Int J Life Cycle Assess (2013) 18:926–938
DOI 10.1007/s11367-013-0558-4

DATA AVAILABILITY, DATA QUALITY IN LCA

Adaptation of environmental data to national and sectorial context: application for reinforcing steel sold on the French market

Fernanda Gomes · Raphael Brière · Adélaïde Feraille · Guillaume Habert · Sébastien Lasvaux · Christian Tessier

Received: 27 September 2012 / Accepted: 8 February 2013 / Published online: 27 February 2013

Abstract
Purpose Environmental data for steel products are generally proposed at a continental or a global scale. The question we are tackling here is: does the fact that steel as a global market necessarily reduces the need for national data?
Methods In this study, the environmental impact of reinforcing steel sold in France is evaluated. To do so, a specific environmental inventory is adapted from Ecoinvent database. CML method is used for impact calculation and both methods "recycled content" as well as "end of life recycling approach" are tested.
Results and discussion This study shows that there is a specificity of reinforcing steel products sold in France compared to European value. It is due to the fact that reinforcing steel is mainly made with recycled steel as the market growth for construction product in France is limited allowing a very high recycled content. This result is not sensitive neither to the allocation method used for recycling (cut-off approach or system expansion) nor to transport distance and electricity country mix used.
Conclusions The result of this study can be used with confidence in every construction site work located on the French territory. Furthermore, the present study advocates for an adaptation of global database to local context defined by a specific industrial sector and a geographic region even for product such as steel that may be considered as a first approximation as a global product.

Keywords LCA · National data · Steel product

Responsible editor: Martin Baitz

F. Gomes · R. Brière · A. Feraille
Navier Laboratory, Ecole des Ponts ParisTech,
Université Paris-Est, Marne la Vallée, France

R. Brière · G. Habert
IFSTTAR, Materials Department, Université Paris-Est,
Paris, France

G. Habert (✉)
Institute for Construction and Infrastructure Management,
ETH Zurich, Wolfgang Pauli Strasse 15,
8092 Zurich, Switzerland
e-mail: guillaume.habert@ibi.baug.ethz.ch

S. Lasvaux
Division Environnement et Ingénierie du Cycle de Vie,
Centre Scientifique et Technique du Bâtiment (CSTB),
Université Paris-Est, 24 rue Joseph Fourier,
38400 St. Martin d'Hères, France

C. Tessier
IFSTTAR, MAST, LUNAM University, 44341 Bouguenais,
France

1 Introduction

One of the major characteristic of the early twenty-first century is the intensification of transcontinental products exchanges. As noticed by Frischknecht (2006), a Swiss watch may contain lithium from Chile; can be packed in brushed aluminium boxes made in China with bauxite from Australia and sold via Hong Kong dealer. In this economy, steel is a product that seems to be representative of this global market. A 1.4 Gt of steel has been produced in 2010, 50 % of this was used in the construction (Worldsteel 2011). Since metal markets are global, datasets available in LCA database are most of the time representatives of the world or of the European situation (e.g. Worldsteel, ELCD, Ecoinvent). Among the most commonly used LCA database for steel, Worldsteel is providing data at the world and the European scale (Worldsteel 2011) and Ecoinvent as well as the ELCD are providing data at the European scale (Althaus and Classen 2005). For the USA, the steel market development institute is working with Worldsteel to consider Life Cycle Analysis for environmental regulation (prnewswire 2012).

In this study, the question we are interested in is: "does the fact that steel as a global market necessary to induce the fact that the environmental impact of one steel product will be the same in every country?" Actually, do the facts that steel has similar properties in every country and that iron ore is extracted in a few countries and then exported all over the world necessarily means that every product has travelled throughout the planet during its processing?

These questions are fundamental because if steel is effectively a global product, then a global or a continental value is sufficient. But if the steel market for one product is restricted and specific to one country, then global data are not sufficient and national datasets are needed. The ILCD Handbook provides some guidance for the development of generic and specific LCI data. A difference is made between a "supply mix" which is the available mix in the country for consumption and a production mix which is the effective production of the country (EU 2010). The supply mix being equal to: "production+importation−exportation". Environmental Product Declarations (EPD) data actually take into account of the volume of products that are currently sold on a national market. German and Dutch EPD for steel products have already been published (Intron 2003; PE International 2011). German EPDs are doing a difference between sections and reinforcing bars. The EPD for sections is very similar from Worldsteel environmental data, however, EPD for reinforcing bars, as well as the Dutch one, are quite different from European or world based data for reinforcing steel products. However, few explanations or justifications of the results are provided with the EPD. The objective of the present study is then to perform a new environmental evaluation of the supply mix at the country scale in order to evaluate if this difference observed for the Netherlands and Germany is observed for another European country.

In this study, we will focus on the French context and a comparison will be made between European data from Ecoinvent and Worldsteel with specific data representative of reinforcing steel bars sold in France.

During the first part of the study, the environmental impacts of reinforcing steel sold on the French market are evaluated. A sensitivity analysis is performed to strengthen the results. Secondly, these impacts are compared with environmental impacts of reinforcing steel calculated with European database.

This study is mainly focused on assessing the environmental impacts of the reinforcing steel from cradle to construction site. However, as metals are highly recyclable and that a large percentage of the metallic products are effectively recycled, the question of the end of life of the product is a particular concern for these products. It has been very much debated in recent publications (de Schrynmakers 2009; Dubreuil et al. 2010; Kim et al. 1997) and can roughly be presented as two different approaches: the "recycled content approach" (also known as the cut-off approach) and the "end-of-life recycling approach" (also known as the avoided burden approach). Both approaches are compliant with the current ISO standards (ISO 14044 2006). A recent paper from Frischknecht (2010) highlighted the fact that these two approaches are dealing with two drastically different visions of sustainability and, as a consequence, involve value judgement which will never allow reaching a consensus. The end of life recycling approach would represent the weak sustainability concept while the recycled content would be in agreement with the strong sustainability concept (Frischknecht 2010). As no clear preference can be justified, it is necessary to have clear and transparent modelling. It is also necessary, as it is stated in the ISO standards, to perform a sensitivity analysis whenever several alternatives on allocation procedure seem applicable.

As a consequence, it has been chosen to use the recycled content approach and to evaluate in the "Discussion" section, the consequences of the second method, which is promoted by the European standard EN 15804 (2012) with the use of the module D and allows developing the end of life recycling approach (Atherton 2007). This choice may be due to the fact that authors are members of national authorities and public institutions and will therefore rather follow the strong sustainability concept as noted by Frischknecht (2010):

Whereas the metal industry may well endorse the end of life recycling approach and by that follow the weak sustainability concept and adopt a risk-seeking strategy, national authorities may be indebted to long-term welfare and environmental protection and thus may rather follow the strong sustainability concept and act rather risk-averse. National authorities may therefore tend to apply the recycled content approach.

2 Materials and methods

2.1 Functional unit and system boundaries

The system studied is 1 kg of reinforcing steel from B500A and B500B grade. In this nomenclature, 500 is specifying a yield stress of 500 MPa, the capital letter B preceding the yield strength denotes reinforcing steel and the capital letters A & B following the yield strength denotes the ductility class, with A being the lowest. These two steel grades are the most commonly used for reinforcing bars and correspond to various standards (NF EN 10 020 2000; NF EN 10080 2005; ISO 6935-2 2007). The boundaries of the study are limited to the production and delivery on site of 1 kg of steel bars (Fig. 1). The part of the life cycle considered is then from cradle to construction site.

The transport between the factory gate and the construction field is taken into account because the aim of the study is to evaluate the impact of the materials used in France, which means the supply mix (ELCD 2012) even if they are not all produced in France.

Steel of both B500A and B500B are produced through two fundamentally different routes: blast furnace (BF) or electric arc furnace (EAF). In this study, we have considered that the BF route uses mainly iron ore and 19 % of recycled steel introduced as scrap in the basic oxygen furnace. This ratio is the one used in the Ecoinvent report for “steel, converter, unalloyed, at plant” (Classen et al. 2011) and is coherent with other data such as the World Steel Association methodology report which evaluates the recycled content between 10 and 35 % (Worldsteel 2011). For the EAF route, we considered that most of the steel introduced is recycled steel.

After the steel production, treatments are done to confer to steel its required mechanical properties. Both products are hot rolled after the furnace. The main difference between the two studied products (B500A and B500B) lies in the fact that the B500A production includes an additional cold rolling process that can be operated in a factory independent from the hot rolling plant. An additional transportation phase has then to be potentially included. B500B are only submitted to quenching and self-tempering or stretching after hot rolling, which are much less energy-consuming than cold rolling and are done in the same plant as the hot rolling process. This difference in production route while function is often similar, justifies the fact that we have studied both products.

2.2 Environmental and technical data collection

To build an environmental inventory specific to the reinforcing steel sold in France, the Ecoinvent database has been adapted to the French context. This has been done with the help of steel experts by adding or removing processes and by modifying input/output data from the remaining processes detailed in the Ecoinvent report (Blaser et al. 2009). Experts are mainly from AFCAB (French association for concrete’s reinforcing steel certification) which is an independent association settled in 1990 to deliver certificates of conformity to companies that manufacture or fix on site concrete reinforcing steels or their accessories and sell them in France (AFCAB 2011a).

When values could not be validated by experts, it has been chosen to use a parameter having a mean, a maximum and a minimum value and covering the wide range of possible values. The hypotheses used to build the inventory for both reinforcing steels are shown in Tables 1 and 2 respectively. It has to be noted that with this method, no change in the methodological choices of the Ecoinvent database such as the allocation rules in the entire database have been performed. It means that no system expansion for the co-products from the fabrication of the reinforcing steel are included. The consequences of this choice will be discussed later in the paper.

Concerning the steel production process, close to 100 % of the reinforcing steel consumed in France nowadays is produced from unalloyed steel billets (NF EN 10 020 2000)

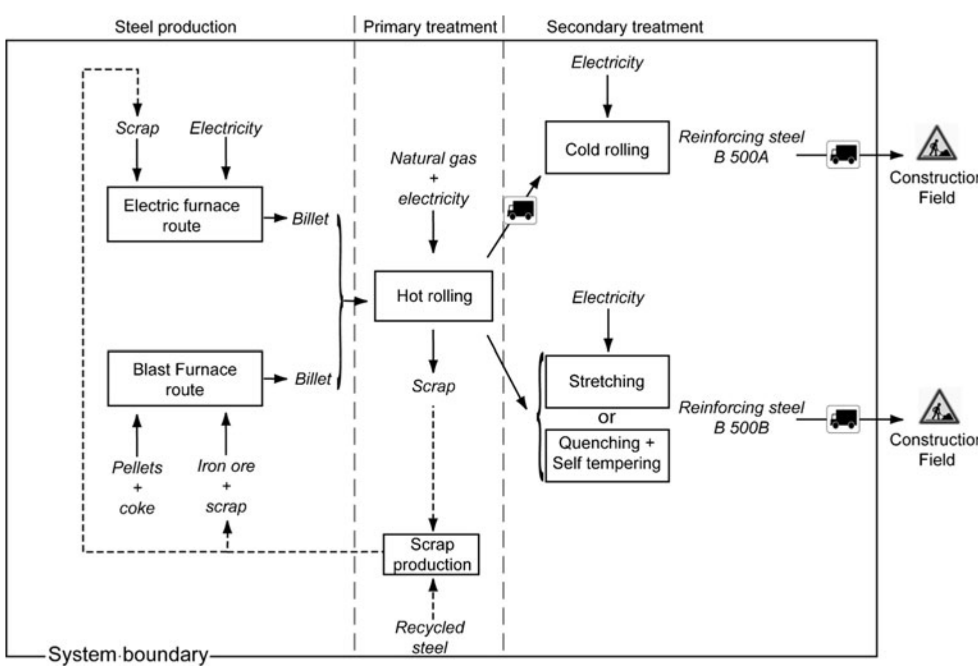

Fig. 1 System boundary of the products studied

Table 1 Parameters used to build LCI of B500A reinforcing steel

Parameters	Origin of data	Mean	Minimum	Maximum
Steel production process				
Direct reduced iron/electric furnace (%)	Ecoinvent process: "steel, electric, un- and low-alloyed, at plant/RER"	98 %	95 %	100 %
Blast furnace/basic oxygen furnace (%)	Ecoinvent process: "steel, converter, unalloyed, at plant/RER"	2 %	5 %	0 %
Electricity used				
Electricity by country (production + importation)	Ecoinvent process: "electricity, medium voltage, at grid"	Reference mix	French electricity	German electricity
Treatment				
Hot rolling	Adapted Ecoinvent process (see Table 5): "hot rolling, steel/RER"	–	–	–
Cold rolling	Industrial data	–	–	–
Transport distance				
To the cold rolling plant	Ecoinvent process: "transport, lorry >32 t, EURO 4/RER"	300 km	0 km	1,000 km
To the construction site	Ecoinvent process: "transport, lorry >32 t, EURO 4/RER"	686 km	0 km	1,445 km

produced by electric route (EAF) (AFCAB 2011b). The Ecoinvent process "steel, electric, un-low-alloyed, at plant/RER" used as the chemical composition of steel is similar to the chemical composition required in the EN standard (NF EN 10080 2005) for steel used in reinforcing bars production. This process has been created in 2007 and updated in 2011. It is based on measurements validated by R. Hischier and entered in the database by H.J. Althaus (Classen et al. 2011). We have only adapted the amount of EAF slag dumped in landfill as it influences very significantly the environmental impacts for ecotoxicity (see in "Results" and "Discussion" sections). In Ecoinvent process, 0.09 kg of slag per kg of steel is disposed in landfill which represents 60 % of the slag produced. This value is confirmed by a report from the European commission (European Commission 2000). However, two recent reports written by steel and slag producers show a much lower value (around 15 %) (Apfel 2002; Eurofer and Euroslag 2012). As a consequence, we have decided to modify the Ecoinvent process and consider that 15 % of the slag is disposed in landfill.

Furthermore, even if it is certain that 100 % of the plants that are producing reinforcing steel for the French market have an electric arc furnace (AFCAB 2011b), sometimes, due to economic reasons, one plant might have to buy some billets from another plant. This can happen for instance if an unplanned maintenance has to be done on the furnace while the production has to keep going. In that context, billets can be bought and introduced directly in the hot rolling plant and these billets could at that time come from a BF. As these events happens very rarely, experts hesitate between 0 and 5 % of the steel produced from BF (AFCAB, personal communication), that is why it has been chosen to consider that 2 % of BF billets were used as a mean value, but that uncertainty on the exact value were between 0 and 5 %.

Table 2 Parameters used to build LCI of B500B reinforcing steel

Parameters	Origin of data	Mean	Minimum	Maximum
Steel production process				
Direct reduced iron/electric furnace (%)	Ecoinvent process: "steel, electric, un- and low-alloyed, at plant/RER"	98 %	95 %	100 %
Blast furnace/basic oxygen furnace (%)	Ecoinvent process: "steel, converter, unalloyed, at plant/RER"	2 %	5 %	0 %
Electricity used				
Electricity by country (production + importation)	Ecoinvent process: "electricity, medium voltage, at grid"	Reference mix	French electricity	German electricity
Treatment				
Hot rolling	Adapted Ecoinvent process (see Table 5): "hot rolling, steel/RER"	–	–	–
Stretching	Industrial data	50 %	100 %	0 %
Transport distance				
To the construction site (km)	Ecoinvent process: "transport, lorry >32 t, EURO 4/RER"	686 km	0 km	1,445 km

Table 3 Distribution of B500A produced between different countries for French consumption (Source: AFCAB 2011b)

Country	France	Germany	Belgium	Netherlands
Relative contribution	76.0 %	10.0 %	13.0 %	1.0 %

Finally, the inventory of the steel production is dependent on the electricity used for the electric furnace, which is country specific. As steel sold on the French market is not only produced in France, we simulated a mean value of the electricity mix, called "reference mix", with the relative production volume of reinforcing steel coming from the different producing countries, available through AFCAB (2011b) and the electricity specific inventory of this country which is given in Ecoinvent database (Electricity medium voltage + import, at grid, by country). This reference mix is different between B500A and B500B as country producers as well as the amount of each steel category produced by one country is different between the two steel categories (Tables 3 and 4). French and German electricity productions are used as a proxy to minimum and maximum values for electricity mix. Note that, in our specific case, with the set of indicators used (see next section), those two countries have effectively the most extreme environmental impact for 1 kWh used (Ecoinvent v2.2). Only Turkey has a higher environmental impact for electricity than Germany. However, its steel production sold on the French market is negligible (0.1 %). We have then considered that German electricity mix was more relevant to be used to evaluate the variability of the reinforcing steel environmental impact due to the type of electricity used. It should be noted that the choice of these two countries is highly dependent on the set of indicators chosen. For instance, if nuclear waste was assessed independently and not spread between the different toxicity categories, French electricity mix would had the highest impact for that category and another balance between countries might have been chosen.

Concerning the steel "treatment", the inventory for the hot rolling has been built by using only among the generic Ecoinvent hot rolling process (Ecoinvent 2011), the sub-processes that were relevant for the specific production of B500 A and B500 B. We did not change the inventory for each sub-process, but just removed sub-processes that were irrelevant for the hot rolling of reinforcing steel. The sub-processes considered in the study are shown in Table 5 and can be briefly described as follows:

Table 5 Processes involved for steel hot rolling

Processes involved	
Ecoinvent process details	Hot rolling, steel, furnace
	Hot rolling, steel, descaling
	Hot rolling, steel, hot rolling
	Hot rolling, steel, waste water treatment plant
	Hot rolling, steel, overall
	Hot rolling, steel, packaging

2.2.1 Hot rolling, steel, furnace

It represents the heating for rolling temperature. Actually, to be rolled, steel temperature should be between 1,050 and 1,300 °C. As during the continuous casting, billets lose heating, billets are placed in a reheating furnace.

2.2.2 Hot rolling, steel, descaling

Scale formed during heating must be removed prior to rolling in order to avoid a contamination of the stock surface by scale impressed. A common method of descaling is breaking and spraying off the scale by means of high-pressure water. Scale has been considered as a residual material to landfill and scale contaminated by oil as hazardous waste for incineration.

2.2.3 Hot rolling, steel, hot rolling

It represents the rolling mechanical process of the billets. Electricity and water are used. Water consumption depends on whether the water flow design is an open, a semiclosed or a closed circuit. Dust and fugitive oil are emitted to the air.

2.2.4 Hot rolling steel, waste water treatment plant

Contaminated water is treated in internal waste water treatment plants. Details about purified water pollutants composition can be found in the Ecoinvent report (Classen et al. 2011), as well as sludge pollutants composition generates by the water treatment. Five kilos of sludge per cubic meter of treated water are produced, which is assumed to be disposed in a residual material landfill type with cement stabilisation.

Table 4 Distribution of B500B produced between different countries for French consumption (Source: AFCAB 2011b)

Country	France	Germany	Spain	Italy	Luxemburg	Switzerland	Belgium	UK	Turkey	Netherlands
Relative contribution, %	66.5	13.0	9.3	6.0	3.9	0.7	0.2	0.2	0.1	0.1

2.2.5 Hot rolling, steel, overall

It represents all the flows which are not included in the main hot rolling sub-processes, such as: heat waste, transport of all materials not produced at the plan and the transport to disposal of waste.

2.2.6 Hot rolling, steel, packaging

It represents wood, plastic and steel coils for the packaging of reinforcing steel products.

All details of the inventory of these sub-processes can be found in Ecoinvent report (Classen et al. 2011). In the same way, the modelling of the Ecoinvent sheet rolling process—standing for cold rolling process—has been investigated to identify the sub-processes relevant for reinforcing steel treatment. From this analysis, most of the processes were not adapted to the cold rolling used in reinforcing steel production as these processes have been defined for cold rolled plates and sheets used in the car or in the households market. This process has then been simply modelled as an electricity consumption of 0.035 kWh per kg of steel. This energy value comes from specific industrial data (AFCAB, personal communication). Other data from the literature evaluate energy consumption between 0.1 and 0.6 kWh per kg (US EPA 2012; Worrell et al. 2008), but these values are for steel sheets used in the car industry. In these cases, cold rolling is incredibly more intense than for reinforcing bars as the size reduction is higher than 50 % (Full hard cold rolling) while in our studied process, size reduction is lower than 1 % (Skin rolled) (Beddoes & Bibbly 1999). As a consequence, we estimate that 0.035 kWh per kg is a reasonable value for the studied cold rolling. It should also be noted, as illustrated in the result section that increasing by a factor 2 to 10 the energy consumption for cold rolling will not drastically change the results.

The production route for B500B includes either a stretching process or a 'quenching + self-tempering' process. The stretching process is estimated to have an electricity consumption equal to half of the cold rolling process (AFCAB, personal communication). Furthermore, considering experts advice, 'quenching + self-tempering' process which follows hot rolling involves negligible supplementary energy, essentially to run small electric motors and water pumps (AFCAB, personal communication). Industry data are however not very accurate concerning the relative proportion between these two options. As a consequence it has been considered that B500B production was split in half between both processes, but that there could be variations between 100 % of one or the other option (see Table 2).

The transportation distances have been estimated according to the distances between capitals of steel producing countries and Paris (Table 6), balanced according to the countries' relative contribution to the total production (see Tables 3 and 4). The distance considered for French production is 500 km. It has to be noted that this approach overestimates the transport distances as the main foreign producing plants (Germany, Spain, Italy) are very close to the border with France. All transports are considered to be made by truck except for Turkey where the distance between Istanbul and Marseille has been considered to be made by boat. The mean value is 686 km, but potential variations have been considered. A minimum value of 0 km and a maximum of 1,445 km have been chosen. This maximum value corresponds to the distance separating Paris from Rome Actually, the longest distance is between Paris and Istanbul, however, as two third of the travel is made by boat; it is the transport by truck from Rome to Paris that has the maximum impact for most impact categories.

An additional transport distance has been included for B500A due to the fact that cold rolling plants and hot rolling ones are not always at the same factory. It has been modelled by a lorry transportation over a distance ranging from 0 to 1,000 km and with an average value of 300 km (AFCAB, personal communication).

Finally, to compare our results with the values from Worldsteel data (available in the ELCD database) and Ecoinvent, the transport phase between the gate of the factory and the construction field which is not included in reinforcing steel modules of both databases has been added in this study with the same assumption as our calculation (686 km by truck, see Table 1). Worldsteel and Ecoinvent databases do not introduce any LCA modelling difference between B500A and B500B reinforcing bars. Only one value for each database has then been calculated.

Table 6 Evaluation of the distance between a steel plant located in a specific country and a construction site work in France

Location of the production site	France	Germany	Spain	Italy	Luxembourg	Switzerland	Belgium	UK	Turkey	Netherlands
Average distance from production site to construction site	500	1,053	1,272	1,445	400	585	309	451	3,870[a]	517

Distance are approximated through distance between capital cities and for French production plant, a mean distance of 500 km is used

[a] 2,800 km by boat and 1,070 km by truck

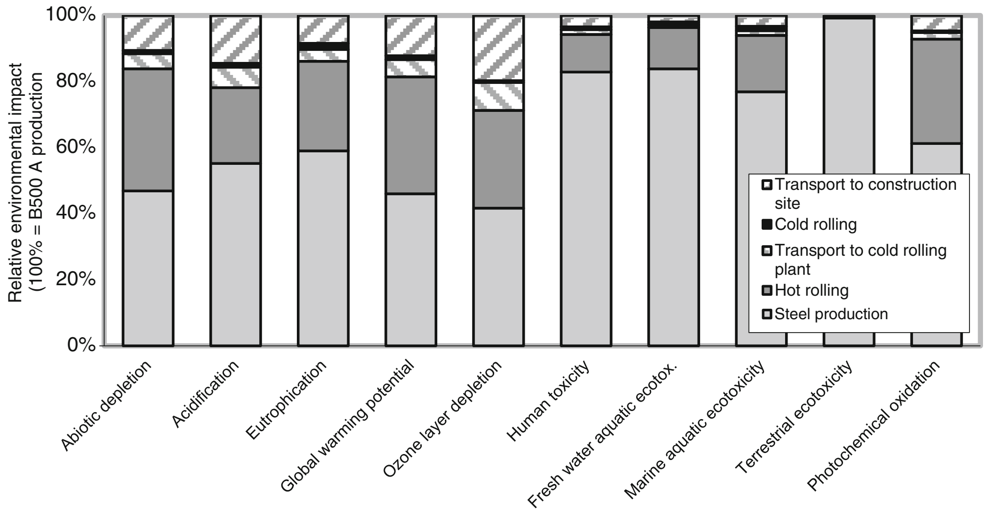

Fig. 2 Relative contribution of the different processes involved in the production and transport of B500A type reinforcing steel for CML environmental impact categories

2.3 Impact calculation method

In this study, we choose to apply the CML life cycle impact assessment method (Guinee et al. 2002). The following indicators are then computed: abiotic depletion (kilogramme Sb $_{eq.}$), acidification (kilogramme $SO_{2\ eq.}$), eutrophication (kilogramme $PO_4{}^{-3}{}_{eq.}$), global warming potential (kilogramme $CO_{2\ eq.}$), ozone layer depletion (kilogramme CFC-11 $_{eq.}$), human toxicity (kilogramme 1,4-DB $_{eq.}$), fresh water aquatic ecotoxicity (kilogramme. 1,4-DB $_{eq.}$), marine aquatic ecotoxicity (kilogramme 1,4-DB $_{eq.}$), terrestrial ecotoxicity (kilogramme 1,4-DB $_{eq.}$) and photochemical oxidation (kilogramme $C_2H_{4\ eq.}$). The simulations are done with SimaPro v7.3.3 software (Goedkoop & Oele 2004).

Furthermore, to evaluate the robustness of the results, the values where we could not be sure of the exact value have been modelled with a parameter having a mean, a maximum and a minimum value. With these intervals a Monte Carlo analysis has been done in order to have a mean value of the environmental burden of the steel product and a standard deviation around this value.

3 Results

3.1 Contribution of the different processes

The relative contribution of the different processes involved in the environmental impacts of B500A reinforcing steel is shown in Fig. 2. Our results show that all transport phases represent less than 20 % for all impact categories except ozone layer depletion, even when transport from the factory gate to the site work is included. The steel production process is the major contributor for impact categories related to ecotoxicity, while it represents 50 % of the impacts for the other ones. The contribution of the hot rolling process is not negligible for abiotic depletion, global warming potential, ozone layer depletion and photochemical oxidation.

The relative contribution of the different processes for B500B production and transport are shown in Fig. 3. Comparing B500A and B500B, very similar results can be observed. Actually, the secondary treatments for reinforcing steel production, which include stretching for B500B and cold rolling for B500A are negligible (see Figs. 2 and 3).

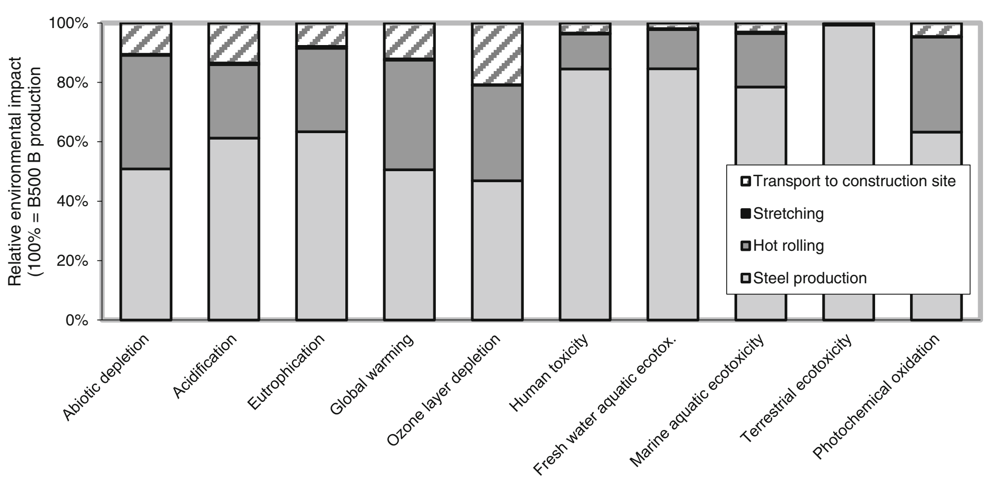

Fig. 3 Relative contribution of the different processes involved in the production and transport of B500B type reinforcing steel for CML environmental impact categories

The only significant difference is the impact from the transport to the cold rolling plant for B500A production as no transport exists between primary and secondary treatment plants for B500B.

3.2 Sensitivity analysis

For B500A, four values are submitted to uncertainty. The first one is the fact that the exact share between BF and EAF is not known because even if 100 % of the plants for the French market have an electric arc furnace, one plant might have to buy some billets from another plant which could use a BF. The second one is the nature of the electricity used for the furnace as the electric mix is different depending on the country where the plant is installed. And finally, the two other variations come from transport distance variation.

The sensitivity analysis consists of evaluating the environmental consequences when one of the four parameters is set to its maximum and minimum value. This uncertainty analysis shows that the results are not very sensitive to uncertainty on steel production process (Fig. 4). This was expected as variations in BF/EAF ratio are very small (0 to 5 % of BF, see Table 1). However, the choice of the electricity country mix will largely influence the results, particularly for eutrophication, abiotic depletion, global warming potential and marine aquatic ecotoxicity (see Fig. 4). It can be noted that as most of the plants are located in France (66 %, see Table 4), the mean value is closer to the French electricity mix, which induces that the low impact scenario (French electricity) is not as much different from the mean scenario than the high impact scenario (German electricity) is. In the high impact scenario, we can clearly see that the use of a greater amount of coal power plant (as in Germany) increases the previously cited impacts; however, it should also be noted that the choice of the environmental method is here determinant on the interpretation. Actually, a distinct evaluation of the radioactive waste generated would induce radically different results. This impact category would be largely predominant in the French scenario compared to the German one. Therefore, it should be reminded that this study, more than evaluating who has the lowest environmental impact (which is then highly dependent on the assessment method) is rather willing to assess the potential variability of the LCA results due to geographic location of the plant.

Finally, the influence of the transport is not negligible and can represent between 15 and 40 % for all impact categories except toxicity and photochemical oxidation for which variations are very small (see Fig. 4). It is due to the fact that: first, a steel bar can be transported from 0 (lowest impact scenario) to 1,445 km (highest impact scenario) between the production plant and the site work; and that secondly an internal transport distance between the EAF and the cold rolling plant can vary also between 0 and 1,000 km. These values are of course extreme value and only a small part of the steel will go through these long transport distances.

For B500B, the same sensitivity results are observed except that there is only one transport variation possibility; but its contribution still represents 10 to 20 % for abiotic depletion, acidification, eutrophication, global warming potential and ozone layer depletion.

3.3 Comparison with European databases

In that simulation, all the four parameters which were evaluated separately in the previous paragraph are now simulated all together with a triangle distribution between minimum and maximum value throughout a Monte Carlo simulation (Huijbregts 1998). Mean values for B500A and B500B as well as standard deviation are then compared with other database. The impact values assessed from the various database and models are presented on Fig. 5. It is clear that the global warming potential for the reinforcing steel sold on the French market is lower than European data calculated with

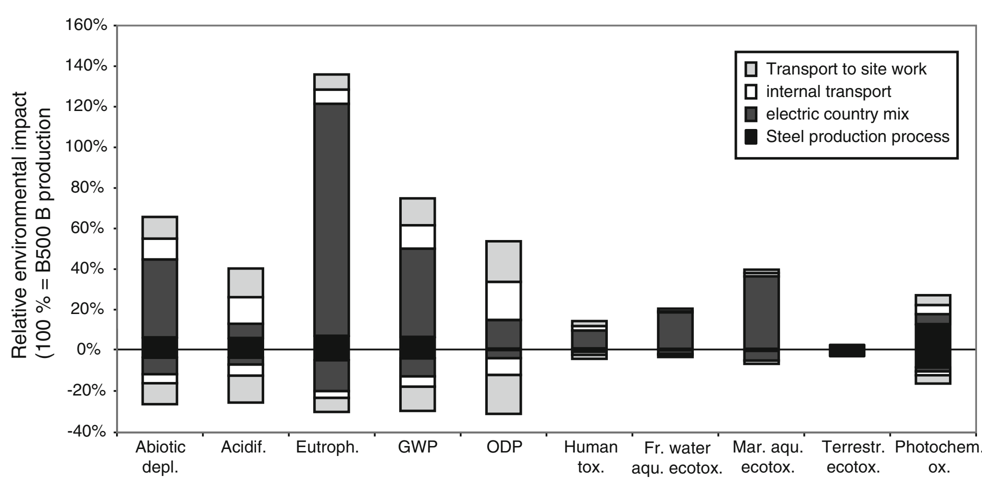

Fig. 4 Contribution of steel plant location (transport and electricity) and production process (electric furnace vs blast furnace) to uncertainty of LCA results for B500A type of reinforcing steel

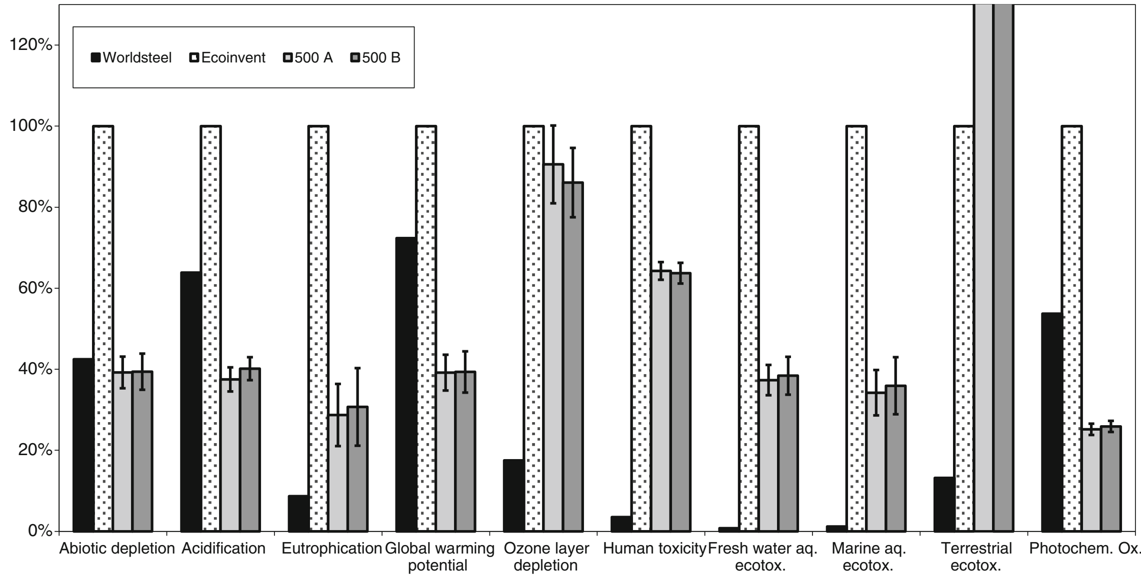

Fig. 5 Comparison between Worldsteel, Ecoinvent data and results from this study for the different impact categories

both database (Ecoinvent and Worldsteel). If results from our study are compared with Ecoinvent data, the reinforcing steel consumed in France has a lower impact than the generic European value for all impact categories except terrestrial ecotoxicity, where our results are significantly higher. The profile is different when the results are compared with Worldsteel values. Actually, our results are considerably higher for eutrophication, stratospheric ozone depletion and ecotoxicity. These differences will be discussed in the next section.

Finally, it has to be noted that the uncertainties that have been introduced (transport, electricity, steel production process) do not induces large variation when a Monte Carlo simulation is done. Variations for B500A and B500B are estimated around 10 %, which is somehow a commonly accepted variation in industrial practice (Cimbeton 2010). The ±10 % of variations confirms also the fact that no significant difference can be made between B500A and B500B steel products.

The details of the values for each impact category are shown in Table 7.

4 Discussion

4.1 Differences between Worldsteel and Ecoinvent data

The difference between Worldsteel, Ecoinvent and our study for acidification, global warming potential and photochemical oxidation can be explained by the fact that EAF is used at more than 95 % in our study. Actually, Ecoinvent generic European value considers that only 37 % of reinforcing steel is produced throughout EAF and it is known that EAF is less energy and fossil resources intensive than BF (Li et al. 2002). For Worldsteel LCA data, the exact proportion between EAF and BF is not specified in the ELCD website (2012). However, it can be reasonably estimated that the BF/EAF ratio is higher than in our results as the global

Table 7 Environmental impact of reinforcing steel sold on the French market

Impact categories	Worldsteel	Ecoinvent	500 A	500 B
Abiotic depletion	$5.58·10^{-3}$	$1.32·10^{-2}$	$5.16·10^{-3}$	$5.18·10^{-3}$
Acidification	$3.44·10^{-3}$	$5.38·10^{-3}$	$2.02·10^{-3}$	$2.16·10^{-3}$
Eutrophication	$2.83·10^{-4}$	$3.26·10^{-3}$	$9.35·10^{-4}$	10^{-3}
Global warming (GWP100)	1.12	1.54	0.605	0.607
Ozone layer depletion (ODP)	$1.19·10^{-8}$	$6.78·10^{-8}$	$6.14·10^{-8}$	$5.84·10^{-8}$
Human toxicity	$3.13·10^{-2}$	0.888	0.57	0.565
Fresh water aquatic ecotoxicity	$5.57·10^{-3}$	0.993	0.37	0.381
Marine aquatic ecotoxicity	16.4	1,380	472	496
Terrestrial ecotoxicity	$3.62·10^{-3}$	$2.75·10^{-2}$	$6.34·10^{-2}$	$6.34·10^{-2}$
Photochemical oxidation	$4.41·10^{-4}$	$8.21·10^{-4}$	$2.07·10^{-4}$	$2.13·10^{-4}$

warming impact is higher. The difference between Ecoinvent and Worldsteel can be due to a difference in this ratio but it could also be explained by the amount of scrap introduced in the BF. It is actually equal to 19 % for ecoinvent and between 10 and 35 % for Worldsteel (2011). Furthermore, it can be noted that the ELCD data takes into account avoided impact for some co-products which is leading, for instance, according to the Worldsteel methodological report to around 5 to 20 % difference for GWP or acidification impact categories (Worldsteel 2011).

The fact that European ratio between EAF and BF is lower than the one observed in France, for ELCD as well as for Ecoinvent, in addition to the fact that similar results are observed for reinforcing steel sold in Germany and Netherlands (Intron 2003; PE International 2011) urge us to decide between two answers. Either the European ratio between EAF and BF chosen by Ecoinvent and ELCD are not appropriate for the specific reinforcing steel products and an urgent need to change has to be done; or there is a discrepancy between European countries and it will be necessary to have specific ratio between EAF and BF used for reinforcing steel in each country. This could follow the same structure as what is done for electricity. As steel is one of the major materials for environmental impact of the construction, it is actually fundamental to have these accurate data.

Concerning ecotoxicity, our results are lower than Ecoinvent data for all ecotoxicity impacts except for terrestrial ecotoxicity (see Fig. 5). It is a combination of two effects related to the impact of steel production. In Figs. 2 and 3, we had actually shown that ecotoxicty was controlled by steel production.Firstly terrestrial ecotoxicity impact in Ecoinvent database is much more important for EAF than BF, so a higher EAF/BF ratio as in French reinforcing steel is likely to increase this impact. Secondly, we have modified the Ecoinvent data concerning the slag disposal and reduce the percentage which reduces the associated ecotoxicty impact. To better understand these two aspects, the details of the different processes involved in the impact of EAF steel production are shown in Fig. 6.

In this figure, it is highlighted that the terrestrial ecotoxicity is due to direct emissions on the EAF plant. An evaluation of the emission flow shows that it is essentially the mercury that is responsible of this impact (not shown). This aspect is confirmed by two other studies (US EPA Pacyna et al. 2005; US 2004), which estimate mercury emissions to be usually one order of magnitude higher for EAF than BF. These emissions come from the scraps that often contain minor elements emissions. In these study emissions are estimated to be equal to 4 to $5{\cdot}10^{-5}$kg per ton. As a comparison Ecoinvent report estimates that mercury emissions are equal to $2{\cdot}10^{-6}$kg per ton of steel produced with EAF. Therefore, these studies confirm the fact that there is effectively a problem regarding terrestrial ecotoxicity for EAF due to mercury emissions and that our results correspond rather to an underestimation as they are based on Ecoinvent and not other reports from US EPA ($2{\cdot}10^{-6}$ vs $4{\cdot}10^{-5}$). However, it can be noted that these values are reducing regularly

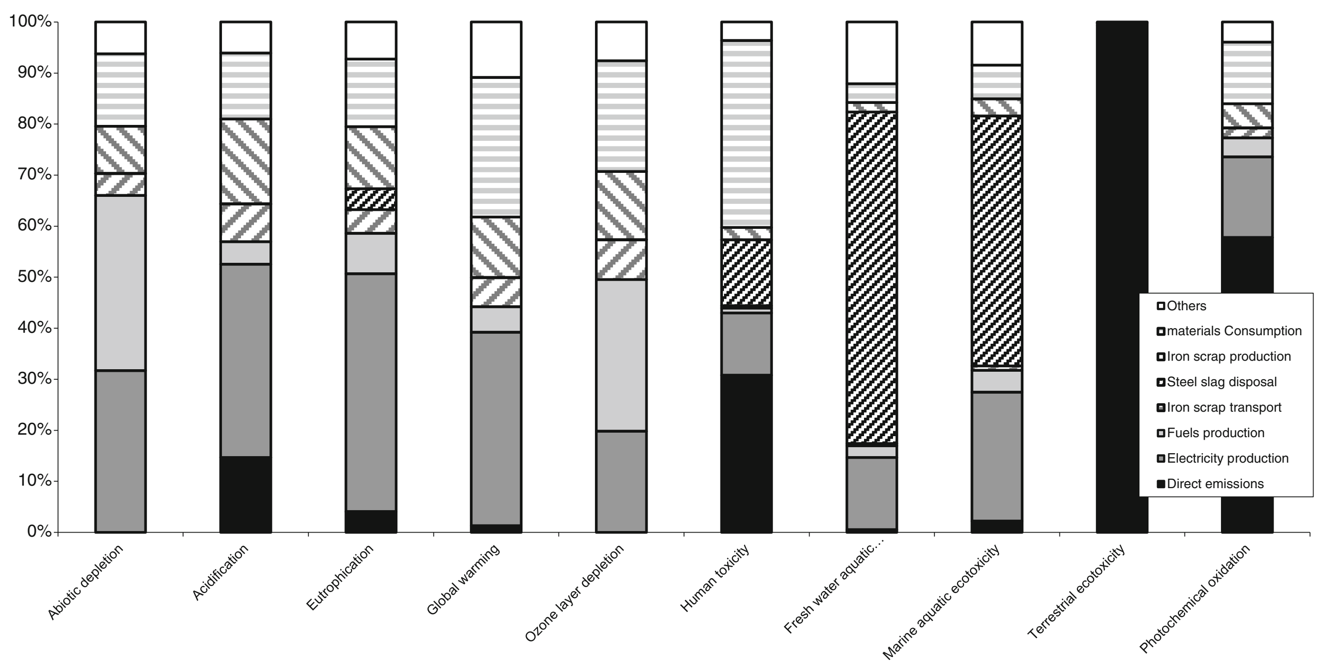

Fig. 6 Relative contribution of the different processes involved in the production of steel with EAF

because new recycled materials have less minor elements (especially mercury). The European Pollutant emission and transfer register shows that mercury emissions from iron production plants are reducing (E-PRTR 2012). Therefore, in a long-term perspective, we can be confident on the fact that EAF route will have a lower environmental impact than BF route for all impact categories and that terrestrial ecotoxicity will not be a major concern for reinforcing steel produced by EAF anymore.

Concerning the other ecotoxic impacts, it is interesting to note that the main contribution is due to steel slag disposal (see Fig. 6). Therefore, even with only 15 % of EAF slag dumped at landfill compared to the 60 % initially considered in Ecoinvent, steel slag disposal still controlled ecotoxic impacts. These impacts are however reduced which explain that our results have a lower impact than Ecoinvent reference value. In a long-term perspective, it can be expected that a better valorisation of steel slag will reduce its disposal as these slags have many different potential uses such as: high-quality natural aggregate in asphalt-wearing courses (Wu et al. 2007), high-strength concrete aggregates (Maslehuddin 2003), additions for cement industry (Monshi and Asgarani 1999) or use up to 10 % in clay brick production (Shih et al. 2004).

Finally, very large differences can be observed between Ecoinvent and Worldsteel data for ecotoxicity impacts as well as for eutrophication (see Fig. 5). These differences could be due to incomplete inventory for background data or to some irrelevant emissions integrated in the Ecoinvent database. As stated by Frischknecht (2010), a transparency on the calculation hypothesis (especially long-term and avoided impacts) as well as on the environmental inventory data collection is probably the best option to be able to understand the differences. A careful comparison of the complete inventory is then needed.

4.2 Recycled content vs end of life recycling approaches

As written in the "Introduction" section, two different methods are used to model the recycling. In this study, the recycled content approach has been used. To evaluate the sensitivity to the calculation method as recommended by ISO standards (ISO 2006), the end-of-life recycling approach should then be tested. This can be done by the calculation of the module D introduced in the EN 15804 standard. In this module, the fact that steel is recycled at the end of life is considered to avoid the use of virgin materials. For example, in the following configuration proposed by Leroy et al. (2012): it is estimated that the steel produced with EAF is equal 85 % on average while the recycling rate of steel from such building product reaches 95 % at the end of the product life cycle. Therefore, if 1 kg of steel is considered, its recycling at the end of life will generate 0.95 kg of recycled steel while only 0.85 kg has been used at the production stage. Hence, such product system is a net producer of 0.1 kg of recycled steel that can be used in other industries and avoid the production of the same amount of BF steel. The module D is calculated in order to highlight this potential benefit of using this product as it avoid the extraction of raw materials and the production of 0.1 kg of steel by the BF route which is known to have a higher environmental impact than the recycling route.

However, for the specific case of our study, more recycled steel is used for the production of the reinforcing bars than the amount that can be potentially recycled at its end of life. Actually, 98 % (between 95 and 100 %) of recycled steel is used for the production of reinforcing bars (see Table 1) while around 95 % of steel is considered to be recycled at the end of life of a building (Leroy et al. 2012). In this specific case, the production of reinforcing

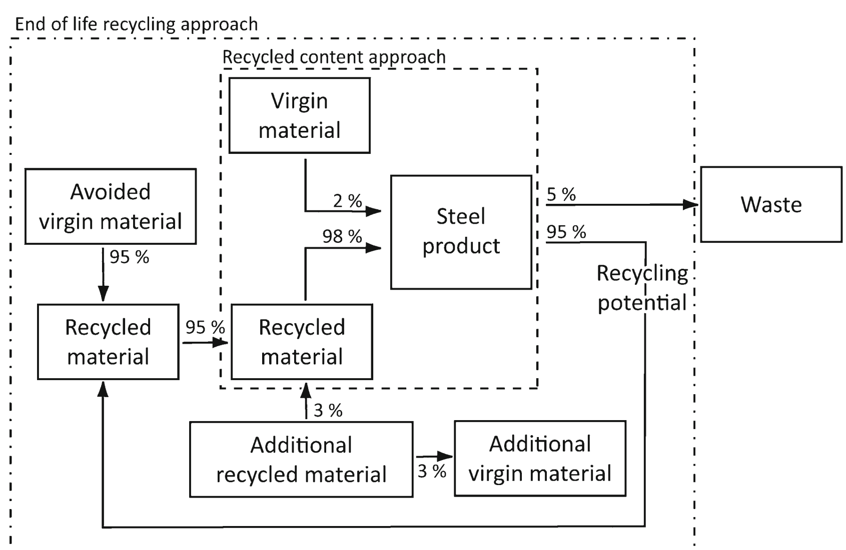

Fig. 7 Boundaries of the system studied for steel production depending on the end of life approach considered: end of life recycling (system expansion) approach or recycled content (cut-off) approach

bar is therefore a net consumer of recycled materials (3 %) and only 95 % of virgin materials is avoided, as shown in Fig. 7.

In this case, module D shall report the fact that this extra consumption of recycled steel will induce the extra production of steel with BF for the products from which these recycled materials have been used.

In this very simplistic calculation, the scrap introduced in the BF route has not been considered, but it will even increase the module D value. In this case, and considering the uncertainties that exist on the exact recycled content of the product (98 %) and its recycling potential at the end of life (95 %), it is clear that the two approaches have very similar results and therefore it can be stated that the choice of assessment method for recycling product does not influence the result. It would, of course not be the case if the recycled content of reinforcing steel was not so high.

5 Conclusions

Our study shows that reinforcing steel products sold in France have a different environmental impact than calculation which could have been done with generic European database. It is due either to the fact that French reinforcing steel is mainly made with recycled steel and to the fact that the market growth for construction products in France is limited allowing a very high recycled content.

This result is not very sensitive neither to the allocation method used for recycling (cut-off approach or system expansion) nor to transport distance and electricity country mix used. This result can therefore be used with confidence in every construction site work located on the French territory and is due to the very high recycled content of reinforcing steel. This conclusion is not necessarily valid for other steel products.

Furthermore, the present study advocates for an adaptation of global database to local context defined by a specific industrial sector and a geographic region even for products such as steel that seem to be sold, as a first approximation, on a global market. National legislations on country specific EPDs might engage this adaptation.

Finally, further works needs to be done for ecotoxicity values as large differences, which can not only be explained with long-term impacts influences, have been noticed between database.

Acknowledgements This study was carried out within the frame of DIOGEN group created by the French Association of Civil Engineers (AFGC) which is acknowledged. The authors would also like to thank the AFCAB for the help provided in the understanding of production processes and for the access of steel production data. FG and AF thank the Chair ParisTech-VINCI "Ecodesign of buildings and infrastructure" for the scientific and financial support to develop this French civil engineering database, and therefore this study. Inter-Carnot VITRES is acknowledged for financial support of RB.

References

AFCAB (2011a) Certification Acier pour Béton Armé. RCC03, AFNOR 58 pp

AFCAB (2011b) Annual reinforcing steel production of certified products for the French market: Details by steel plants. Confidential document. AFCAB, Paris, 4pp

Althaus H-J, Classen M (2005) Life cycle inventories of metals and methodological aspects of inventoring material resources in Ecoinvent. Int J Life Cycle Assess 10:43–49

Apfel J (2002) Electric Arc Furnace Slag, a product not a waste: saving or earning money by using slag as building material. Tech. report, BSE Badische Stahl Engineering, 6 pp

Atherton J (2007) Declaration by the metals industry on recycling principles. Int J Life Cycle Assess 12:59–60

Beddoes J, Bibbly MJ (1999) Principles of metal manufacturing process, Arnold, 326 pp. ISBN 0-470-35241-8.

Blaser S, Althaus HJ, Jungbluth N et al (2009) Metal processing, Part XV. In: Classen (ed) Life cycle inventpry of metals. Final report Ecoinvent data v2.1, no. 10. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Switzerland

Cimbéton (2010) En,vironmental quality of buildings, B56. Collection technique Cimbéton, 140 pp

Classen M, Althaus H-J, Blaser S, Tuchschmid M, Jungbluth N, Doka G, Faist, Emmenegger M, Scharnhorst W (2011) Life Cycle Inventories of metals. Final report ecoinvent data v2.2, n°10. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland, Online-version under: www.ecoinvent.ch

de Schrynmakers P (2009) Life cycle thinking in the aluminium industry. Int J Life Cycle Assess 14(supl 1):S2–S5

Dubreuil A, Young SB, Atherton J, Gloria TP (2010) Metals recycling maps and allocation procedures in life cycle assessment. Int J Life Cycle Assess 15:621–634

E-PRTR (2012) The European Pollutant Release and Transfer Register http://prtr.ec.europa.eu. Accessed 20 February 2013

Ecoinvent (2011) Ecoinvent Report part XV. 'Metal processing', Data v2.2, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland

ELCD (2012) European Life Cycle Database. http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm. Accessed 20 June 2012

EN 15804 (2012) Sustainability for construction works. Environmental product declarations. Core rules for the product category of construction products. European Committee for Standardization

European Commission (2000) Best available techniques reference document on the production of iron and steel. Institute for prospective technological studies. European IPPC Bureau, Seville

European Commission (2010) Joint Research Centre—Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance, 1st edn. Publications Office of the European Union, Luxembourg, EUR 24708 EN

Euroslag, Eurofer (2012) Position paper on the status of ferrous slag complying with the waste framework directive 2008/98/CE (articles 5/6) and the REACH regulation. European Slag Association and European Steel Association, April 2012

Frischknecht R (2006) Notions on the design and use of an ideal regional or global LCA database. Int J Life Cycle Assess 11:40–48

Frischknecht R (2010) LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency. Int J Life Cycle Assess 15:666–671

Goedkoop M, Oele M (2004) Simapro database manual, Methods library. Pre consultants BV

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, van Oers L, Wegener Sleeswijk A, Suh S, Udo de Haes HA, de Bruijn H, vanDuin R, Huijbregts MAJ (2002) Life cycle assessment: an operational guide to the ISO Standards. Kluwer, Dordrecht

Huijbregts MAJ (1998) LCA methodology application of uncertainty and variability in LCA. Int J Life Cycle Assess 3(5):273–280

Intron (2003) MRPI van constructiestaal, INTRON-rapport R20020491, 29 October 2003

ISO 14044 (2006) Environmental management—life cycle assessmen—principles and framework. 1st edn. 2006-07-01 Geneva

ISO 6935-2 (2007) Steel for the reinforcement of concrete—part 2: ribbed bars

Kim S, Hwang T, Lee KM (1997) Allocation for cascade recycling system. Int J Life Cycle Assess 2:217–222

Leroy C, Thomas J-S, Avery N, Bollen J, Tikana L (2012) Tackling the recycling aspects in EN 15804. International Conference on LCA & Construction, July 10–12, Nantes, France

Li G, Nie Z, Zhou H, Di X, Liu Y, Zuo T (2002) An accumulative model for the comparative life cycle assessment case study: iron and steel process. Int J Life Cycle Assess 7:225–229

Maslehuddin M, Sharif AM, Shameem M, Ibrahim M, Barry MS (2003) Comparison of properties of steel slag and crushed limestone aggregate concretes. Constr Build Mater 17:105–112

Monshi A, Asgarani MK (1999) Producing Portland cement from iron and steel slags and limestone. Cement Concrete Res 29:1373–1377

NF EN 10 020 (2000) Definition and classification of grades of steel, September, 2000. European Committee for standardization

NF EN 10080 (2005) Steel for the reinforcement of concrete—Weldable reinforcing steel—General, September, 2005. European Committee for standardization

Pacyna JM, Munthe J, Larjava K, Pacyna EG (2005) Chap 3: Mercury emissions from anthropogenic sources: estimates and measurements for Europe. In: Pirrone N, Mahaffey KR (eds) Dynamics of mercury pollution on regional and global scales. Atmospheric processes and human exposures around the world. Springer, Heidelberg

PE International (2011) EPD-BFS-2010111-E. Structural steel: sections and Plates

Pr new Wire (2012) http://www.prnewswire.com/news-releases/steel-industry-calls-for-shift-in-vehicle-regulations-131779808.html. Accessed 12 May 2012

Shih PH, Wu ZZ, Chiang H (2004) Characteristics of bricks made from waste steel slag. Waste Manage 24:1043–1047

US EPA (2004) U.S. EPA Toxics Release Inventory Reporting Year 2004 Public Data ReleaseToxic release inventory. US EPA, 228 pp

US EPA (2012) Available and emerging technologies for reducing greenhouse gas emissions from iron and steel industry. US EPA, 78 pp

Worldsteel (2011) Worl Steel Association methodology report. Life cycle inventory study for steel products, July 2011, 41 pp

Worrell E, Price L, Neelis M, Galitsky C, Nan Z (2008) World best practice enery intensity values for selected industrial sectors. Tech. Report, Ernst Orlando Lawrence Berkley National laboratory, Feb. 2008, 51 pp

Wu S, Xue Y, Ye Q, Chen Y (2007) Utilization of steel slag as aggregates for stone mastic asphalt (SMA) mixtures. Build Environ 42:2580–2585