y-type of transport vehicle [tons]
TD_y = Transport distance with carrier y [km]
n = Number of types of carriers

The environmental value $M_{trsp,y}$ can be found in [1 and 5], where the figures 0.043 and 0.012 kg CO_{2equ}/tonkm can be evaluated for the actual truck and ship respectively.

According to Eq. (2) the total environmental *savings* during transport is:

Δ M_{trsp} = [(0.043 * (2968-2388) * (85+616)] + [0.012 * (2968 - 2388) * 275] = 19397 kg CO_{2equ}.

The overall environmental benefits because less steel need to be manufactured and transported is: 1369154 + 19 397 = 1388551 kg of CO_{2equ}.

7.1.3 Calculation of environmental benefits in manufacture the of construction

Although there should be a number of environmentally positive factors in the manufacture and installation of the upgraded design, the manufacturer have difficulties to quantify those. Positive factors include the handling of lighter parts, less welding because of thinner steel thicknesses, lighter bracing during installation, etc. This analysis does not take these differences into account because they are considered to be relatively small compared to the total savings.

7.1.4 Calculation of environmental load and credit of scrap added and recycled

In order to determine the total environmental impact over a design lifetime one can in some cases also make credit for the recycled scrap. Although it will probably take some time before the end of life is reached for this structure the result of such a procedure is shown here.

In doing so the added scrap at steel production must be loaded with an environmental burden since in a "cradle to gate analysis" the added scrap is namely considered free of environmental burden. Estimating the environmental value of recycled scrap is rather complicated and software developed in the Steel Eco-Cycle research program for the full “cradle to grave lifecycle” is used to demonstrate this effect. This is included in the graphs showing the total results described in paragraph 7.1.5 below. To make the results more general a recycling rate of 60 % has been assumed, this value commonly used for building constructions.

7.1.5 Total environmental result of upgrading the Swedbank Arena

The overall results calculated by the software tool EcoSteel expressed as global warming and non-renewable energy resources is shown in Figure 8 and 9 respectively. The total saving decreases slightly when taking into account the scrap recycling. This is because the larger amount of the conventional steel is recycled since the design is heavier before upgrading.

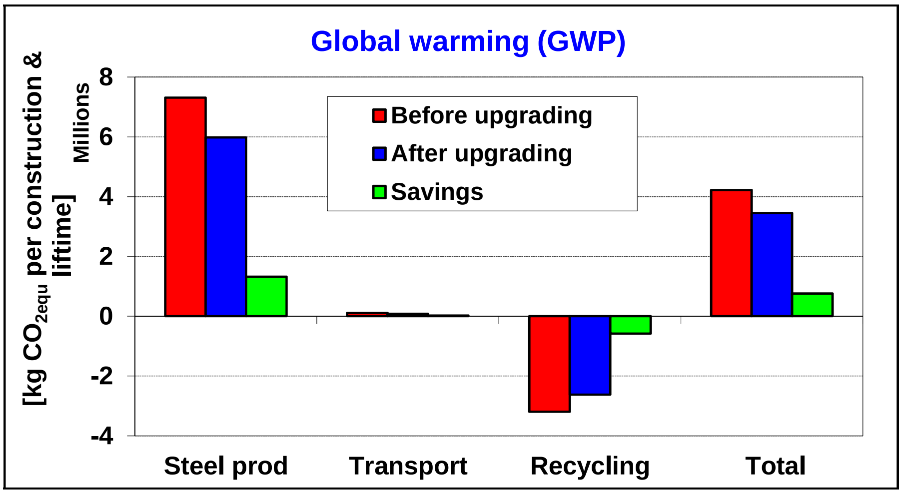

Fig. 8: Total results for Global warming, Swedbank Arena, results from EcoSteel

7.2 Trailer for timber transports

In order to make a full life cycle assessment of the environmental impact on an *active structure* a case study has been performed on a trailer for timber transports, Figure 10. This trailer is manufactured by Mjölby Släp & Trailer AB, MST in Sweden. The life time of the vehicles are 7 years with an average mileage of 175 000 km/year. It is assumed that 50 % of the distance is driven with empty vehicles.

7.2.2 Structural details

The longitudinal beams of the trailer have been upgraded from conventional rolled IPE profiles in S310 steel to welded beams in steel S 700. The grade of the cross members were unchanged. The trailer frame arrangement after upgrading is shown in Figure 10. Data on strengths and weights for the trailer before and after upgrading is shown in Table 2.

Fig. 10: The analysed timber trailer

Trailer chassies	Before upgrading				After upgrading			
	Steel grade	Yield strength [MPa]	Thick-ness [mm]	Weight of part [kg]	Steel grade	Yield strength [MPa]	Thick-ness [mm]	Weight of part [kg]
Flanges	HS310	310	12.7	943	Domex 700	700	8	593
Web plates	HS310	310	8		Domex 700	700	4	
Cross members	HS350	350		257	HS350	350		257
Total main steel parts, chassis				1200				850
Total tare weight of trailer				6330				5270

Table 2: Main parts of upgraded trailer chassis

The weight reduction of upgraded parts was 350 kg, which correspond to a weight reduction of 37 % on these parts. This is in good agreement with the root formula rule described in figure 4, which indicates a weight reduction of 33 % for an average increase in yield strength of 2.3 times, which is in place in this case for the upgraded parts.

The total weight reduction due to the steel upgrading only (350 kg) means that the curb weight of the trailer was reduced from 5770 kg to 5420 kg or by 6,1 %. In addition to this the weight was further reduced by 150 kg due to changes in design and weight savings in other parts of the chassis. This meant that the total payload capacity of the trailer was increased by 500 kg from 30230 kg to 30730 kg at a maximum gross weight of the trailer of 36 tonnes.

7.2.3 Calculation of environmental savings in steel production, transport and manufacturing

The environmental impacts of steel production, transports and manufacturing of constructions are assessed in the same way as for the passive constructions. The methodology for doing this is shown in detail in the previous case study on the Swedbank Arena.

As in the previous case there is no information on differences in energy consumption in manufacturing of the structures before and after upgrading. The manufacturing phase has therefore also here been excluded from this analysis.

The environmental savings due to the fact that less amount of steel needs to be produced and transported after upgrading is 800 kg of CO_{2equ} for each trailer. About 6 % of that is related to savings during transports.

7.2.4 Calculation of environmental savings in using the vehicle

For the share of the transports which are *weight critical transports*, the entire weight reduction can be used to increase the payload. The increased payload means fewer trips to transport a certain amount of goods with corresponding savings in environmental impact.

If the transport is *volume critical* which include empty trips it is, as mentioned, not possible to convert all weight reduction into reduction in energy used, since some resistance factors are not mass dependent [2].

In order to analyse the fuel savings resulting from a weight reduction for the *volume critical* and empty loaded parts of the transports, the specific fuel saving (SFC) for a certain weight reduction (litres/km and kg weight reduction) could be evaluated. The reason for this is that under the same driving conditions the correlation between energy consumption and vehicle weight is linear [6 and 7]. Eq. (3) gives the equation for calculating SFC.

$$SFC = (FC_{full} - FC_{empty})/MPL \tag{3}$$

SFC = Specific saving in fuel comsumption [litre/(km and kg weight reduction]
FC_{full} = Fuel consumtion fully loaded [litre/km]
FC_{empty} = Fuel consumtion empty loaded [litre/km]
MPL = Maximum pay load [kg]

Data on fuel consumption and maximum pay load for the entire vehicle including the tractor which also takes timber load is given by MST as follows: FC_{full} = 0.71 litre/km, FC_{empty} = 0.35 litre/km and MPL = 40000 kg for the entire vehicle.

According Eq. (3) the specific fuel saving is: SFC = (0.71 - 0.35)/40000 = $9 \cdot 10^{-6}$ litres/(km and kg weight reduction) and the environmental saving according to Eq. (4).

$$\Delta M_{use,vc} = SFC * WR * M_{fuel} * LTD_{vc} \tag{4}$$

$\Delta M_{use,vc}$ = Total environmental saving due to weight reduction [kg CO_{2equ}/vehicle]
SFC = Specific saving in fuel comsumption [litre/(km and kg weight reduction)
WR = Weight reduction [kg steel]
FC_{full} = Fuel consumtion fully loaded [litre/km]
M_{fuel} = Environmental value for production and burning of fuel [kg CO_{2equ} per litre of diesel fuel = 3 kg CO_{2equ}/litre incl. production of the fuel]
LTD_{vc} = Life time driving distance for volume critical or empty loaded transports [km]

For the empty loaded or volume critical parts of the transports the life time fuel saving are calculated according to eq. (4): $\Delta M_{use,vc} = 9 \cdot 10^{-6} * 500 * 3 * 175000 * 7 * 0.5 = 8268$ kg CO_{2equ}/vehicle.

For the *weight critical* parts of the transports (50 %) the corresponding environmental savings can be calculated according to Eq. (5).

$$\Delta M_{use,wc} = FC_{full} * WR/MPL * M_{fuel} * LTD_{wc} \qquad (5)$$

Δ $M_{use,wc}$ = Total environmental saving due to weight reduction [kg CO_{2equ}/vehicle]
FC_{full} = Fuel consumtion fully loaded [litre/km]
M_{fuel} = Environmental value for production and burning of fuel
[kg CO_{2equ} per litre of diesel fuel = 3 kg CO_{2equ}/litre incl. production of the fuel]
WR = Weight reduction [kg steel]
MPL = Maximum pay load [kg]
LTD_{wc} = Life time driving distance for the weight critical transports [km]

For the weight critical parts of the transports the life time environmental saving can then be calculated according to eq. 4: $\Delta M_{use,wc} = 0.71 * 500/40000 * 3 * 175000 * 7 * 0.5 = 16308$ kg CO_{2equ}/vehicle.
This adds up to a total life time saving of 8268 + 16308 = 24576 kg CO_{2equ}/vehicle for the use phase. In addition a life time cost saving of 12300 €e (1.5 €/litre) per vehicle is saved due to reduced fuel consumption.

7.2.5 Calculation of environmental load and credit of scrap added and recycled

Considering a full life cycle (cradle to grave) it is, as mentioned, possible to take into account the environmental burden and credit for scrap. The analysis shows that the input and output of scrap during the life cycle have little influence on the total savings since it is an active structure.

7.2.6 Total environmental results of upgrading the Timber trailer

The overall environmental savings expressed as global warming is shown in Figure 11. This figure shows the total dominance of the use phase savings for active structures.

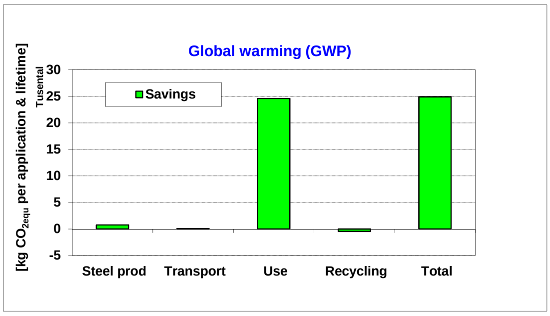

Fig. 11: Summary of savings in carbon dioxide due to upgrading, per trailer

8 Merit number for the environmental value of high strength steel

In order to facilitate the understanding of the environmental value of using advanced high strength steel, a general merit number has been defined. This is done by relating the environmental savings to the difference in de specific emissions by producing advanced high strength steel instead of conventional steel. It is defined in such a way that if the merit number is above one there is an environmental advantage to perform the upgrading to the advanced steel.
The merit number will of cause differ from one field of application to another especially if the analysed structure is passive or active. Merit numbers for case studies performed in the Steel Eco-Cycle research program is shown in Figures 12 and 13.

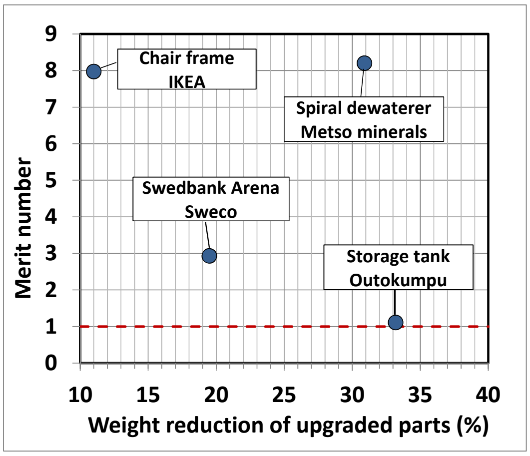

Fig. 12: Merit number for passive structures

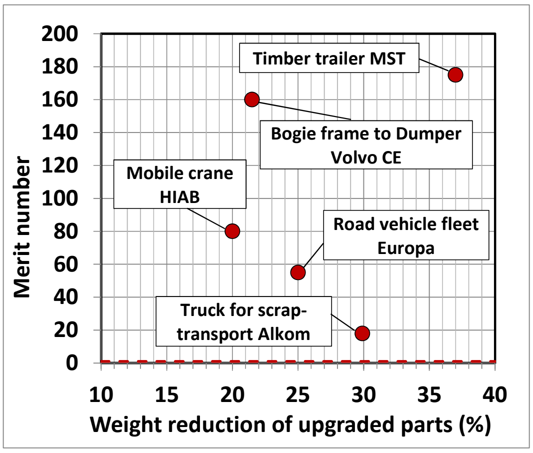

Fig. 13: Merit number for active structures

9 Potential for global environmental savings

The environmental savings of the case studies shown above may look like a drop in the ocean but the main reason here is to show the methodology of calculation. The global production of crude steel was 1400 million tonnes year 2010. If only 10 million (0.7 %) of these tonnes where advanced high strength steel substituting 13 million tonnes of conventional steel in the road vehicle fleet this would result in a life time saving of 80 million tonnes of CO_2-emissions [1]. This is more than the total yearly CO_2-emissions in Sweden of 66 million tonnes.

10Conclusions

The main conclusions from this investigation can bu summarized as follows:

1. Although the manufacture of advanced high strength steel lead to a small additional environmental impact this is more than outweighed by light weighting benefits and less use of natural resources.
2. Case studies on the Swedbank arena and a trailer for timber transports show that substantial environmental life time savings can be achieved by using advanced high strength steel.
3. For the case studies a merit number is defined by relating the total environmental savings to the additional specific burden there is by producing advanced high strength steel instead of conventional steel. For the case studies performed in the Steel Eco-Cycle project the environmental savings outweigh the burden by a factor of 20 to 180 for active structures and of 3 to 8 for passive structures.
4. The overall result from this study can be illustrated by the example: If ten million tons of the global yearly production of steel, i.e. 0.7 %, is advanced high strength steel which replaces conventional steel in the road vehicle fleet, 80 million tons of CO_2-emissions would be saved.

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