Sustainable bridges – LCA for a composite and a concrete bridge

AL. Hettinger[1], JP. Birat[1], O. Hechler[2] & M. Braun[2]

Keywords: Life Cycle Assessment, bridges, composite bridges, steel production, emission.

Abstract: Life Cycle Assessment addresses the environmental impacts of a product's life cycle, from raw material extraction through production, use and end-of-life. In this paper, we apply this standardized method to two bridges: one designed as a composite bridge and one as a prestressed concrete bridge. The environmental profile of the bridges, defined by eleven indicators, is strongly connected to the bill of quantities. As a result, the composite bridge generates significantly less environmental impacts than its equivalent made of prestressed concrete, much heavier. The study also demonstrates that recycling is not necessarily beneficial depending on the material. On the one hand, the recycling of structural steel avoids the emission of 32 tCO2eq, thus decreasing the overall impact of the composite bridge, and, on the other hand, reinforced concrete requires a pre-treatment before recycling that is not counterbalanced by the benefits of recycling, thus downgrading the overall environmental profile of the prestressed bridge.

1. Introduction

This paper presents the results of the Life Cycle Assessment (LCA) carried out on two bridges: one designed as a composite bridge and one as a prestressed concrete bridge. An LCA is a standardised methodology that addresses "the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal" [1]. Because of this holistic approach, LCA is a powerful tool to evaluate environmental aspects of the built environment. A change in product design will indeed affect different phases of the life cycle (recyclability, scarcity of resources…) and the life cycle approach will help understand the distribution of the burdens among the life cycle stages and avoid overcharging one stage by a change of design.

The LCA of the bridges has been conducted according to this standard and reviewed by external experts [2]. This paper first briefly describes the two bridges and then develops their LCA, following the four stages described in the standard ("Fig. 1").

1 ArcelorMittal Global Research & Development
2 ArcelorMittal Long Carbon Europe – Technical Advisory

E. Petzek, R. Băncilă (Eds.), *Economical Bridge Solutions based on innovative composite dowels and integrated abutments,* DOI 10.1007/978-3-658-06417-4_3,

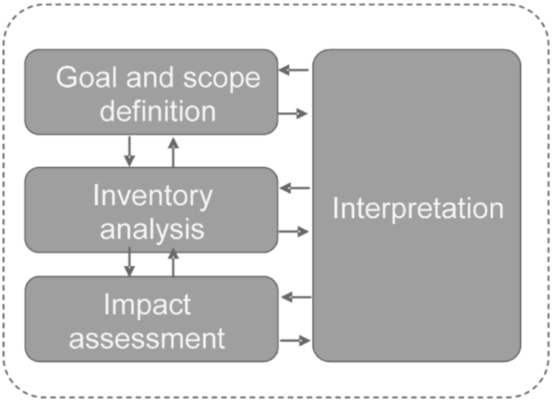

Figure 1: Steps of a Life Cycle Assessment as defined by ISO standards [1].

2. Description of the bridges

The two bridges exhibit a typical layout with two spans of 2 x 29.27m. They were designed to fulfil the same function. Fig. 2 shows the example of a typical two-span composite bridge.

Figure 2: Composite bridge over A5 highway at Bremgarten (D) with 2 x 30m span, rolled beams in HISTAR460 and concrete crossbeams

Two alternatives have been compared: solution A, a prestressed concrete bridge, and solution B, a composite bridge made of a steel bearing structure and partially prefabricated concrete elements. The section of this latter bridge is shown in Fig. 3 and the bill of quantities for both solutions is shown in Fig. 4.

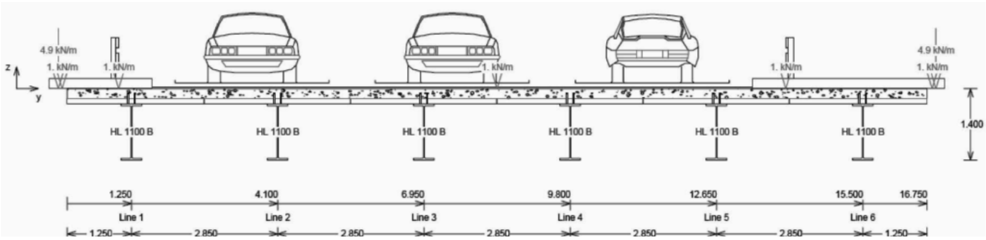

Figure 3: Cross section of the composite bridge

A. Prestressed concrete		**B. Composite bridge**	
Concrete	2 926 t	Concrete	860 t
Reinforcing steel	145 t	Reinforcing steel	47 t
Prestressing steel	40 t	Sections	139 t
		End plates	4 t
		Shear studs	2 t
Total A	3 111 t	Total B	1 052 t

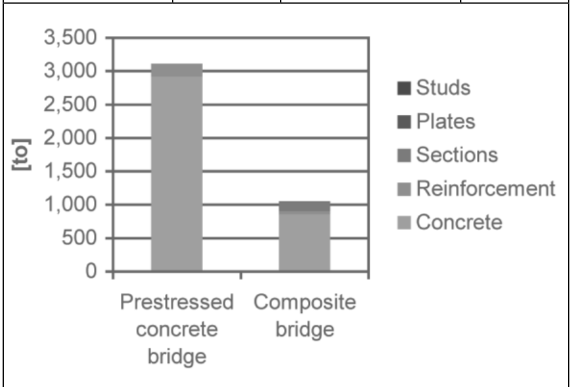

Figure 4: Bill of quantities of the two solutions

3. Description of the LCA

The evaluation aims at determining the environmental burdens generated by the bridge life cycle and comparing the results.
The environmental impacts of the bridges are defined in this paper by eleven parameters, which describe the environmental burdens generated by the bridges like global warming or toxicity.

These indicators, described in Tab. 1, are common LCA indicators. We have used the methods of the Institute of Environmental Sciences (CML) [3] to evaluate them, except for primary energy demand and water consumption which directly stem from mass and energy balances.

Table 1: List of indicators evaluated

Indicator	**Abbreviation**	**Model used**
Global Warming (tCO2eq)	GWP	CML2001 – Nov. 09 [GUINEE 2001], Global Warming Potential 100 years
Primary Energy Demand (GJ)	PED	Net calorific values
Acidification (tSO2eq)	AP	CML2001 – Nov. 09 [GUINEE 2001], Acidification Potential
Eutrophication (tPO4eq)	EP	CML2001 – Nov. 09 [GUINEE 2001], Eutrophication Potential
Photochemical Ozone Creation (tC2H2eq)	POCP	CML2001 – Nov. 09 [GUINEE 2001], Photochem. Ozone Creation Potential
Ozone Depletion (tR11eq)	ODP	CML2001 – Nov. 09 [GUINEE 2001], Ozone Layer Depletion Potential
Water consumption (t)	WCP	None
Freshwater Toxicity (tDCBeq)	FTP	CML2001 – Nov. 09 [GUINEE 2001], Freshwater Aquatic Ecotoxicity Pot.
Human Toxicity (tDCBeq)	HTP	CML2001 – Nov. 09 [GUINEE 2001], Human Toxicity Potential
Marine Toxicity (tDCBeq)	MTP	CML2001 – Nov. 09 [GUINEE 2001], Marine Aquatic Ecotoxicity Pot.
Terrestrial Toxicity (tDCBeq)	TTP	CML2001 – Nov. 09 [GUINEE 2001], Terrestrial Ecotoxicity Potential

The system considered here is based on the life cycle of the bridges ("Fig. 5") that comprises several processes:

- The production phase of steel and concrete elements, from raw materials extraction to the production of finished products
- Transportation of steel and concrete elements to the construction site
- Erection of the bridge
- Use phase
- Dismantling
- Transportation to end-of-life treatment sites
- End-of-life (EOL) phase

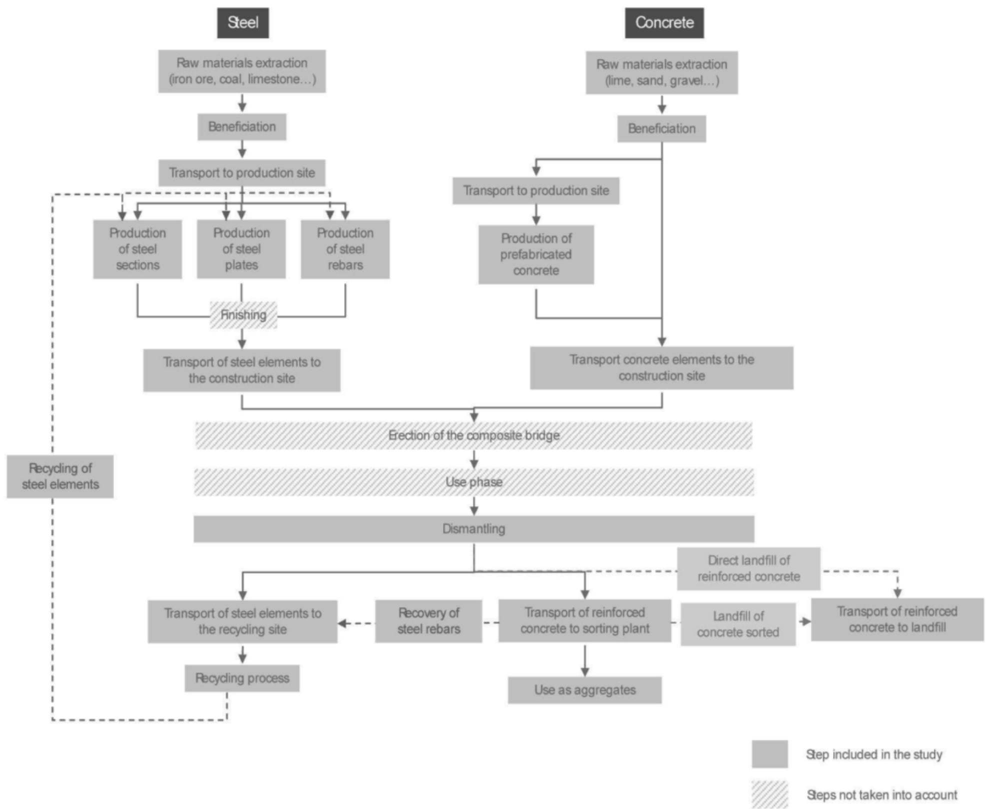

Figure 5: Life cycle of the bridge

However, some stages of the life cycle are excluded from the study: the finishing steps of steel elements, the erection of the bridge and its use phase. These stages are shown in Fig. 5 by a different colour pattern.

The finishing of steel elements consists in cutting and welding. A previous study has shown that this step is negligible in an LCA of steel products because it is very small [4] and has therefore not been included in this evaluation. Similarly, we assumed that the erection phase was also fairly small and therefore was neglected. Finally the use phase of the bridges is equivalent between the two solutions and is therefore not taken into account.

4. Life Cycle Inventory

4.1 General

The Life Cycle Inventory (LCI) collects the mass and energy balances for each process of the life cycle. LCIs for unit processes are listed in Tab. 2.

4.2 LCI of steel elements

The LCI of steel products are compiled by WorldSteel, from data collected on steel sites between 2005 and 2007 [5]. Among the 14 LCI of steel products of WorldSteel, four have been used in this LCA: "sections" for beams, "rebars" for shear studs and concrete reinforcement, and "plates" for end plates.

During the dismantling of the composite bridge, steel sections, end plates and shear studs are easily separated. Reinforcing steel which is physically linked to concrete is more difficult to recover. The structural steel is directly transported from the dismantling site to the recycling site, while reinforcing steel, embedded in concrete, is partially transported to a sorting plant, separated from concrete and transported to the recycling site while the remainder is sent to a landfill facility, cf. Fig. 6.

As a consequence, the recycling rate for sections, plates and studs is 99%, which corresponds to the findings of the European study on steel construction products [6] and 65% for reinforcing steel, in line with the statistics recorded by the Steel Recycling Institute [7] and the information gathered by [8].

Recycling of steel products avoids the production of virgin steel. The methodology used by WorldSteel to integrate this benefit is the multi step recycling method [9], which is implemented in a practical way by calculating an avoided impact that provides a credit to the steel elements recycled at the end-of-life of the bridge.

4.3 LCI of concrete

The cement content required for this type of application is 320 kg/m^3 of concrete [10]. We have used the unit process "concrete, normal, at plant" of the Ecoinvent database [11] for the production of concrete with 300 kg/m^3 of cement and extrapolated the results proportionally for 320 kg/m^3.

At the end of life, concrete can either be land filled, or crushed and used to replace aggregates [12]. After discussion with internal experts the following scenario has been chosen for the EOL of reinforced concrete (schematized in "Fig. 6"):

- 35% of reinforced concrete is directly sent to landfill – thus embedded rebars are also 100% land filled;
- 65% of reinforced concrete is sorted: it is crushed to separate rebars from concrete, that steel being 100% recycled;
- For concrete, it was considered that after the sorting plant, 15% of the concrete is used as aggregates and 85% is land filled.

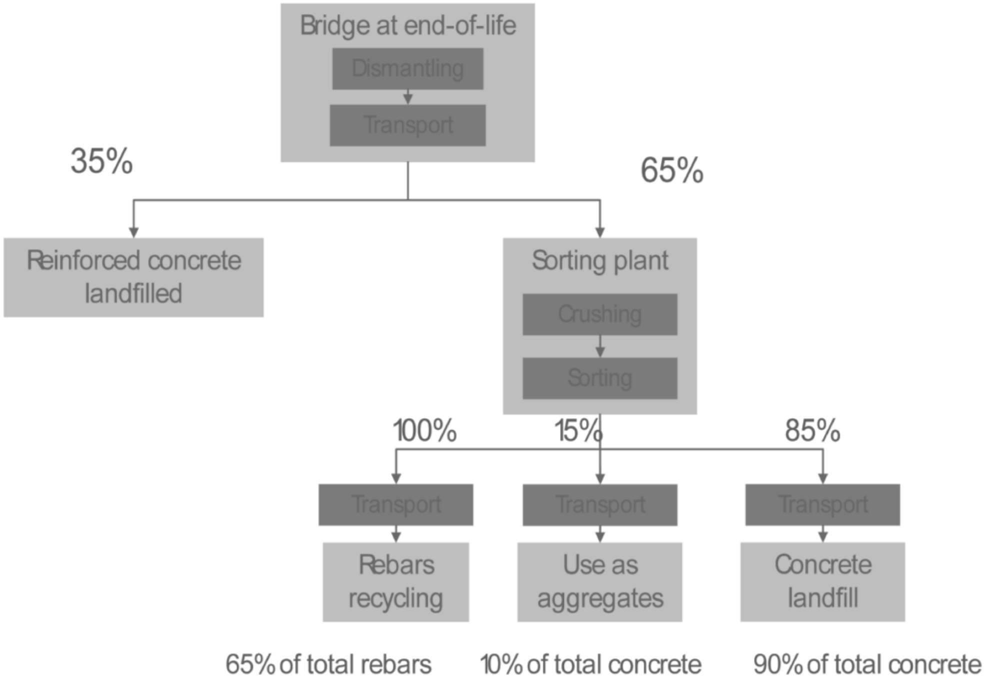

Figure 6: End of life scenario – reinforced concrete

Use of EOL concrete avoids the consumption of aggregates. This environmental benefit is taken into account in the evaluation by providing a credit to the EOL concrete that is reused.

For concrete, LCIs corresponding to each EOL process are provided by the Ecoinvent database, as shown in Tab. 2.

4.4 LCI of additional processes

Steel and concrete elements are assumed to be transported by truck only, either regular truck for steel elements and prefabricated concrete, or mixer truck for ready-mixed concrete. The consumption linked to transportation is calculated by taking into account partial load and empty return trips [13]. Expert opinions were collected to estimate transport distances. Steel elements are supposed to be transported on an average distance of 1000km, and prefabricated concrete on 500km. Concerning on-site concrete, a transport distance of 50 km for the ready-mixed concrete is assumed.

Other information (fuel production, emissions linked to transportation, etc.) is provided by the models of the consulting group PE International [14].

Table 2: List of data and sources for unit processes

Process	LCI associated	Source
Production and recycling of steel beams	EU: Sections	WorldSteel 2010
Production and recycling of steel studs	GLO: Studs – 99%	WorldSteel 2010
Production and recycling of steel end plates	EU: Plates– 99%	WorldSteel 2010
Production and recycling of reinforcement	GLO: Rebar– 65%	WorldSteel 2010
Concrete production	CH: concrete, normal, at plant	Ecoinvent 2011
Separation of concrete and reinforcement	CH: disposal, building, concrete, not reinforced, to sorting plant	Ecoinvent 2011
	CH: disposal, building, reinforcement steel, to sorting plant	Ecoinvent 2011
Landfill	CH: disposal, building, concrete, not reinforced, to final disposal	Ecoinvent 2011
	CH: disposal, building, reinforcement steel, to final disposal	Ecoinvent 2011
	CH: disposal, concrete, 5% water, to inert material landfill	Ecoinvent 2011
Use as aggregates	CH: gravel, unspecified, at mine	Ecoinvent 2011

5. Life Cycle Impact Assessment

5.1 Calculation of environmental burdens

The Life Cycle Impact Assessment stage evaluates the potential environmental impacts of a product's life cycle by associating the LCI results (mass and energy balances) with the models of impacts, such as those listed in Tab. 1.

For example, let us describe the calculation method for the global warming indicator. The Global Warming Potential (GWP) is defined by the United Nations Framework Convention on Climate Change as "an index representing the combined effect of the differing times greenhouse gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation" [15]. This indicator was constructed by the Intergovernmental Panel for Climate Change. These climate experts have analyzed the radiative forcing of greenhouse gases and deduced a conversion factor for each greenhouse gas to an equivalent emission of carbon dioxide. For example, over 100 years, 1 kg of methane emitted will have the same radiative forcing as the emission of 25 kg of carbon dioxide.

5.2 Comparison of environmental profiles

In this paper,"environmental profile" refers to the environmental burdens generated during the life cycle of the bridges and characterized by the eleven indicators of Tab. 1.

Fig. 7 shows a comparison of the environmental profiles of the two bridges. To facilitate the reading, the indicators have been normalised to the burden of the concrete bridge. Abbreviations used in Fig. 7 are defined in Tab. 1.

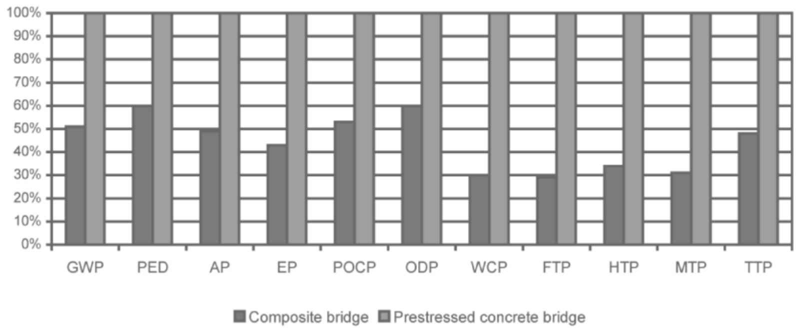

Figure 7: Comparison of the environmental profiles of the two bridges

The environmental impacts of the composite bridge are lower than those of the prestressed concrete bridge for all indicators. The difference varies from 40% (primary energy demand, PED and ozone depletion potential, ODP) to 70% (for water consumption, WCP and freshwater, HTP, human, HTP, and marine toxicity, MTP).

This result is consistent with the bill of quantities shown in Fig. 4, the composite bridge being three times lighter than the prestressed concrete bridge.

5.3 Contribution analysis

In order to better understand the results presented in Fig. 7, the stages of the life cycles have been analysed to identify their hot spots. To this aim, we focus here on the results for the global warming indicator and show the contribution of each phase of the life cycle: production, end-of-life and overall life cycle impacts. As transportation is not differentiated among phases, it is added to the overall impact without further detail.

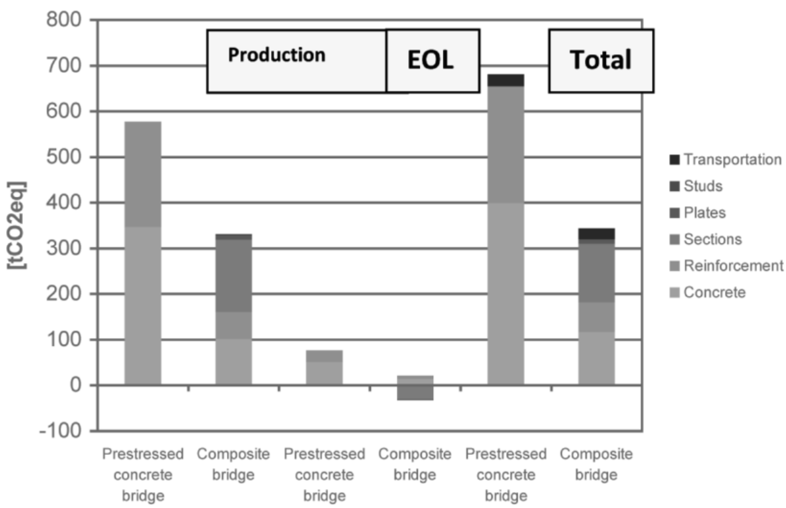

Figure 8: Global Warming Potential of both bridges, distributed amongst production, transportation and end-of-life

Production phase

The GWP of the production phase is dominated by concrete production for case A, and by steel production for case B, which respectively accounts for 60% and 69% of the impacts. Comparatively, the composite bridge production (330 tCO2eq) generates 43% less GWP than the prestressed concrete (580 tCO2eq).

End-of-life phase

As explained in 4.2 and 4.3, a credit is given to materials that are reused or recycled at their end-of-life.

For the composite bridge, recycling of steel avoids 32 tCO2eq and reuse of concrete 0.2 tCO2eq. This is compensated by the impacts linked to the dismantling of the bridges, the treatment before reuse (separation of concrete and rebars) and the landfill (22 tCO2eq). Altogether, the EOL phase of the composite bridge has a negative value (-10 tCO2eq) and thus slightly decreases the overall life cycle GWP of the bridge.

On the other hand, for the prestressed concrete bridge, the GWP of the dismantling, separation of concrete and steel and landfill (78 tCO2eq) is larger than the credit provided by recycling (1 tCO2eq). As a result, the EOL phase of the prestressed concrete bridge has a positive value (77 tCO2eq) and thus increases the overall life cycle GWP.

These results are sensitive to a change in EOL assumptions; therefore another scenario was tested to evaluate the effect of a 100% recycling of reinforcing steel and concrete. In this scenario, all reinforced concrete needs to be crushed. In that case, the recycling compensates the burden of sorting only because of the recycling of steel while the benefit of recycling concrete is not high enough.

Altogether, for the two bridges, the EOL phase has a much lower contribution to the life cycle GWP than the production phase.

Life cycle results

The production phase (from extraction of raw materials to semi-finished products) is the main contributor to the GWP. This is also true for seven of the other indicators, except for ozone depletion (ODP), acidification (AP), human (HTP), marine (MTP) and freshwater toxicity (FTP) where the EOL phase contributes much more to the overall results. This is related to the treatments in the sorting plant which has a large effect on these particular indicators.

Finally, the contribution of transportation of concrete and steel elements represents a rather low share of the overall GWP results, respectively 4% and 7% for the prestressed concrete bridge and the composite bridge.

6. Conclusions

There is a direct connection between the mass of the bridge as shown in the bill of quantities and the environmental burdens. The heavier concrete bridge has a significantly higher burden.

The production phase is more important than the end-of-life phase and the transportation of materials for most indicators. In addition, the end-of-life phase is sensitive to the fate of materials, whether they are recycled, reused, or land filled. The avoided impact by the EOL of reinforced concrete being smaller than that of the treatment necessary to crush it, the EOL of reinforced concrete downgrades the overall impact of bridges. On the contrary, the other steel elements (sections, plates and studs) avoid environmental impacts and improve globally the profile of the bridges.

In the case of the composite bridge, recycling of steel reduces the emissions by 10% (32 tCO_2eq) savings which are equivalent to 246.000 km driven by a car emitting 130 gCO_2/km [16].

The conclusion of this work shows clearly that the composite bridge has significantly smaller environmental burdens than the other bridge: this directly related to the use of steel in the first bridge. Moreover, the difference is very large: 40% to 70% depending on the indicator.

Another interesting result of this work is that recycling does not necessarily reduce the environmental burdens as the cost of recycling may be higher than the benefits it brings. A material like steel, the recycling of which avoids using virgin iron ore, should thus always be recycled – and indeed it is in general recycled to a very high level (more than 80%). A material like concrete, which is recycled as an aggregate, i.e. a low energy low greenhouse gas material, generates more burdens by recycling than by land filling. This is true of primary energy use and CO2 emissions, but is even more significantly true of ODP, AP, HTP, FTP and MTP.

When designing a bridge, it is essential to carry out an LCA and to use the results to improve on the design. Software tools such as AMECO [17], which calculates a simplified LCA of buildings or bridges focussing on energy and greenhouse gases, help to achieve this.

References

[1] ISO 14040-44: “Environmental management – Life cycle assessment – Principles and framework” and “Environmental management – Life cycle assessment – Requirements and guidelines”; 2006

[2] PE INTERNATIONAL, “Critical review report of the method for the environmental evaluation of bearing structures made of steel and concrete”, 2010

[3] J.-B. Guinée, “Handbook on Life Cycle Assessment”, P GUINEE, 2001

[4] A.-L. Hettinger, F. Labory, Y. Conan, “Environmental assessment of building structures made of steel or concrete”, 2010

[5] WORLDSTEEL, www.worldsteel.org, 2010

[6] ECSC Final Report, “Life-cycle assessment (LCA) for steel construction”, 2002

[7] SRI, “Steel Recycling Institute”, www.recycle-steel.org, 2008

[8] M. Sansom, J. Meijer, “Life-cycle assessment for steel construction”, SANSOM, 2002

[9] BIRAT, “The value of recycling to society”, 2006

[10] ZEMENT, “Bauberatung Zement – Expositionsklassen von Beton und besondere Betoneigenschaften”, 2004

[11] D. Kellenberger, H-J Althaus, T. Künninger, “Concrete Products and Processes – Ecoinvent”, ECOINVENT, 2007

[12] Jeannette Sjunnesson, “Life Cycle Assessment of Concrete” – Master thesis, LUND University, Department of Technology and Society, September 2005

[13] INRETS, Institut National de Recherche sur les Transports et leur Sécurité

[14] PE International – GaBi databases, 2010

[15] IPCC, http://unfccc.int/, 2010

[16] Ademe report, “Car Labelling”, http://www2.ademe.fr/, 2011
[17] AMECO, “Software on Life Cycle Assessment of bearing structure”, www.arcelormittal/sections, 2010