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# Mapping Product Knowledge to Life Cycle Inventory Bounds: A Case Study of Steel Manufacturing

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## Abstract

This study develops and demonstrates a bounding methodology to quantify uncertainty in Life Cycle Inventory (LCI) results arising from lack of detailed information on constituent materials. The method starts with the observation that the LCI of a material can change significantly with different attributes such as country of origin and recycled content, information often not specified in available bill-of-materials data. This lack of detailed information can be mapped to numerical bounds for LCI results. We demonstrate this idea via a case study of the contribution of steel manufacturing to the cumulative energy demand (CED) and life cycle global warming potential (GWP) of residential buildings. If steel type, recycled content and country of origin are all unknown, life cycle CO<sub>2</sub>-equivalent emissions of steel can vary from 0.7-5.9 kg CO<sub>2</sub>eq/kg. When used in compiling an LCI of a building, this wide range leads to overlapping results in a comparison of life cycle GWP impact between steel- and concrete-framed buildings. That is, without knowledge of the particulars of steel used, Life Cycle Assessment (LCA) cannot distinguish between the two building types. In contrast, with knowledge that the steel is low or un-alloyed, produced in the U.S., and has greater than 60% recycled content, uncertainty bounds are reduced to 0.8–1.4 kg CO<sub>2</sub>eq/kg steel. With this range, the net impact of concrete-framed buildings is unambiguously smaller than steel-framed residences. While demonstrated here for steel manufacturing, this bounding approach is broadly applicable in LCA.<sup>1</sup>

**Keywords:** Life cycle assessment, Uncertainty, Product knowledge mapping, Steel Manufacturing, Bill of Attributes

## 1. Introduction

Uncertainty analysis has long been recognized as an important aspect of life cycle assessment (LCA) (Heijungs, 1996). However, serious analysis of uncertainty continues to be the exception rather than the rule in LCA practice (Blengini and Di Carlo, 2010; Finnveden et al., 2009; Heijungs and Huijbregts, 2004; Björklund, 2002). This is problematic because as LCA becomes more influential in informing policy decisions, uncertainty analyses become imperative due to

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<sup>1</sup> Abbreviations: LCA: Life cycle assessment; CED: cumulative energy demand; GWP: global warming potential; GHG: greenhouse gases; LCI: life cycle inventory; EAF: electric arc furnace; BOF: blast oxygen furnace.

the large costs associated with these decisions (Lloyd and Ries, 2007). There are many prior frameworks to describe and assess uncertainty in LCA, e.g. (Heijungs, 1996; Björklund, 2002; Huijbregts, 1998; Heijungs and Huijbregts, 2004; Williams et al., 2009, Lloyd and Ries, 2007; Finnveden et al., 2009; Huijbregts et al., 2003). The bulk of work focuses on uncertainty in the Life Cycle Inventory (LCI) stage of an LCA.

Among the different types of uncertainty, parameter uncertainty of LCI is most often studied. Characterizing parameter uncertainty involves quantifying the range in model outputs that arise from uncertainty and variability in input parameter values. The central challenge in treating parameter uncertainty is how to develop robust distributions for input parameters. Developing uncertainty distributions mixes differing degrees of input from empirical data, modeling and expert opinion. Empirical input can take several forms. For a specific facility, uncertainty can arise from measurement error and/or temporal variability in inputs and outputs. For a generic process, uncertainty/variability can be characterized using multiple data points for the “same” quantity, e.g. a process input-output table. Often sample size is small, e.g. there may be only two or three publicly available sources of data for a particular process.

In modeling uncertainty, analysts must choose a form of distribution, i.e. rectangular, normal, log-normal or otherwise. When data and/or knowledge of the sampling process are limited, the choice of rectangular (or uniform) distribution, while yielding the largest variability in results, is presumably most robust. Rectangular distributions are equivalent to bounds or intervals (Heijungs, 1996; Chevalier and Le Téo, 1996; Björklund, 2002; Williams et al., 2002; Deng et al., 2011). LCA analysts have fit empirical data to other distributions, e.g. normal in (Williams, 2004) and log-normal in (Ciroth et al 2013). Note that the process of gathering LCI data often does not match the statistical concept of a random sample. Using estimators for a particular distribution thus represents an assumption by the analyst.

We explore how to develop numerical bounds to treat parameter uncertainty for process data in LCA. Our focus on rectangular, as opposed to other distributions, is motivated by their robustness given the typical paucity of process data. In particular, we investigate how knowledge of product or material attributes can be used to derive quantitative bounds. Bills-of-attributes vary in specificity, for example the content of a type of material (e.g. kg of steel) might be listed, but no details on the quality or origin of the material. The cradle-to-gate inventory of a material can vary substantially on location of production (Puettmann et al., 2010), purity (Williams et al., 2002; Williams et al. 2011), recycled content (Hammond and Jones, 2008; Eckelmann, 2010) and other attributes. Our method maps what is known about the attributes of a constituent material or component to bounds on its life cycle inventory. The more that is known about a product, the narrower the bound on LCI. In prior literature, e.g. (Chevalier and Le Téo, 1996), methods are developed to obtain bounds in LCI results given numerical bounds for individual processes. Olivetti et al (2013) introduce the idea that under specification of attributes of constituent materials connects to the degree of uncertainty. Our contribution to the literature is an approach to derive numerical bounds for LCI results given different levels of product knowledge.

This method is demonstrated through a case study showing how knowledge of the attributes of steel in a residential building affects its life cycle energy and carbon flows. The motivation for studying energy related to steel in buildings for the case study is threefold. First, the large volume of steel produced means its global energy footprint is significant. Around 5% of global energy demand is due to steel production (Williams et al., 2012a). Second, because buildings consume 40% of global energy and resources, it is important to understand the variability in commonly used construction materials, such as steel, in order to better inform policy on the

environmental impacts of choices made in building design and construction (UNEP, 2013). While the materials extraction and production life cycle energy make up a smaller share (4-20%) of the total life cycle energy of a building as compared to operation energy (80-95%) in prior building LCA studies, the choice of materials impacts the entire life cycle, including total operation energy (Cole and Kernan, 1996; Adalberth, 1997; Keoleian et al., 2001; Junnila et al., 2006; Ramesh et al., 2010; Sharma et al., 2011). For example, (Xing et al. 2008) suggest that while a steel-framed office building demands less energy for materials extraction and production than a comparable concrete-framed office building, the steel-framed office building had higher operation energy, resulting in higher total life cycle energy. Third, the high variability in both the energy and carbon intensities used for steel in previous LCA work, e.g. (Hammond and Jones, 2008; Keoleian et al., 2008; Buchanan and Honey, 1994; Zabalza Bribián et al., 2011; Scheuer et al., 2003) suggests a need to understand uncertainty.

## 2. Materials and Methods

### 2.1 Overview

Figure 1 summarizes the method to obtain bounds for a LCI result based on lack of specific data on material characteristics. The first step is to use process modeling to obtain relationships connecting characteristics and LCI results. LCI results depend on material characteristics. For example, higher recycled content often results in lower embedded energy (Hammond and Jones, 2008). The purity of a product can affect the life cycle inventory. For example, the energy needed to produce electronics grade silicon is 160 times that of industrial grade silicon (Williams et al., 2002). Differences between manufacturing facilities lead to intra and international variability in material flows to make a similar product. For example, (Puettmann et al., 2010) analyze and identify distinctions in life cycle inventory of hardwood and softwood manufacturing processes across four different regions of the United States. The authors found that the Northeast/Northcentral regions of the United States use more wood biomass fuel than the western regions whose primary fuel is natural gas (Puettmann et al., 2010). (Macmillan and Keoleian, 2010) examine temporal and geographic variation in life cycle greenhouse gas (GHG) emissions of primary aluminum ingots, finding that the GHG emission intensity relates to the type of fuel used for electricity production, which varies substantially by region (Macmillan and Keoleian, 2010).

In the second step, the ranges of materials characteristics are determined from the bill of materials, or more generally, bill of attributes. The bill of attributes for a product specifies physical quantities of constituent materials and components. Bills of attributes vary widely in their specification of material characteristics, often times simply listing the material type (e.g. steel, copper) without specifying the composition (e.g. recycled content) or history (e.g. country of origin). We use rectangular distributions to describe material characteristics, e.g. if no information is presented on recycled content, it is safest to assume that it varies from 0 to 100%. The third step combines the first two steps to translate the ranges in material characteristics to ranges in LCI results.

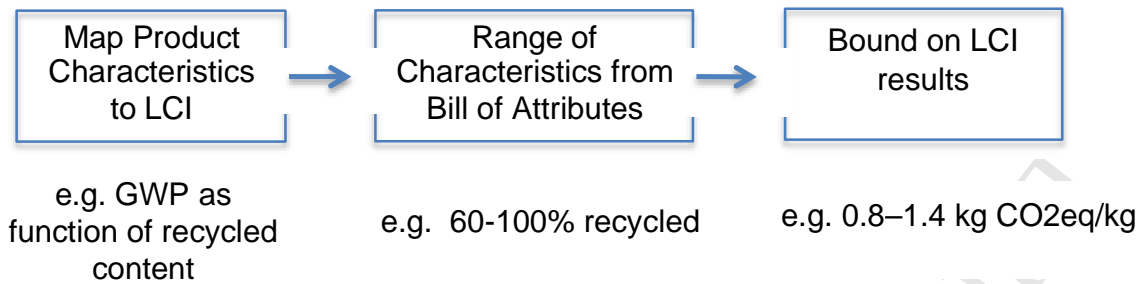


Fig. 1. Overview of method to develop numerical bounds for Life Cycle Inventory (LCI) result (GWP = Global Warming Potential).

## 2.2 Case study of mapping product characteristics to LCI results: steel

We implement the method from the previous section via a case study of steel used in a U.S. building. We treat three sources of variability in steel production: region of production (U.S., Europe or China), recycled content (0-100%) and steel type (low alloy or chromium). First, spatial variability is examined due to regional differences in production technologies, including in electricity grid mixes. For example, in 2012, the U.S. used coal as a fuel for 37% of the electricity generation, in contrast with 65% of coal-based electricity in China in 2011 (U.S. EIAa and c, 2013). These differences can cause significant variability in the impacts of GWP, particularly from an electric arc furnace (EAF) process that relies almost entirely on electricity.

The second potential source of variability, recycled content, changes as a function of the technology used for steel production. Two processes currently dominate steel manufacturing, the blast oxygen furnace (BOF) process and the EAF (Fenton, 2005). The BOF process reduces iron from ore, then makes steel by blasting oxygen through molten pig iron. While iron ore is the main source of iron in BOF steel, scrap can constitute up to 30% of the “charge” (AISI, 2012). In contrast, the EAF process uses an electric arc as the heat source, and scrap constitutes up to 100% of the charge (AISI, 2012). Not surprisingly, the energy requirements of the two technologies are very different, with BOF process requiring 19 GJ/tonne on average versus 8MJ/kg for EAF steel (Williams et al., 2012a).

Finally, types of finished steel are also examined for potential influences to CED and GWP. Alternative types of steel such as low- or high-alloyed steel require the use of different processes. Low-alloyed steels contain small amounts of alloyed elements, less than 5% in total, and are characterized by high strength (Fenton, 2005; Classen et al., 2009). In contrast, high-alloyed steels or stainless steels, contain larger amounts of alloyed elements such as chromium, at a minimum of 10%, and are characterized by high strength and resistance to abrasion (Fenton, 2005; Classen et al., 2009). Therefore process data for these different types of finished steels are examined.

## 2.2 LCI methodology

A process-sum methodology is utilized to complete a cradle-to-gate LCA of steel manufacturing. This common approach is a bottom-up process model, based on facility level



material flow data and resulting environmental impacts between processes. We analyze cradle-to-gate energy and greenhouse gas emissions including the material extraction and manufacturing. As a result, the study scope only includes those elementary material, energy, and emission flows that contribute to the CED (MJ/kg steel produced) and the GWP (kg CO<sub>2</sub>eq/kg steel produced) in the manufacture of steel (IPCC, 2007). The system boundary diagram appears in figure S1 of the supporting documentation.

The process-sum approach is used to examine the impacts to CED and GWP as a result of varying specific aspects of the steel manufacturing process. First, the type of finished steel (either low-alloyed or chromium steel) is varied requiring two functional units for the process-sum approach: 1 kg of low alloy steel and 1 kg of chromium steel (high alloy). Second, spatial variability is considered by taking into account the different regional electrical grid mixes from the U.S. Europe and China. Finally, the technology used to produce the steel is varied in order to model differing recycled steel content (secondary steel content). It is assumed in this study that the BOF process reflects primary steel, or steel that has no recycled content (no secondary content). In contrast, it is assumed that the EAF process reflects secondary steel or steel that has 100% recycled content (100% secondary content). Therefore, the reference flows are 1 kg of finished steel, both low-alloyed and chromium (high-alloyed) steel, produced in different regions, while varying the amounts of primary and secondary steel used.

The data points for CED and GWP for the process-sum approach comes from the ecoinvent database (ecoinvent Centre, 2007). The finished steel types from the database used in this study are 1 kg of low-and un-alloyed steel, and 1 kg of chromium (18%) steel (ecoinvent Centre, 2007). Modifications were made to the database to reflect the electricity grid mixes for Europe, the U.S. and China. This was not an exhaustive modification, rather only the top 5 processes with the highest impacts from electricity consumption were modified. Moreover, for each region, the amount of primary versus secondary steel used was varied in 25% increments. For example, if 1 kg of low- and un-alloyed steel contained 0% primary steel, then it must contain 100% secondary steel. Similarly, if 1 kg of low- and un-alloyed steel contains 25% primary steel, secondary steel content is 75%, and so on. As a result, there are 30 different data points modeled each for CED and GWP, reflecting the variations in types of steel, regions of production, and % primary and secondary content. Tables S1 and S2 of the supporting documentation contain sample input and output flows (life cycle inventory) for primary low- and un-alloyed and chromium steel from U.S., China and Europe.

## **2.3 Contribution of cradle-to-gate steel LCI bounds to overall uncertainty in LCA of multi-family residence**

Steel is not in itself of interest to household consumers; rather it is an important constituent material of many consumer goods. In order to get a sense of how the uncertainty bounds for steel might affect the life cycle of a final consumer product, we analyze the effect of the bounds on the GWP of a multi-family residence. We base this analysis on the previous study of (Gong et al., 2012) who analyze the GWP of concrete-framed construction (CFC) and steel-framed construction (SFC). The analysis involves removing the contributions to life cycle GWP from steel in the original study and replacing these contributions using the three bounded ranges established in the previous section. Table S6 in the supporting documentation details the contributions from the original study.

### 3. Theory

LCI is the compilation of supply chain resource use and emissions associated with a product or service. Constructing an LCI proceeds by combining bill-of-attributes with process input-output data. Bill-of-attributes, a generalization of bill-of-materials, specifies quantities and other attributes of materials and components contained in a product. Given a bill-of-attributes, materials flows in associated processes are modeled by following the supply chain upstream, finding material input-output data for individual processes. The degree to which bill-of-attributes data specify information beyond mass, e.g. origin and recycled content, is variable and often incomplete. For process data, it is common for analysts to gather specific data on a few critical processes and rely on commercial database such as (ecoinvent Centre, 2007) for other processes.

Parameter uncertainty is the type most commonly addressed in LCA. Parameter uncertainty relates to how choices in numerical values for process input-output tables and bill-of-attributes influence results. Sources of parameter uncertainty include data quality, representativeness, and timeliness. Data quality issues relate to how well the numerical values for process input-output tables and weight/composition from bill of attributes accurately reflect the targeted process/product LCI. Assessing data quality is difficult given a general lack of information on how process and bill-of-attributes data were collected. Representativeness is the question of how closely the choices of data reflect the actual processes for the product in question. It is typical for much of the supply chain to be modeled with “standard” production processes data, as opposed to a specific set of facilities in the supply chain. Representativeness is thus a potential issue for most LCA studies. Finally, timeliness is related to the potential changes in process and product attributes over time not accurately represented in the LCI.

Parameter uncertainty is generally treated by representing a parameter as a distribution rather than a single number. Given distributions for model inputs, distributions of model outputs are typically calculated using Monte Carlo Analysis, a numerical simulation approach (Sonnemann et al., 2003). For specific distributions, such as rectangular, there are analytical approaches to estimate outputs (Chevalier and Le T  no, 1996).

Expert opinion is also used to develop uncertainty distributions. The pedigree matrix is a well-known and popular theoretical approach to estimate variance in process data. Developed by Weidema and used in LCA software tool SimaPro (PRe<sup>+</sup> Consultants, 2012) and database (ecoinvent Centre, 2007), the pedigree matrix is a formula that converts analysts’ judgments of data quality to quantitative uncertainty distributions (Weidema, 1996; Weidema, 1998; Frishknecht et al., 2007; Goedkoop et al., 2010; Blengini and Di Carlo, 2010). While an expert-opinion driven approach could, in principle, give results comparable to empirical measures, this remains an open question. To our knowledge, Citroth et al (2013) is first to begin exploring this issue. We argue that using theoretical approaches such as the pedigree matrix should be predicated on work that establishes correlation with empirical measures. Empirical methods such as the one developed here can hopefully inform such future work.

### 4. Results

#### 4.1 CED and GWP of steel as a function of country of origin, recycled content and steel type

Figures 2 and 3 contain the results for GWP and CED versus percent secondary steel content by region and type of steel, respectively. Tables S3 and S4 in the supporting documentation contain the data point values. Moreover, in order to examine the results in the context of the broader literature, values for GWP, CED and percent secondary steel content used in previous studies and published reports are included in the respective figures, and, are detailed in S5 in the supporting documentation.

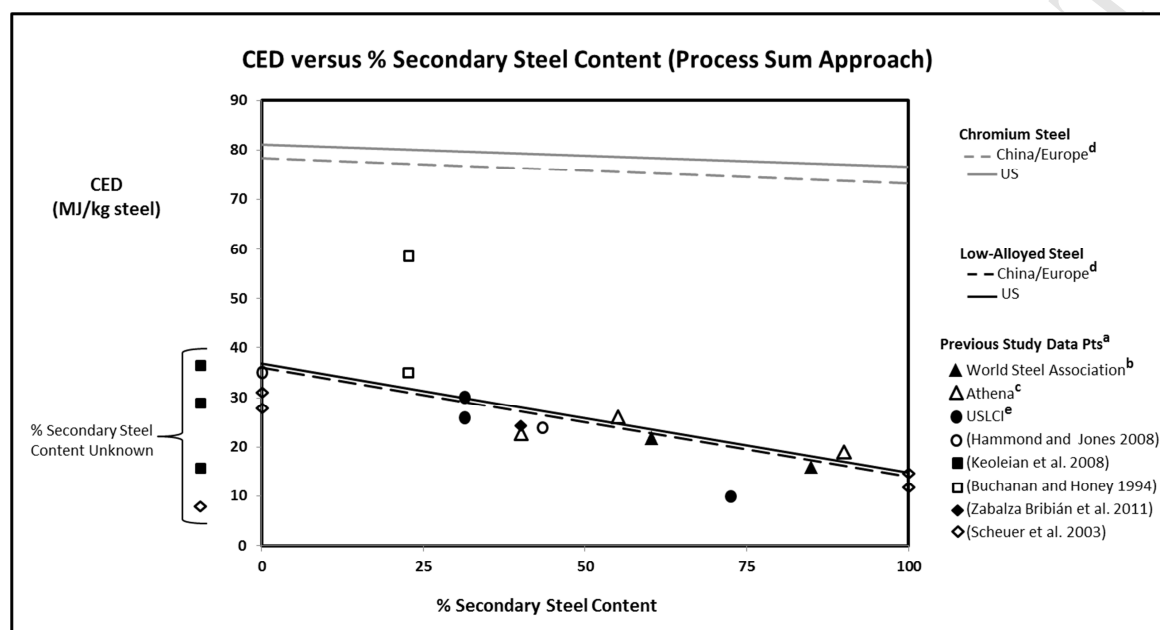


Fig. 2. Process-sum model results for cradle-to-gate cumulative energy demand for steel as a function of secondary steel content, region and type of steel (solid and dashed lines), and prior process LCA studies (circles, triangles, squares and diamonds). CED = cumulative energy.

<sup>a</sup> Actual values are included in table S5 in the supporting information.

<sup>b</sup> (Crawford, 2013).

<sup>c</sup> (Markus Engineering Services, 2002).

<sup>d</sup> CED trendlines for China and Europe overlap.

<sup>e</sup> (NREL, 2012)



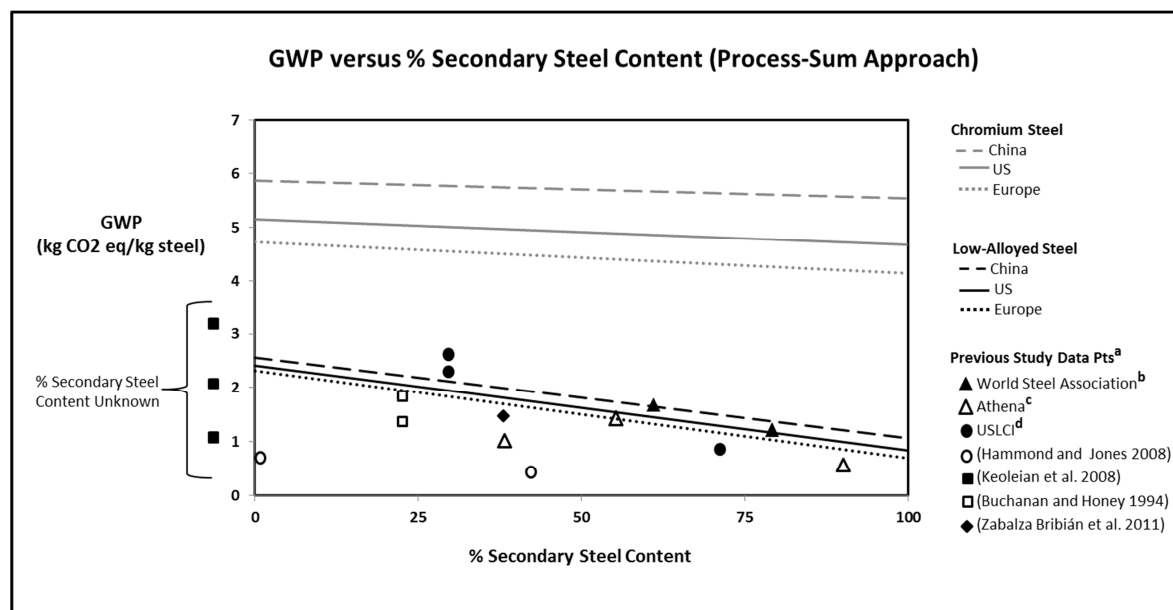


Fig. 3. Process-sum model results for cradle to gate global warming potential for steel as function of secondary steel content, region and type of steel (solid and dashed lines), and prior process LCA studies (circles, triangles, squares and diamonds). GWP = global warming potential; kgCO<sub>2</sub>eq/kg steel = kilogram carbon dioxide equivalent per kilogram of steel.

<sup>a</sup> Actual values are included in table S5 in the supporting information.

<sup>b</sup> (Crawford, 2013).

<sup>c</sup> (Markus Engineering Services, 2002).

<sup>d</sup> (NREL, 2012)

Figures 1 and 2 illustrate the expected impacts from different regional electricity grid mixes, the benefits of recycling, and, the impacts of differing amounts of alloys in steel. One notable finding is the large degree of variability in results in previous studies and reports. This indicates a need to develop distribution versus point estimate approach.

## 4.2 Combining LCI relationships and product knowledge to obtain LCI bounds for steel

In this section, the relationships between LCI and product characteristics from section 4 are combined with different levels of product knowledge to realize bounds in the cradle-to-gate LCI for steel. The first step is to develop three cases of specification to product characteristics that might be seen in a bill of attributes. These cases are shown in Table 1. They are intended as illustrative examples, in general one would extract the level of product knowledge from a bill of attributes. If the bill of attributes only lists “steel”, the steel might be any type, manufactured anywhere, and have any recycled content. We call this “General Product Knowledge”. If the bill of attributes were to list “low-alloyed steel”, then one could rule out chromium and other high alloy steels. We call this “Finished Product Knowledge”. If the bill of attributes listed country of origin (e.g. the U.S.) and recycled content range, for example, we call this “Finished Product and Origin” knowledge.

Table 1: Product knowledge cases used in this study.

Product Knowledge	Details
General Product Knowledge	An LCA practitioner may not be an expert in steel manufacturing, and therefore, not familiar with processes used, material composition, finished products, region of production or applications. This general knowledge maps to a lower and upper bounding range of .70 – 5.9 kgCO <sub>2</sub> eq/kg steel. <sup>a</sup>
Finished Product Knowledge	Finished product knowledge of low-alloyed steel maps to a lower and upper bounding range of .70 – 2.6 kgCO <sub>2</sub> eq/kg steel. <sup>a,b</sup>
Finished Product and Origin Knowledge	Product knowledge revealing region of production in the U.S., and percent secondary steel content of between 64% and 99.9%, maps to a lower and upper bounding range of .8 - 1.4 kgCO <sub>2</sub> eq/kg steel. <sup>c</sup>

Note: kg CO<sub>2</sub>eq/kg steel = kilogram carbon dioxide equivalent per kilogram of steel.

<sup>a</sup>. Values found in table S6 of the supporting documentation.

<sup>b</sup> Source: (Classen et al., 2009)

<sup>c</sup> Source: (Nucor Corporation, 2013); upper bound value was determined using the regression line for U.S. (max):  $y = (-.4)x + 2.8$ . Lower bound is from table S4 (for the U.S.) in the supporting documentation.

Product knowledge leads to bounds for LCI via the following approach, described for the example of Finished Product and Origin Knowledge. Knowledge that the steel is low-alloyed and produced in the U.S. implies that the production process is some combination of U.S. average primary and EAF steel. The only variable is recycled content, known to range between 64% and 99.9%. The lower/upper bound for a given inventory items is the lower/higher value for a process (64% EAF + 36% primary) or (99.9% EAF + 0.1% primary). The results of calculation for select energy resources inputs are shown in Table 2. Note that while only process inputs are shown in Table 2, the method is equally applicable to outputs, including emissions.

Table 2: Bounded LCI for Energy Inputs for Finished Product and Origin Knowledge (Steel produced in U.S., secondary steel content 64%-99.9%)

1 kg of Low-Alloyed Steel <sup>a,b</sup>		ecoinvent <sup>a</sup>	
		US	
Inputs <sup>b</sup>	(64%-99% secondary content)	unit	
Coal, hard, unspecified, in ground	2.6E-01 - 5.8E-01	kg	
Coal, brown, in ground	3.9E-02 - 4.8E-02	kg	
Gas, natural, in ground	1.2E-01 - 1.3E-01	m <sup>3</sup>	
Gas, mine, off-gas, process, coal mining/m <sup>3</sup>	2.0E-03 - 5.1E-03	m <sup>3</sup>	
Crude Oil	4.4E-02 - 5.5E-02	kg	
Uranium, in ground	4.2E-06 - 4.3E-06	kg	
Energy, solar, converted	4.7E-04 - 5.0E-04	MJ	
Energy, potential (in hydropower reservoir), converted	2.6E-01 - 7.4E-01	MJ	
Energy, kinetic (in wind), converted	1.7E-02 - 2.0E-02	MJ	
Energy, gross calorific value, in biomass, primary forest	1.2E-05 - 1.4E-05	MJ	
Energy, gross calorific value, in biomass	1.3E-01 - 1.7E-01	MJ	
<b>Total CED (MJ/kg)</b>		<b>1.5E+01 - 2.2E+01</b>	
Outputs <sup>b</sup>			
Carbon Dioxide	7.89E-01 - 1.30E+00	kg	
Methane	1.82E-03 - 3.68E-03	kg	
<b>Total CO<sub>2</sub>eq (kg/kg)</b>		<b>8.3E-01 - 1.4E+00</b>	
Conversions	value	unit	
Coal, hard, unspecified, in ground	19.1	MJ/kg	
Coal, brown, in ground	9.9	MJ/kg	
Gas, natural, in ground	38.3	MJ/m <sup>3</sup>	
Gas, mine, off-gas, process, coal mining/m <sup>3</sup>	39.8	MJ/m <sup>3</sup>	
Crude Oil, in ground	45.8	MJ/kg	
Uranium, in ground	5.6x10 <sup>5</sup>	MJ/kg	
Methane GWP <sup>b</sup>	25		

Note: LCI = life cycle inventory; kg = kilogram; m<sup>3</sup> = cubic meter; MJ = megajoule; MJ/kg = megajoules per kilogram = MJ/m<sup>3</sup>: megajoules per cubic meter.

<sup>a</sup> Source: (ecoinvent Centre, 2007); Available data are for low-and un-alloyed steel.

<sup>b</sup> Source: (IPCC, 2007).

The results for CED from bounded LCI for all three product knowledge cases are shown in Figure 4, overlaid with graphical representation of how the bounding process works. Explaining the Finished Product and Origin Knowledge example in this graphical format, knowledge that the steel is low-alloy produced in the U.S. restricts process to follow the lower solid line on Figure 4. The 64% and 99.1% bounds on recycled content map to the two FO points on Figure 4, thus GWP is bounded between 0.8 and 1.4 kg CO<sub>2</sub>eq per kg of steel.

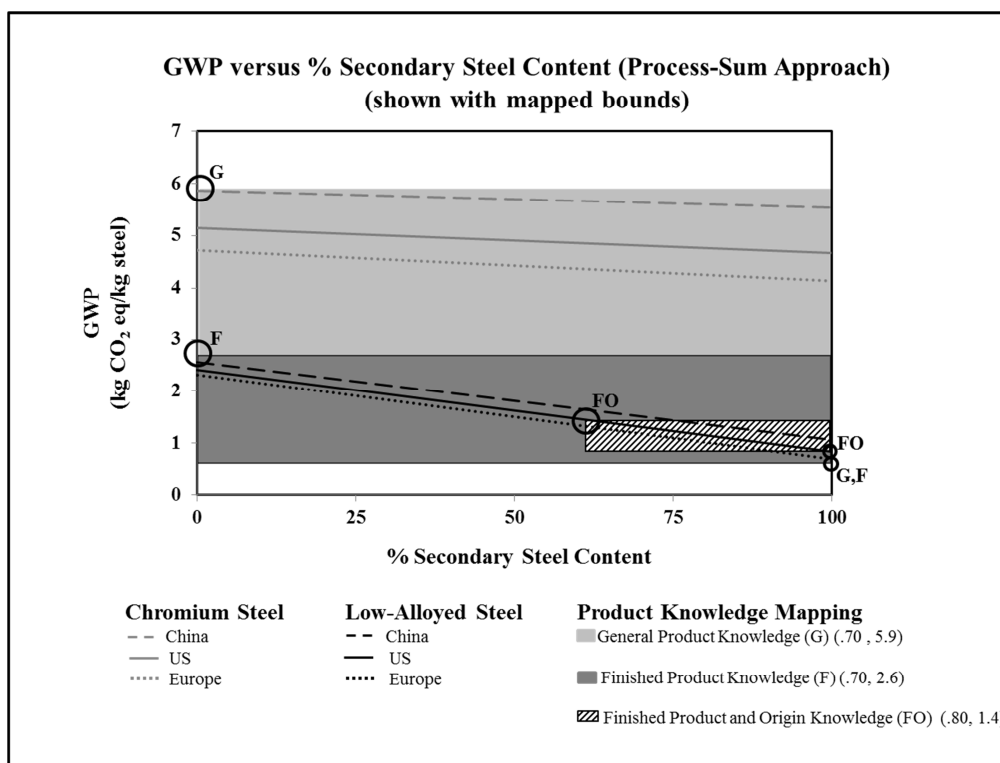


Fig. 4. Bounds mapped from product knowledge. Circles denote reference points used in bounding. GWP = global warming potential; kgCO<sub>2</sub>eq/kg steel = kilogram carbon dioxide equivalent per kilogram of steel. The circles in the graph identify the bounds mapped from different types of product knowledge. General Product Knowledge = steel type, % secondary steel content and region of production unknown; Finished Product Knowledge = steel type known, % secondary steel content and region of production unknown; Finished Product and Origin Knowledge = steel type, % secondary steel content and region of production known.

Recall the degree of variability in values from previous studies and reports illustrated in Figures 1 and 2. Using Finished Product Knowledge mapping would capture most of the variability from prior studies for GWP. Assuming knowledge that the steel is low-alloyed, choosing Finished Product Knowledge bounds would account for potential variability from different data sources/model assumptions.

#### 4.3 Effects of Steel product knowledge bounds on the LCI of multifamily residences

As discussed in section 2.3, we explore how ranges in the LCI of a constituent material (steel) affect the LCI of a finished product (multifamily residence). Figure 5 shows uncertainty bounds for different levels of steel product knowledge yield ranges in the LCI of concrete frame construction (CFC) and steel frame construction (SFC) multifamily residences. With General Product knowledge, a definitive statement on the relative GWP intensity of the two construction types cannot be made. With Finished Product Knowledge, an unambiguous distinction can be made: SFC buildings emit less GWP than CFC. If the purpose of the LCI study is to establish this order, more detailed product knowledge on the secondary steel content of the building would not be needed.

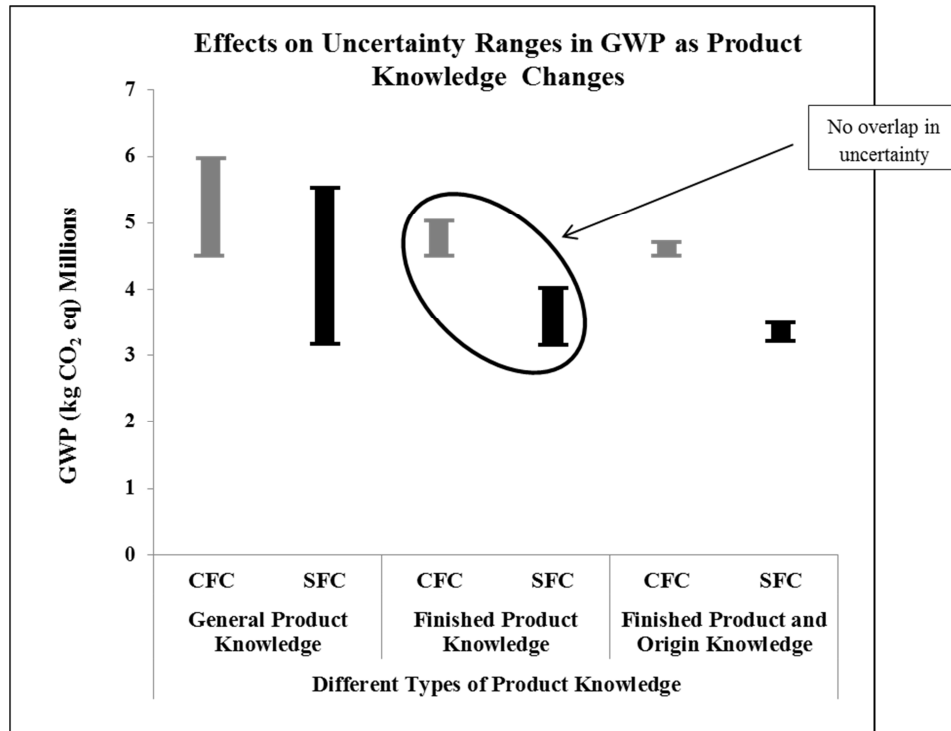


Fig. 5. Effect of knowledge-based bounds for steel on total life cycle GWP of multifamily residential building. GWP = global warming potential; kgCO<sub>2</sub>eq = kilogram carbon dioxide equivalent; CFC = concrete-framed construction; SFC = steel-framed construction; General Product Knowledge = steel type, % secondary steel content and region of production unknown; Finished Product Knowledge = steel type known, % secondary steel content and region of production unknown; Finished Product and Origin Knowledge = steel type, % secondary steel content and region of production known.

Tables 3 and 4 show in numerical form the results contributing to Figure 5. Table 3 details the contribution of steel to life cycle GWP of a multifamily residence. Table 4 shows the ranges for total GWP with ranges arises from the product knowledge of steel.

Table 3: Steel contribution to life cycle GWP of multifamily residence

Construction Type	Quantity of steel (tonne)	GWP General Product Knowledge (kg CO <sub>2</sub> eq)		GWP Finished Product Knowledge (kg CO <sub>2</sub> eq)		GWP Finished Product and Origin Knowledge (kg CO <sub>2</sub> eq)	
		lower bound <sup>a</sup>	Upper bound <sup>a</sup>	lower bound <sup>a</sup>	upper bound <sup>a</sup>	lower bound <sup>a</sup>	upper bound <sup>a</sup>
CFC	282	2x10 <sup>5</sup>	1.7x10 <sup>6</sup>	2x10 <sup>5</sup>	7.3x10 <sup>5</sup>	2.3x10 <sup>5</sup>	3.9x10 <sup>5</sup>
SFC	459	3.2x10 <sup>5</sup>	2.7x10 <sup>6</sup>	3.2x10 <sup>5</sup>	1.2x10 <sup>6</sup>	3.7x10 <sup>5</sup>	6.4x10 <sup>5</sup>

Note: GWP = global warming potential; kgCO<sub>2</sub>eq = kilogram carbon dioxide equivalent. General Product Knowledge = steel type, % secondary steel content and region of production unknown; Finished Product Knowledge

= steel type known, % secondary steel content and region of production unknown; Finished Product and Origin Knowledge = steel type, % secondary steel content and region of production known.

<sup>a</sup> Previously established bounds from figure 4 in terms of kgCO<sub>2</sub>eq/kg of steel, or, kilogram carbon dioxide per kilogram of steel.

Table 4: Total Life Cycle GWP of multifamily residence from three levels of steel product knowledge.

Construction Type	GWP General Product Knowledge (kg CO <sub>2</sub> eq)		GWP Finished Product Knowledge (kg CO <sub>2</sub> eq)		GWP Finished Product and Origin Knowledge (kg CO <sub>2</sub> eq)	
	lower bound <sup>b</sup>	Upper bound <sup>b</sup>	lower bound <sup>b</sup>	upper bound <sup>b</sup>	lower bound <sup>b</sup>	upper bound <sup>b</sup>
	.7	5.9	.7	2.6	.8	1.4
CFC	4.5x10 <sup>6</sup>	6x10 <sup>6</sup>	4.5x10 <sup>6</sup>	5x10 <sup>6</sup>	4.5x10 <sup>6</sup>	4.7x10 <sup>6</sup>
SFC	3.1x10 <sup>6</sup>	5.5x10 <sup>6</sup>	3.1x10 <sup>6</sup>	4x10 <sup>6</sup>	3.2x10 <sup>6</sup>	3.4x10 <sup>6</sup>

*Note:* GWP = global warming potential; kgCO<sub>2</sub>eq = kilogram carbon dioxide equivalent; General Product Knowledge = steel type, % secondary steel content and region of production unknown; Finished Product Knowledge = steel type known, % secondary steel content and region of production unknown; Finished Product and Origin Knowledge = steel type, % secondary steel content and region of production known.

<sup>a</sup> Previously established bounds from figure 3 in terms of kgCO<sub>2</sub>eq/kg of steel, or kilogram carbon dioxide per kilogram of steel.

## 5. Discussion

There is always uncertainty in the uncertainty. In this section we describe some of the uncertainties in the previous analysis. This data source used for steel manufacturing, ecoinvent (ecoinvent Centre, 2007), relies heavily on data from Europe to establish electricity grid mixes, for example Dones et al. (2007). Therefore, additional sources were examined in order to put the results in context with the broader literature and reports. While variable, these data points were found to generally fall within the bounds identified using Finished Product Knowledge mapping, further highlighting the appropriateness of using a bounding approach rather than a single value approach.

Another area of uncertainty is introduced as part of the regional electricity grid mixes. The impacts to GWP and CED from different electricity grid mixes was completed by modifying the default European grid mix in SimaPro (Pre Consultants, 2012) to reflect the region of interest. This was not an exhaustive modification. Only the top 3-5 highest CED and GWP contributing processes were modified to reflect the region of interest. This approach was assumed to reveal contrast between regions by focusing on the highest contributors without being excessively time consuming and adding relatively minimal value to the study. As a result, the overall impacts to GWP in particular from electricity grid mix, will be higher in both the US and China. Furthermore, the type of coal used in both the US and China, primarily bituminous and anthracite, respectively, contain higher amounts of carbon as compared to the coal used in Europe, primarily sub-bituminous and lignite (WEC, 2010). Higher amounts of carbon content result in higher emissions of greenhouse gases (GHG) (U.S. EIA, 2013). In fact, between 2007



and 2011, China emitted greater than 3 times the amount of CO<sub>2</sub> as the U.S. and Europe due solely to the consumption of coal (U.S. EIAc, 2013). This distinction is not fully represented in the results. Consequently, the overall impacts to GWP in general will be higher in both the US and China. This is because coal is not only used for electricity generation, but also as an energy source for manufacturing processes such as providing a heat source for the BOF. While uncertainties remain, the analysis did demonstrate a practical approach for mitigating uncertainty in LCA.

## 6. Conclusions

The steel case illustrated the feasibility of the product knowledge mapping method. Future development of the approach involves creating characteristic to LCI mappings for a variety of materials and even, components. In buildings for example, mappings for concrete, wood and gypsum board would be natural next steps to better understand variability in materials production. One could also develop bounds for operational and end-of-life phases. For example, there is significant variability in the energy use of U.S. residences (U.S. EIAc, 2013). Note that the steel attribute to LCI mapping developed here can be used in *any* LCA of a steel-containing product. The critical point is that the mapping need only be developed once. Creating an attribute to LCI mapping is data and time intensive. Presumably for many materials and components, limited data will preclude their construction. While this is a constraint, assuming continued progress in process databases, developing mappings for more materials and components will become feasible. It is also important to note that the mappings themselves can be improved with further work. We mentioned uncertainty issues associated with our steel mapping, further work could presumably address these.

A second element to further the product knowledge mapping method is work to gather more detailed bills of attributes. It is typical for bills of attributes to specify materials and components in general terms and it is likely that the resulting range from knowledge-based bounds will, in many cases, be large. In contrast with process material flows, bills of attributes in LCA have received almost no attention in research and data development (Kahhat et al., 2011; Kasulaitis et al 2015). It is worth distinguishing between extrinsic (e.g. country of origin) and intrinsic (quality attributes). While quality can in principle be determined from a sample of the product, in general, extrinsic attributes require knowledge of its history available only to manufacturers. Depending on the material, there are opportunities to improve product knowledge. Considering steel, for example, recent trends and technologies contribute to better product knowledge. Materials documentation required for Leadership in Energy and Environmental Design (LEED) certification leads to better information on product origin. The type of steel used in a structural design is typically specified by the steel code and/or the design (in the US), and handheld XRF analyzers allow simple measurement of steel type.

In summary, increased attention to product knowledge will enable better measurement and management of LCI uncertainty.

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## Supporting Information

Supporting information may be found in the online version of this article:

**Supporting Information S1:** The supporting information contains: details on the system boundary, life cycle inventory data and life cycle impact assessments, and, uncertainty range details for product knowledge mapping.

**Highlights**

- We use life cycle assessment to examine environmental impacts of steel production.
- We map life cycle inventory bounds to product characteristics.
- Increasing product knowledge decreases life cycle inventory bounds.
- We demonstrate a practical method to quantify uncertainty in life cycle assessment.



**Supporting Information for:  
Mapping Product Knowledge to Life Cycle Inventory Bounds:  
A Case Study of Steel Manufacturing**

Kim R. Bawden, Eric D. Williams, Callie W. Babbitt

Number of pages: 8  
Number of figures: 1  
Number of tables: 6

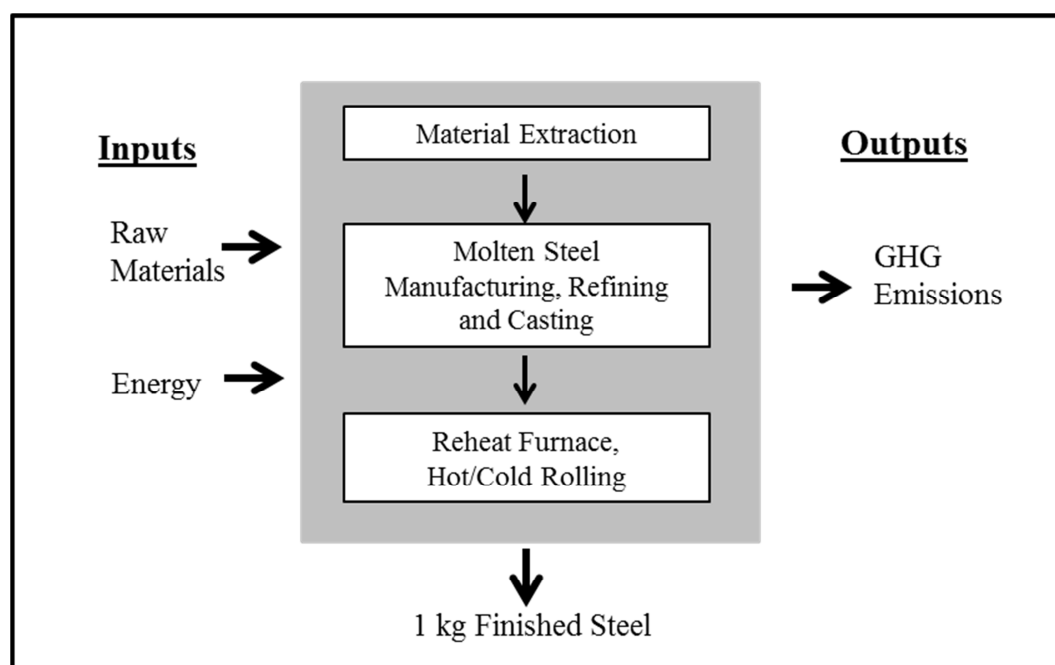


Figure S1: System Boundary Diagram

**Table S1** Input and output flows to produce 1 kg of primary, low-alloyed steel in the U.S., China and Europe.

<b>1 kg of Low- and Un-Alloyed Steel<sup>a,b</sup></b>	<b>ecovinent<sup>a</sup></b>		<b>ecoinvent<sup>a</sup></b>		<b>ecoinvent<sup>a</sup></b>	
	<b>US</b>		<b>China</b>		<b>Europe</b>	
<b>Inputs<sup>b</sup></b>	primary	unit	primary	unit	primary	unit
Coal, hard, unspecified, in ground	1.2E+00	kg	1.2E+00	kg	1.1E+00	kg
Coal, brown, in ground	7.3E-02	kg	6.0E-02	kg	1.3E-01	kg
Gas, natural, in ground	1.4E-01	m <sup>3</sup>	1.2E-01	m <sup>3</sup>	1.4E-01	m <sup>3</sup>
Gas, mine, off-gas, process, coal mining/m <sup>3</sup>	1.1E-02	m <sup>3</sup>	1.2E-02	m <sup>3</sup>	1.0E-02	m <sup>3</sup>
Crude Oil	7.5E-02	kg	7.5E-02	kg	7.5E-02	kg
Uranium, in ground	4.7E-06	kg	2.7E-06	kg	5.3E-06	kg
Energy, solar, converted	5.9E-04	MJ	3.7E-04	MJ	7.8E-04	MJ
Energy, potential (in hydropower reservoir), converted	1.6E+00	MJ	1.7E+00	MJ	1.7E+00	MJ
Energy, kinetic (in wind), converted	3.0E-02	MJ	2.6E-02	MJ	5.4E-02	MJ
Energy, gross calorific value, in biomass, primary forest	1.9E-05	MJ	1.8E-05	MJ	1.9E-05	MJ
Energy, gross calorific value, in biomass	2.4E-01	MJ	2.2E-01	MJ	2.4E-01	MJ
<b>Total CED (MJ/kg)</b>	<b>3.7E+01</b>		<b>3.6E+01</b>		<b>3.6E+01</b>	
<b>Outputs<sup>b</sup></b>						
Carbon Dioxide	2.2E+00	kg	2.3E+00	kg	2.1E+00	kg
Methane	7.1E-03	kg	9.1E-03	kg	6.9E-03	kg
<b>Total CO<sub>2</sub>eq (kg/kg)</b>	<b>2.4E+00</b>		<b>2.5E+00</b>		<b>2.3E+00</b>	
<b>Conversions</b>	<b>value</b>	<b>unit</b>				
Coal, hard, unspecified, in ground	19.1	MJ/kg				
Coal, brown, in ground	9.9	MJ/kg				
Gas, natural, in ground	38.3	MJ/m <sup>3</sup>				
Gas, mine, off-gas, process, coal mining/m <sup>3</sup>	39.8	MJ/m <sup>3</sup>				
Crude Oil, in ground	45.8	MJ/kg				
Uranium, in ground	5.6x10 <sup>5</sup>	MJ/kg				

Methane GWP<sup>b</sup>

25

*Note:* kg = kilogram; m<sup>3</sup> = cubic meter; MJ = megajoule; MJ/kg = megajoules per kilogram = MJ/m<sup>3</sup>: megajoules per cubic meter.

<sup>a</sup> Source: (ecoinvent Centre, 2007); Available data is for low-and un-alloyed steel.

<sup>b</sup> Source: (IPCC, 2007).

**Table S2 .** Input and output flows to produce 1 kg of primary, chromium steel in the U.S., China and Europe.

<b>1 kg of Chromium Steel<sup>a</sup></b>	<b>ecoinvent<sup>a</sup></b>		<b>ecoinvent<sup>a</sup></b>		<b>ecoinvent<sup>a</sup></b>	
	<b>US</b>		<b>China</b>		<b>Europe</b>	
<b>Inputs<sup>b</sup></b>	<b>primary</b>	<b>unit</b>	<b>primary</b>	<b>unit</b>	<b>primary</b>	<b>unit</b>
Coal, hard, unspecified, in ground	1.9E+00	kg	2.2E+00	kg	1.5E+00	kg
Coal, brown, in ground	1.2E-01	kg	5.7E-02	kg	4.0E-01	kg
Gas, natural, in ground	4.7E-01	m <sup>3</sup>	3.8E-01	m <sup>3</sup>	4.6E-01	m <sup>3</sup>
Gas, mine, off-gas, process, coal mining/m3	1.6E-02	m <sup>3</sup>	2.2E-02	m <sup>3</sup>	1.5E-02	m <sup>3</sup>
Crude Oil	1.7E-01	kg	1.7E-01	kg	1.7E-01	kg
Uranium, in ground	1.3E-05	kg	3.6E-06	kg	1.6E-05	kg
Energy, solar, converted	1.4E-03	MJ	3.5E-01	MJ	2.3E-03	MJ
Energy, potential (in hydropower reservoir), converted	9.6E+00	MJ	1.0E+01	MJ	9.9E+00	MJ
Energy, kinetic (in wind), converted	4.9E-02	MJ	2.8E-02	MJ	1.6E-01	MJ
Energy, gross calorific value, in biomass, primary forest	6.0E-05	MJ	5.8E-05	MJ	6.1E-05	MJ
Energy, gross calorific value, in biomass	6.2E-01	MJ	5.6E-01	MJ	6.3E-01	MJ
<b>Total CED (MJ/kg)</b>	<b>8.1E+01</b>		<b>7.9E+01</b>		<b>7.8E+01</b>	
<b>Outputs<sup>b</sup></b>						
Carbon Dioxide	4.8E+00	kg	5.3E+00	kg	4.4E+00	kg
Methane	1.2E-02	kg	2.2E-02	kg	1.1E-02	kg
<b>Total CO2eq (kg/kg)</b>	<b>5.1E+00</b>		<b>5.8E+00</b>		<b>4.7E+00</b>	

<b>Conversions</b>	<b>value</b>	<b>unit</b>
Coal, hard, unspecified, in ground	19.1	MJ/kg
Coal, brown, in ground	9.9	MJ/kg
Gas, natural, in ground	38.3	MJ/m <sup>3</sup>
Gas, mine, off-gas, process,	39.8	MJ/m <sup>3</sup>

coal mining/m <sup>3</sup>		
Crude Oil, in ground	45.8	MJ/kg
Uranium, in ground	5.6x10 <sup>5</sup>	MJ/kg
Methane GWP <sup>b</sup>	25	

*Note:* kg = kilogram; m<sup>3</sup> = cubic meter; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/m<sup>3</sup> = megajoules per cubic meter.

<sup>a</sup> Source: (ecoinvent Centre, 2007)

<sup>b</sup> Source: (IPCC, 2007).

**Table S3** Results showing CED impacts of steel manufacturing using the process-sum approach.

% Secondary Content	% Primary Content	Low-Alloyed Steel (MJ/kg steel)			Chromium (Stainless) Steel (MJ/kg steel)		
		Europe	China	US	Europe	China	US
0	100	36	36	37	79	78	81
25	75	30	30	31	77	77	80
50	50	25	25	26	76	76	79
75	25	19	19	20	75	74	78
100	0	14	14	15	73	73	77

*Note:* CED = cumulative energy demand; MJ/kg = megajoules per kilogram of steel; % Secondary content = percent of recycled steel (scrap) used in production; % Primary content = percent virgin steel used in production.

**Table S4** Results showing GWP impacts of steel manufacturing using the process-sum approach.

% Secondary Content	% Primary Content	Low-Alloyed Steel (kg CO <sub>2</sub> eq/kg steel)			Chromium (Stainless Steel) (kg CO <sub>2</sub> eq/kg steel)		
		Europe	China	US	Europe	China	US
0	100	2.3	2.6	2.4	4.7	5.9	5.2
25	75	1.9	2.2	2.0	4.6	5.8	5.0
50	50	1.5	1.8	1.6	4.4	5.7	4.9
75	25	1.0	1.4	1.2	4.3	5.6	4.8
100	0	0.7	1.1	0.8	4.1	5.5	4.7

*Note:* GWP = global warming potential; kg CO<sub>2</sub>eq/kg steel = kilogram carbon dioxide equivalent per kilogram of steel; % Secondary content = percent of recycled steel (scrap) used in production; % Primary content = percent virgin steel used in production.

**Table S5** GWP/CED results from previous studies and reports for the process-based approach.

Source	Type of Finished Steel	CED (MJ/kg steel)	GWP (kg CO <sub>2</sub> eq/ kg steel)	Approximate % Secondary Steel Content
World Steel Association (Crawford, 2013)	Sections	16	1.2	85
	Tinplate	22	1.7	60
(A) Athena (Markus Engineering Services, 2002)	Rebar, rod and light sections	19 23	.60 1.0	90 40
	Cold-rolled sheet	26	1.5	55
	Hot-rolled sheet			
USLCI (NREL, 2013)	Iron and steel mix	10	.90	70
	Hot-rolled sheet	26	2.3	30
	Cold-rolled sheet	30	2.6	30
(Hammond and Jones, 2008)	Typical steel 42.3% secondary steel	24	.48	42
	Primary steel	35	.75	0
(Keoleian et al., 2008)	Stainless <sup>e</sup>	16	1.2	Unknown <sup>f</sup>
	Cold-rolled <sup>e</sup>	29	2.1	Unknown <sup>f</sup>
	Extruding/galvanizing	37	3.2	Unknown <sup>f</sup>
(Buchanan and Honey, 1994)	General	35	1.4	24 <sup>d</sup>
	Sections	59	2.0	24 <sup>d</sup>
(Zabalza Bribián et al., 2011)	Reinforcing	24	1.5	40 <sup>e</sup>
(Scheuer et al., 2003)	EAF technology <sup>a</sup>	12	Unknown <sup>f</sup>	100
	Secondary, Hot-rolled <sup>a</sup>	14	Unknown <sup>f</sup>	100
	Primary, Cold-rolled <sup>a</sup>	28	Unknown <sup>f</sup>	0
	Electrogalvanized	31	Unknown <sup>f</sup>	0
	Stainless	8	Unknown <sup>f</sup>	Unknown <sup>f</sup>

*Note:* GWP = global warming potential; CED = cumulative energy demand; EAF = electric arc furnace; BOF = blast oxygen furnace; MJ/kg steel = megajoules per kilogram of steel; kg CO<sub>2</sub>eq/kg steel = kilogram carbon dioxide equivalent per kilogram of steel; Secondary steel = recycled steel; Primary steel = virgin steel.

<sup>a</sup> EAF technology is assumed to be comprised of 100% secondary (recycled) steel; BOF technology is assumed to be comprised of 100% primary (virgin) steel.

<sup>b</sup> Values based on the percentage of EAF and BOF technologies used in these regions in 2002 (WSA, 2013).

<sup>c</sup> Values based on the percentage of EAF and BOF technologies used globally when in 1983 when study was completed (WSA, 2013).

<sup>d</sup> Values based on the percentage of EAF and BOF technologies used in Europe in 2007 when study was completed (WSA, 2013).

<sup>e</sup> Values do not include primary fabrication energy.

<sup>f</sup> Values were not included in previous work.



**Table S6** Quantity, GWP and contribution from steel in original residential building LCA study (Gong et al. 2012).

Construction Type	Quantity (tonne)	GWP (kg CO <sub>2</sub> eq/kg steel)	Contribution to GWP from steel in original study kg CO <sub>2</sub> eq (Gong et al. 2012)
CFC	282	2.2	621
SFC	459	2.2	1011

*Note:* GWP = global warming potential; kg CO<sub>2</sub>eq/kg steel = kilogram carbon dioxide equivalent per kilogram of steel; kg CO<sub>2</sub>eq = kilogram carbon dioxide equivalent.

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