Abstract: Research has been carried out in order to determine the environmental impact of steel bridge construction in terms of energy consumption and global warming potential. Five projects that have been completed recently were fully analysed with respect to the fabrication, corrosion protection, transport and erection phases. This research is a first in this area. This paper describes the general context as well as the research method that has been adopted. Finally the research results are presented and discussed.

1. INTRODUCTION

Sustainable construction can generally be defined and achieved by satisfying the following five criteria:
1. Increase the lifetime;
2. Limit material consumption;
3. Use durable materials;
4. Take into account the environmental impact of the construction process (incl. transport);
5. Use the structure not only for its structural function (mainly for buildings).

Steel bridges have a long track record if it comes to the first three criteria. The design life of a (steel) bridge is generally 100 years. The potential durability of a steel bridge may be summarised in the following quote by top American bridge designer John A. L. Waddell in 1921: “The life of a metal bridge that is scientifically designed, honestly and carefully built, and not seriously overloaded, if properly maintained, is indefinitely long.” Today, the lifetime of a steel bridge is very often determined by its fatigue resistance and its corrosion protection, see EN 1993-2 §4. Furthermore, the bridge components that do not have an equivalently long lifetime should be designed in such a way that they are replaceable (cables, bearings, expansion joints).

Because of its strength properties, steel consumption can be really kept to a strict minimum. The further development of high strength steel grades will help to bring the steel consumption further down. As steel is a 100% fully recyclable material, it is also a great material with respect to natural resources. Once the ore is transformed into steel, it can be reused and/or recycled time after time.
Lately, and due to the global warming issue, every sector of the industry has been forced (sometimes by law, sometimes by contract, sometimes but rarely voluntarily) to determine and measure its environmental impact, mostly defined by the energy consumption (in GJ) and the CO2 emissions (in kg CO2 equivalent). Some other parameters, such as the ozone depletion potential and the acidification potential (to name only two), are sometimes also included. Based on these values, certain industries have developed important programmes to cut down their environmental impact through innovation and new processes.

The western steel production industry (steel mills) has been the leader in the steel construction sector. Today, through Environmental Product Declarations (EPD), the environmental impact of most of the construction materials and products is known and available. They are “cradle to gate” and correspond with the mandatory information modules A.1 to A.3 of EN 15804 [2].

For fabricated structural steel products (other than standardised products such as sheeting, sandwich panels, etc.), this information is still not available in a detailed way. The main reason is related to the fact that the impact values for fabricated steel structures is very much depending on the degree of complexity of the structure, which can range from lightweight structures (handrails) over midweight structures (beams and columns for lightweight buildings) to heavyweight structures (beams and columns for heavy industrial buildings and high rise office buildings) and super heavyweight structures (such as heavily welded bridges).

In the industry, it has been assumed in the past that the environmental impact of the fabrication (and erection) process is only marginal if compared to the impact of the primary steel production process in the mills. Recently, at the Vrije Universiteit Brussel, research has been done in order to determine the different steps of the fabrication and erection process and its environmental impact (in terms of energy consumption and global warming potential) [1]. The research has started with the super heavyweight structures, which are (heavy) steel bridges.

More and more bridge owners (mostly the departments of Public Works and the national railway bodies) are conscious about the environmental impact of the infrastructure works they construct. Some of them have already implemented the requirement for contractors to be conscious about the CO2 emissions of their operations. ProRail, responsible for the Dutch railway network, has i.e. initiated the CO2 performance ladder [3], based on a fixed set of requirements:

A. Insight (into own carbon footprint);
B. CO2 reduction (recorded ambition);
C. Transparency (internal and external communication);
D. Participation in initiatives (with colleague companies in the field of CO2 reduction).

A contractor can be classified into one of the five levels of the performance ladder. In order to qualify (and get certified) for level 3, the company is required to report on its scope 1 (direct emissions) and 2 (indirect emissions such as due to electricity consumption and business travel) CO2 emissions in accordance with ISO 14064-1 and to have quantitatively formulated objectives for reducing these CO2 emissions. The company is also required to communicate the above mentioned objectives both internally and externally and to have an active role in (sector) initiatives relating to climate change.
In order to qualify for the highest level 5, the company is required to demand a CO2 emissions inventory for scope 1 and 2 in accordance with ISO 14064-1 or equivalent from its A suppliers. Furthermore, the company should have, and should report upon, quantitative reduction objectives for scope 1, 2 and 3 (other indirect emissions such as due to paper use and waste disposal). The monitoring of progress with regard to these objectives has to be incorporated into the normal planning and control cycle. The company is required to commit itself publically to a CO2 reduction programme operated by the government or an NGO and to actively participate in the setting up and implementation of a (sector-wide) CO2 reduction programme in collaboration with the government and/or NGO.

In evaluating tenders for construction works, ProRail translates the level of performance ladder into an ‘award advantage’. The higher the level on the certificate, the greater the advantage the company gains in the award weighting. If a company has been certified level 3, this (fictitious) advantage is 4%. For level 5, this is 10%.

In order not to lose out on competition, it is therefore important for steelwork contractors to master with this type of regulation. Victor Buyck Steel Construction (located in Eeklo-Belgium) has been one of the first steelwork contractors to get certified level 3. As such, and in order to qualify for level 5, this steelwork contractor has participated with the research into the environmental impact of the fabrication and erection of steel structures.

2. RESEARCH APPROACH

The research focuses on information modules A.4 and A.5 of EN 15804 [2], which represents the construction process stage (transport from steel mill to fabrication yard and the construction & installation process).

The whole fabrication and erection process has been divided into 5 groups of (in total 85) single activities and (roughly 200) individual factors:

1. Fabrication
   including pre-blasting, preparation (oxy-cutting of plates, cutting of profiles, drilling, punching, assembling, welding, manipulation, etc.);
2. Corrosion protection
   including blasting, painting, and (in case) metal spraying;
3. Transport
   including both external transport (from the steel mills and to the construction site) and internal transport;
4. Erection
   including site welding, gas and fuel consumption, cranes, etc.;
5. Overhead
   which represents office consumption (electricity, heating) and heating, ventilation and lighting of the workshops.

For each single activity, the energy consumption (expressed in MJ) and the global warming impact (expressed in kg CO2 equivalent) have been determined.
2.1 Conversion factors

2.1.1 Machines and tools

For machines working on electricity, the total energy $E$ is expressed by Eq. (1):

$$ E = n \varphi \lambda P \quad [\text{kWh}] $$

or

$$ E = 3.6 n \varphi \lambda P \quad [\text{MJ}] $$

where:
- $P$ the declared power of the machine [kW];
- $n$ the total number of working hours reported by the operator [h];
- $\lambda$ the load factor, which is the percentage of the full capacity that has been used [%];
- $\varphi$ the effectivity, expressing the effective working time of the machine divided by the reported working time of the operator [%].

The global warming potential $GWP$ is expressed by Eq. (2), which is based on [4]:

$$ GWP = 0.615 E \quad [\text{kgCO2eq}] $$

where:
- $E$ the total energy expressed by Eq. (1.a) in [kWh].

Typical values of the load factor $\lambda$ and the effectivity $\varphi$ are shown in Table 1.

<table>
<thead>
<tr>
<th>Load factor $\lambda$</th>
<th>Effectivity $\varphi$</th>
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</thead>
<tbody>
<tr>
<td>Cranes (workshop)</td>
<td>50% 60%</td>
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<tr>
<td>Compressor (workshop)</td>
<td>30% 100%</td>
</tr>
<tr>
<td>Ventilation (workshop)</td>
<td>100% 100%</td>
</tr>
<tr>
<td>Plate oxy-cutting (workshop)</td>
<td>40% 100%</td>
</tr>
<tr>
<td>Drilling, punching, sawing (workshop)</td>
<td>60% 70%</td>
</tr>
</tbody>
</table>

2.1.2 Consumables (gas and other materials)

The energy consumption $E$ and global warming potential $GWP$ have been derived from the recorded actual consumed quantities, using Eq. (3) to (13) which are based on [4] and [5]:

- For propane:
  $$ E = 3.6 c_{pro} m_{pro} \quad [\text{MJ}] $$
  $$ GWP = 3.00 m_{pro} \quad [\text{kgCO2eq}] $$

- For natural gas:
  $$ E = 3.6 c_{nat} v_{nat} \quad [\text{MJ}] $$
  $$ GWP = 1.83 v_{nat} \quad [\text{kgCO2eq}] $$

- For acetylene:
  $$ E = 3.6 c_{ace} v_{ace} \quad [\text{MJ}] $$
  $$ GWP = 2.471 d_{ace} v_{ace} \quad [\text{kgCO2eq}] $$

- For diesel:
  $$ E = 3.6 c_{die} v_{die} \quad [\text{MJ}] $$
  $$ GWP = 3.135 v_{die} \quad [\text{kgCO2eq}] $$

- For thinners:
  $$ GWP = 0.064 v_{thi} \quad [\text{kgCO2eq}] $$

- For the zinc metal spray (ZnAl 85/15) process:
  $$ E = 68 m_{met} \quad [\text{MJ}] $$
  $$ GWP = 4.80 m_{met} \quad [\text{kgCO2eq}] $$
where the calorific value $c$ and the density $d$ of the consumables are given in Table 2. The consumed quantities were recorded in mass [kg] for propane ($m_{pro}$) and zinc metal spray ($m_{met}$), in volume [m$^3$] for natural gas ($v_{nat}$) and acetylene ($v_{ace}$), and in volume [l] for thinners ($v_{thi}$) and diesel ($v_{die}$).

### Table 2: Properties of consumables

<table>
<thead>
<tr>
<th></th>
<th>Calorific value $c$</th>
<th>Density $d$</th>
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<tbody>
<tr>
<td>Propane (pro)</td>
<td>14.99 kWh/kg</td>
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<tr>
<td>Natural gas (nat)</td>
<td>11.60 kWh/m$^3$</td>
<td>0.833 kg/m$^3$</td>
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<tr>
<td>Acetylene (acy)</td>
<td>15.56 kWh/m$^3$</td>
<td>1.160 kg/m$^3$</td>
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<tr>
<td>Diesel (die)</td>
<td>11.61 kWh/l</td>
<td>-</td>
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2.1.3 General consumptions

Some consumables cannot be allocated to one project as they are used in a general way. Examples are natural gas for heating of offices and workshops, electricity for ventilation, lighting and offices and fuel for general transports.

For each of these activities, the annual consumption of 2010 has been used as the basis to determine the project related portion. The portion has been proportional to the total steel consumption of the project (such as in the case of the electricity consumption in the offices) or to the total number of recorded production hours (such as for the heating and ventilation of the workshops and the fuel consumption) or to a combination of both.

2.1.4 Erection equipment

The environmental impact of erection cranes, cherry pickers and other transport equipment (such as barges, ships and SPMT’s) has been derived from their actual fuel consumption.

2.2 The projects

The environmental impact has been determined for four bridges and one lock project (all completed in 2010 and 2011), see also Table 3 for the main technical data and Fig. 1 to 6 for pictures:

1. The road bridge over the Albert canal in Grobbendonk (B);
2. The railway bridges over the river Nete in Duffel (B);
3. The road bridge on rue d’Alsace in Luxemburg;
4. The bridge de la Madeleine over the river Loire in Nantes (F);
5. The mitre gates (and bridge) of the Kattendijk lock in Antwerp (B).

![Figure 1: Bridge over the Albert canal in Grobbendonk (B)](image)
<table>
<thead>
<tr>
<th>Table 3: Main technical data of the analysed projects</th>
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<tbody>
<tr>
<td>Bridge Grobbendonk</td>
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<tr>
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<tr>
<td><strong>Steel consumption</strong></td>
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<tr>
<td><strong>Dimensions</strong></td>
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*Figure 2: Railway bridges over the river Nete in Duffel (B)*
Figure 3: Bridge rue d’Alsace in Luxemburg

Figure 4: Bridge de la Madeleine over the river Loire in Nantes (F)

Figure 5: Mitre gates Kattendijk lock Antwerp (B)

Figure 6: Bridge Kattendijk lock Antwerp (B)
3. RESEARCH RESULTS

The total determined environmental impact values have been divided by the steel consumption so as to be able to compare the results. They are summarised in Table 4 and presented graphically in Fig. 7.

Table 4: Environmental impact of steel construction (steel bridges) during construction phase

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Fabrication</th>
<th>Corrosion protection</th>
<th>Transport</th>
<th>Erection</th>
<th>Overhead</th>
<th>TOTAL</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>MJ/t</td>
<td>kg C02/t</td>
<td>MJ/t</td>
<td>kg C02/t</td>
<td>MJ/t</td>
<td>km</td>
</tr>
<tr>
<td>Grobbendonk</td>
<td>951</td>
<td>150</td>
<td>868</td>
<td>133</td>
<td>625</td>
<td>626</td>
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<tr>
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<td>137</td>
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<td></td>
<td></td>
<td>625</td>
<td>47</td>
<td>416</td>
<td>51</td>
</tr>
<tr>
<td>Duffel</td>
<td>592</td>
<td>139</td>
<td>755</td>
<td>137</td>
<td>941</td>
<td>109</td>
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<tr>
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<td>59</td>
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<td></td>
<td>1,854</td>
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<td>2,260</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>596</td>
<td>51</td>
<td>5,099</td>
<td>565</td>
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<td></td>
<td></td>
<td></td>
<td>5,099</td>
<td>565</td>
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</tbody>
</table>

NOTE: In this Table kgC02 means kgC02eq.

Figure 7: Environmental impact of steel bridge construction: (a) energy consumption (b) CO2 emission
An important difference can be noticed between the environmental impact of the fully welded bridges and the bridge that is partly bolted on site. If only the pure fabrication component is considered, the energy consumption is around 900 MJ/t for fully welded and 600 MJ/t for the partly bolted bridge. The global warming potential is roughly 140 kgCO2eq/t for the former and 90 kgCO2eq/t for the latter. If expressed in kgCO2eq/h, then these values become 37.5 MJ/h and 5.8 kgCO2eq/h for the fully welded bridges (with a very good correlation) and 55 MJ/h and 8.5 kgCO2eq/h for the partly bolted bridge. These values take into account the rather important difference in complexity rate (expressed in fabrication hours per tonne). These values correspond very well with the fully welded components of the lock project.

The values related to fabrication have to be increased with the overhead component, which is around 2,000 MJ/t and 110 kgCO2eq/t for the fully welded structures and 1,000 MJ/t and 60 kgCO2eq/t for the partly bolted bridge, which is only half.

As far as the erection component is concerned, it represents averagely 800 MJ/t and 63 kgCO2eq/t for the fully welded bridges (with a still relatively good correlation) and 700 MJ/t and 57 kgCO2eq/t for the partly bolted bridge. For the Kattendijk lock structures, with a minimum of erection because these structures were brought to the site fully completed (and could therefore be installed straight away), this component is considerably less: 200 MJ/t and 16 kgCO2eq/t only.

Due to the big differences in complexity and systems, it is not realistic to deduce systematic values for the corrosion protection component.

If the transport component is considered, the values for the Nantes project are striking. The importance of the distance between the fabrication workshop and the construction is immediately revealed. From the research results, some typical values can be derived. Transport with inland navigation causes typically around 10 gCO2eq/km.t, trailer transport around 40 gCO2eq/km.t. These values are only around half of those mentioned in the CO2 performance ladder emission tables. The sea transport for the Nantes project caused 85 gCO2eq/km.t (going journey). This value corresponds rather well with the mentioned published emission tables. If the return journey with empty barge is also taken into account (causing 60 gCO2eq/km.t), then the total transport emission is 145 gCO2/km.t.

If the overall environmental impact values are divided by the total number of hours (fabrication and erection), it seems that for the three fully welded bridges the impact is very similar: around 130 MJ/h and around 14 kgCO2eq/h, excluding the transport component. For the partly bolted bridge project (which has considerably less hours per tonne), the values are only marginally higher: 170 MJ/h and 16.5 kgCO2eq/h.

If the corrosion protection and transport components are not taken into account (because they depend on parameters that are predominately not related to fabrication and erection complexity), then it can be concluded that the impact values for the fully welded bridges are 3,500 MJ/t and 300 kgCO2eq/t; for the partly bolted bridge this is 2,300 MJ/t and 200 kgCO2eq/t. For the lock structures these values are 3,700 MJ/t and 340 kgCO2eq/t.
4. CONCLUSIONS AND FUTURE DEVELOPMENTS

1. The environmental impact values for the steel production of steel profiles and plates are 7,300 to 12,350 MJ/t and 480 to 800 kgCO2eq/t. The lower bound values are based on 51% recycled steel and 49% reuse [7], the higher bound values on 11% reuse [6]. For bridges, the higher bound values seem to be more appropriate because reuse of steel components (after dismantling) seem to be very difficult. The environmental impact values for the fabrication and erection are generally less but certainly not negligible.

2. The higher the degree of complexity is, the higher the environmental impact. Fully welded bridges with orthotropic decks have a considerably higher impact than the partly bolted bridge with cross girders and concrete deck.

3. The impact of the transport component becomes very important if large elements are transported over sea and over large distances. Transport for large projects, fully completed at one side of the world (e.g. in low cost countries) and shipped to the other side of the world, could typically cause CO2 emissions exceeding 1,000 kgCO2eq/t, far more than the whole production process.

4. The research finds average values that are more in line with each other than expected. Further research could include:
   a. More data: analysis of the environmental impact of the steel production and erection process for more infrastructure projects executed by a range of steelwork contractors;
   b. Wider range of structures: analysis of the environmental impact of other steel structures (lightweight to heavy-weight structures, going from handrailing to light industrial buildings, small to large office buildings and heavy industry buildings);
   c. Effective actions: research into ways of reducing the environmental impact. This can include the development of new types of paint (with less or no thinner consumption).
   d. Wider perspective: Research into the relation between what is achieved (i.e. bridge span) and the environmental impact.

References