Comparison of Four Environmental Assessment Tools in Swedish Manufacturing: A Case Study

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Supplementary

This section presents the complete description of tool deployment and results from applying each tool to the case in question.

Green Performance Map

GPM was used according to the structure presented by Bellgran et al. [1], which aims to include various environmental aspects of the process, although with some limitations in quantification. Two of the authors, along with an enterprise environmental expert from the same consortium, did an overall GPM for the entire vehicle frame operation process. The mapping took 30 minutes, including walkthroughs on the shop floor and taking notes on both the environmental aspects and prioritization of improvement actions with the help of three technicians responsible for the vehicle frame production. The overall operation process was then divided into seven sub-processes to be studied individually and in detail. Next, seven detailed GPMs were mapped for each sub-process; it took a half day to map all the sub-processes. The categorization of the vehicle frame operation process into different sub-processes was mainly based on the types of processes, their consequences and the production layout. Afterwards, GPMs for the sub-processes and an overall GPM was transformed into Visio files, and differences, inputs and outputs were aligned to capture information missing from either the overall GPM or the detailed GPMs. Figure S1 illustrates the visualized GPMs at different levels.

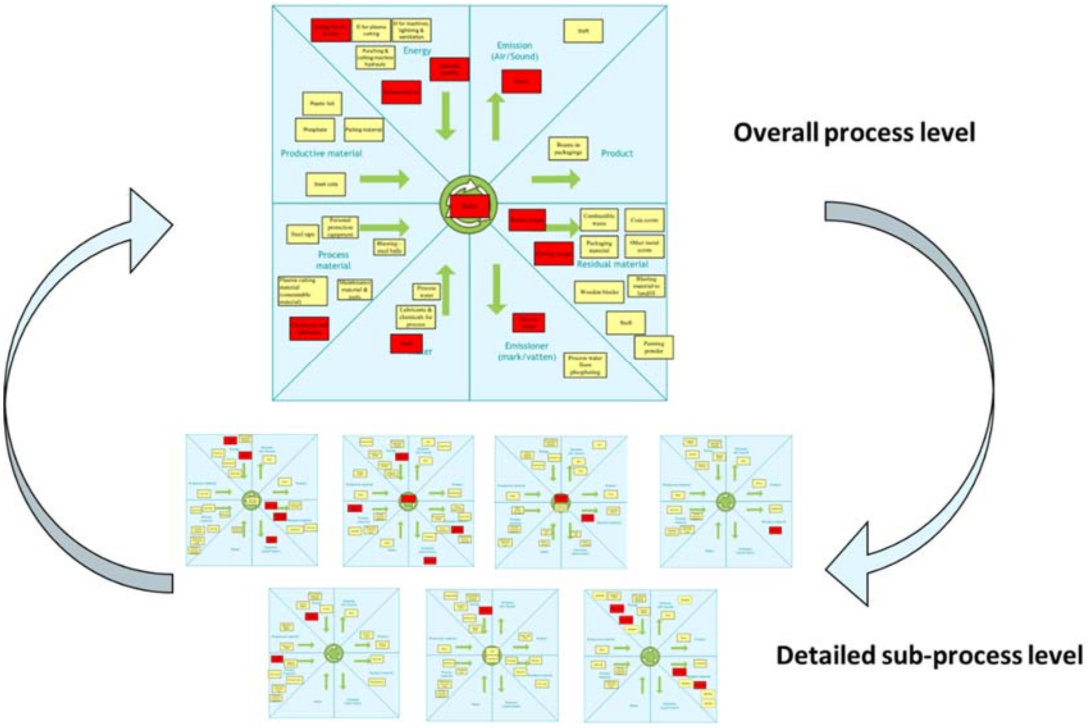


Figure S1. Performance Map Performed in this study at two levels.

Analyzing the process of using GPM to environmentally assess an operation shows that it is time-efficient and easy to learn and implement. The GPM visualization was helpful for quickly understanding the processes and their correlated environmental aspects. In addition, applying GPM at the overall process and sub-process levels supported a detailed identification of environmental aspects; in contrast, focusing on only one level might have caused some environmental aspects to be neglected. Because GPM was also mapped at the lowest operational level, it supported go-to-gemba and increased engagement of employees in improvement actions on the shop floor. However, collecting quantitative data on the cost and amount of environmental aspects was challenging, particularly at the detailed level for each sub-process. For instance, determining the amount of energy consumption by each sub-process was problematic, although it was easy to obtain material and scrap-related data. It was also challenging to prioritize improvement actions considering the environmental impacts, costs, and resource requirements (such as time, personnel, and knowledge). From a conventional operational improvement perspective, GPM could not help improve the production flow and some production aspects such as inventory or information flow.

The results derived from GPM suggested that it was crucial to begin improvement actions regarding the following environmental aspects of vehicle frame production:

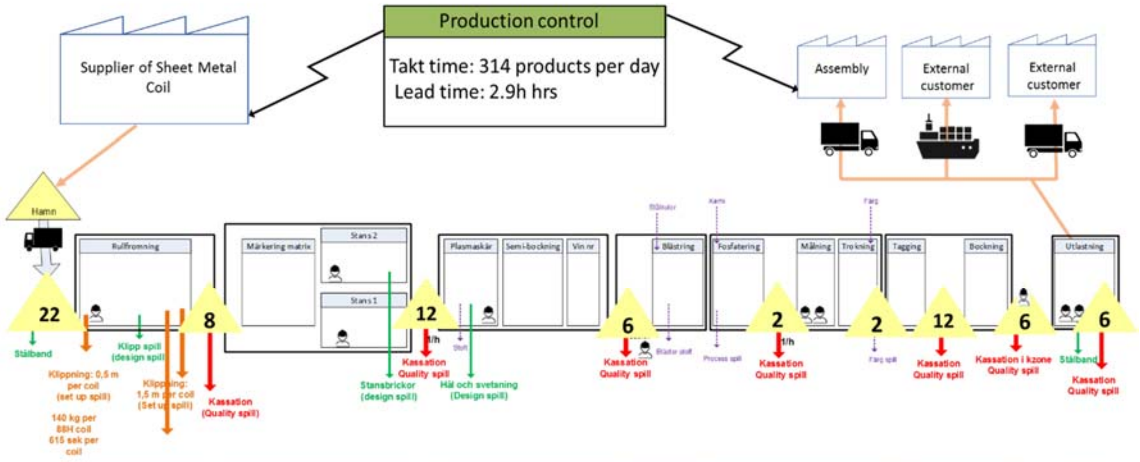
- Energy consumption for compressed air, hydraulic systems, painting and heat treatment
- Hazardous materials, including chemicals and lubricants
- Processed water from heat treatment, including phosphating and blasting
- Scrap generation and waste of productive material
- Noise from punching machines

In addition to these crucial environmental aspects, issues were identified that were less critical and could be improved in later stages, such as the waste of painting powder, incorrect segregation, packaging issues, working environmental issues, and waste of consumable equipment such as safety gloves and glasses.

Environmental Value Stream Mapping

EVSM was conducted following the structure presented by the EPA [2] and based on a predetermined goal focused on productive material; energy and waste flows were studied but not in detail. The EVSM for the entire vehicle frame operation process was mapped by two of the authors and an enterprise environmental expert from the same consortium. It took 30 minutes to map the entire process, including walking through the shop floor and taking notes on production aspects, information flow, inventory and work-in-process levels, and scrap generation. The EVSM procedure also included the same categorization of sub-processes derived from the GPM method. After collecting all necessary data and double-checking their correctness, an EVSM was drawn in Visio software, although it diverged from VSM visualization standards. Figure S2 illustrates the EVSM for the entire process, with a focus on scrap generation.

The results showed that EVSM is easy to use and supports the go-to-gemba concept. The focus on one environmental aspect (scrap generation) in EVSM helped us understand the type, volume and reasons for scrap generation in each sub-process, i.e., where, how much, and why scrap is generated. Based on further investigations using EVSM, the causes of scrap generation can be divided into three categories: (1) design, (2) set up and processing and (3) quality.



Amount & type of scrap	XX kg	XXX kg	XX kg	X kg	XXX kg	XX kg	X kg
	Z kg	-	Z kg	-	-	-	-
	Y kg	Y kg	Y kg	-	-	-	Y kg
Production time	317	370	708	190	4500	646	150

Figure S2. Environmental Value Stream Map performed in this study for the productive material.

Design scrap (Y in Figure S2) included wasted productive material that was designed to be produced and inevitable to avoid, such as coin-form steel pieces from a punching machine. Set-up scrap (Z in Figure S2) included scrap produced because of the machine's set up or manufacturing processes (technology). Some examples are scrap generated by a plasma-cutting machine and scrap generated in a steel-forming machine during the first round of changing a product's specifications. Quality scrap (X in Figure S2) included scrap from quality deviations, insufficient inspections and human error, such as metal sheets cut to the wrong length or scrap from unremoved dross on products. Quality scrap was determined to be of high concern (because of the substantial mass of these scraps) and associated with high cost, and thus should be targeted first. The number of Xs, Zs and Ys in Figure S2 are proportional to the amount of scrap generated by each sub-process. The results of EVSM showed where the highest volume of quality scrap is generated, and hence which steps should be the focus for improvement. One notable drawback of using EVSM is related to the number of environmental aspects considered; it was challenging to include another environmental aspect such as energy consumption because of the difficulty in collecting relevant data for each sub-process, along with the complexity of visualization. Figure S2 depicts only metal scrap generation because the inclusion of other types of material was problematic, as was the inclusion of other environmental aspects such as energy or water consumption. In addition to environmental data (such as the volume of scrap), EVSM can be used to obtain production-related data (such as takt time, lead time, buffer sizes or changeover time).

Waste Flow Mapping

WFM was performed according to the structure presented by Kurdve et al. [15] to study different waste and material flows, though we focused on metal scrap in this study. The WFM for the entire vehicle frame operation process was mapped by two of the authors. It took approximately one day to collect data on site, including eco-mapping, inspection of bins and the collection of waste management data. However, WFM was fully performed only for the metal segment; a sorting analysis for the metal segment was not carried out because all the bins along the line were sorted (in line with a suggestion in the handbook). We included data from 2015 and 2016 regarding an overview of the operation, bins and their contents, in addition to data from internal waste management, waste management entrepreneurs, quality, maintenance and purchasing systems. Interviews and data analysis took several hours and required additional follow-up questions. The studied process was divided into sub-processes in accordance with the performed EVSM and GPM; however, an additional map of the process flow was created to understand the machinery, equipment and production flow (Figure S3). The location of different types of waste bins were mapped with logged amounts from each sub-process. In addition, bin contents were visually inspected, and the transportation infrastructure was investigated. Furthermore, the bins and containers and the transport of outbound waste were analyzed. Root cause analysis of scrap generation was performed for the major sources of scrap generation (in accordance with EVSM), and extensive analyses of each of the quality scrap generation points were performed in later stages, which took several days. The collected data were entered into Microsoft packet software such as Excel and PowerPoint.

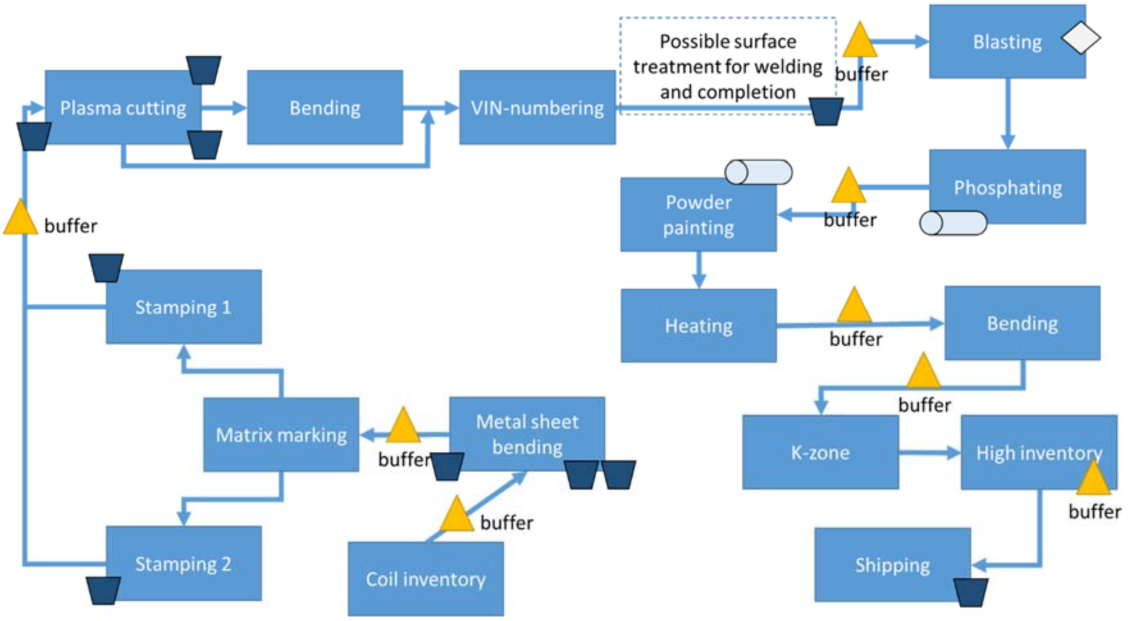


Figure S3. A schematic layout overview of the process.

The use of WFM indicated that a high degree of waste-sorting for the metal segment. Some Key Performance Indicators (KPIs) such as "Total scrap/Produced article" could be used to evaluate the process with respect to the steel waste (scrapped equipment must be excluded). Figure S4 illustrates the waste-sorting analyses performed via WFM. The pie chart on the left shows the different types of waste segments produced in the studied vehicle frame production with their respective percentages; the pie chart on the right shows metal scrap generation based on the identified reasons. For value-adding material (here, steel), root cause analysis is recommended. The different flows resulting from design scrap (holes and cuts needed to fulfill design demands), set-up scrap (cutting and trimming needed to fulfill the process capability) and quality scrap (resulting from process quality failures) were estimated. Exact data for quality scrap during the period from January 1, 2016 to March 14, 2016 were used to estimate the volumes.

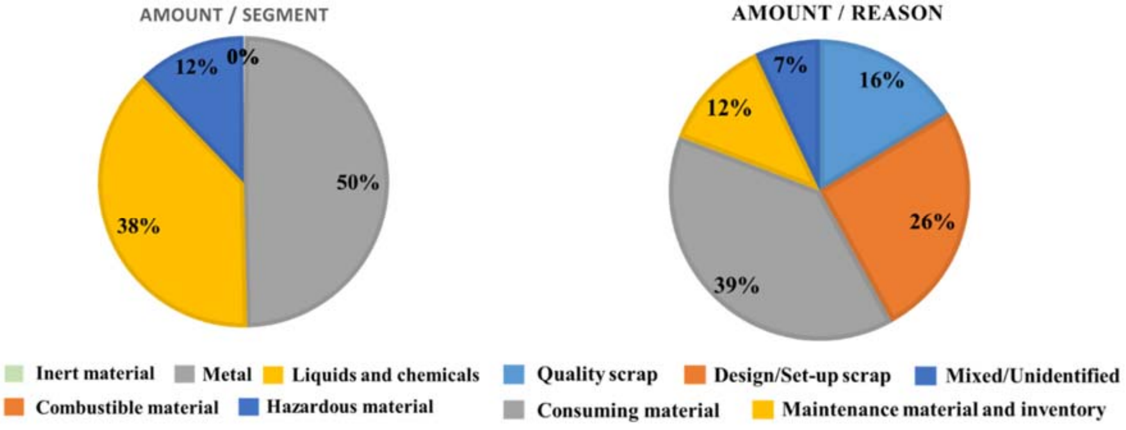


Figure S4. Waste-sorting analyses performed via WFM.

Production rate and scrap generation data from 2015 and 2016 were used to determine the scrap generation rate; the results are shown in Table S1. A vertical analysis of the handling and costs of waste management was performed based on interviews. The bins used were typically "dumping hoppers" for metals and transparent plastic bins for plastic waste, wood and combustibles. There were essentially no bins with mixed metals (other than one bucket in the main workshop). Other scrap metal collection points contained obsolete material, scrapped equipment and construction material.

Table 1. Scrap generation analysis.

	2015		**2016**	
	% of total scrap	**% of total material consumption in vehicle frame production**	**% of total scrap**	**% of total material consumption in vehicle frame production**
Design scrap	59%	4.5%	64%	5.4%
Set-up scrap	1%	0.1%	1%	0.1%
Quality scrap	40%	3.1%	35%	3%
Total		7.73%		8.5%

According to the interviews, the waste generated from vehicle frame production is transported using internal logistics. Metal scrap is internally transported to a determined area, called an environmental zone, for further external transportation by a waste management entrepreneur. External transport of scraps is performed on demand every other day by a waste management entrepreneur. Containers are shipped to an off-site location by truck by a waste management entrepreneur; this process typically uses half of the maximum load of the truck. Two forklifts are used (one large and one regular in size). It is estimated that the forklifts are used two to three hours per week for waste management purposes. With 144 hours of operating time per week, the relative cost is estimated to be 2% of the annual investment, plus 3 h/week of operator time. Hazardous material is internally transported by a forklift to the environmental zone, and phosphating baths are collected in tanks to be emptied by pipes for external transport.

Life Cycle Assessment

A simplified LCA was conducted for the entire vehicle frame operation process and was executed by three of the authors. A simplified LCA involves only the core data on the manufacturing process; material composition and assumptions about the included phases of the live cycle are specified, but generic datasets from databases are used for all background data. The LCA was not performed entirely in accordance with ISO 14044 (2006). While it consisted of the required four stages (scope and goal definition, inventory analysis, impact assessment and interpretation), the execution was modified to test how benefits could be drawn from joint data collection and findings from the other tools applied on the case. It took approximately five working days in total to perform the LCA, including interviews and the additional data collection required for analysis.

Normally, the scope definition stage is carried out with the product owner; but in this case, it was based on a predetermined scope of the studied product system and focused on environmental impacts from the use of materials, energy, water, waste and hazardous materials during the manufacturing of vehicle frames. The data collection is the most time-consuming part of the LCA. However, in this study, the first two stages were mainly performed using previously collected data from GPM, EVSM and WFM. Nonetheless, some additional data were collected to achieve a sufficiently holistic scope in terms of the environmental aspects considered. Some data were also double-checked with the product owner during the LCA calculations. Figure S5 depicts the system scope of the performed LCA, from the input material production (cradle) to the vehicle frame production and waste treatment at the factory (gate). This system boundary and scope definition is coherent with the general rules of the EPD system. According to EPD systems, when waste is generated from manufacturing and products are scrapped, it is recommended to separate the product system where the residual materials have the lowest value and where the payer accounts for any emissions. Consequently, recycled waste is generally excluded from the system boundary but treated waste is included in the system boundary, as shown in Figure S5. This type of system boundary is called cut-off, as there are clear boundaries between different product systems. This practice allows to add product life cycles to each other without double-counting emissions and resources. Internal and external transportation are shown by arrows, which have been included based on the availability of transportation data.

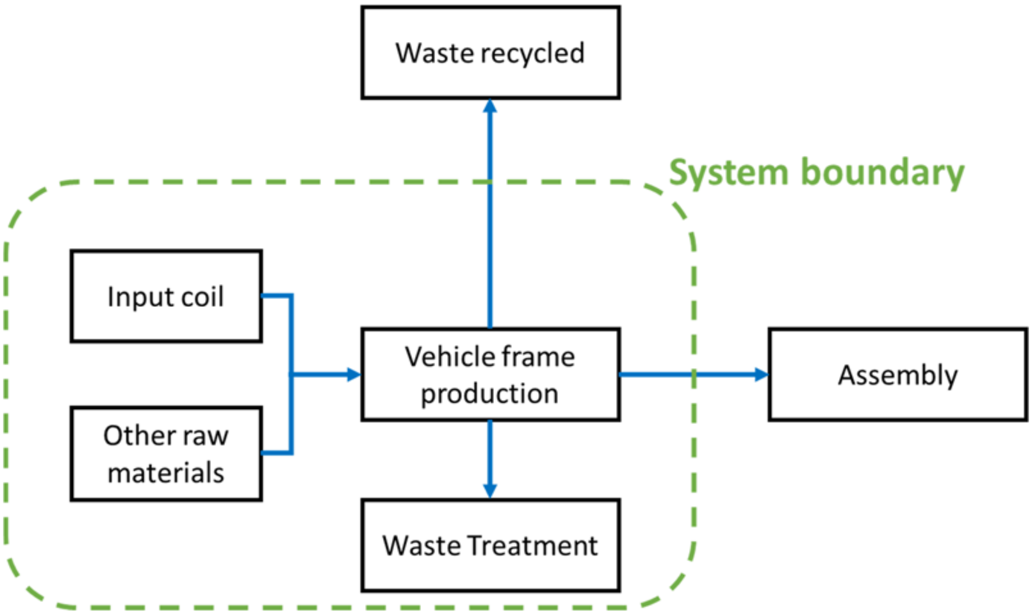


Figure S5. System scope of LCA.

The product owner was involved in the interpretation stage but to a lesser degree than normally; often an interdisciplinary group with insight on the subject area is gathered to review the study and draw relevant conclusions together. However, the practitioners applying the GPM, EVSM, WFM and LCA studies (the authors) reviewed the results and supported the interpretation. Simapro software and the Ecoinvent database were used for analysis. The environmental impacts quantified were climate impact, eutrophication, acidification and smog. Figure S6 illustrates the climate impacts of the studied vehicle frame operation process from the cradle (material production) to the gate at the factory. The thickness of the arrows corresponds to the climate impact measured in carbon dioxide equivalents from each part. In the lower left corner of the process boxes, emissions in kilograms of CO_2 equivalents are given.

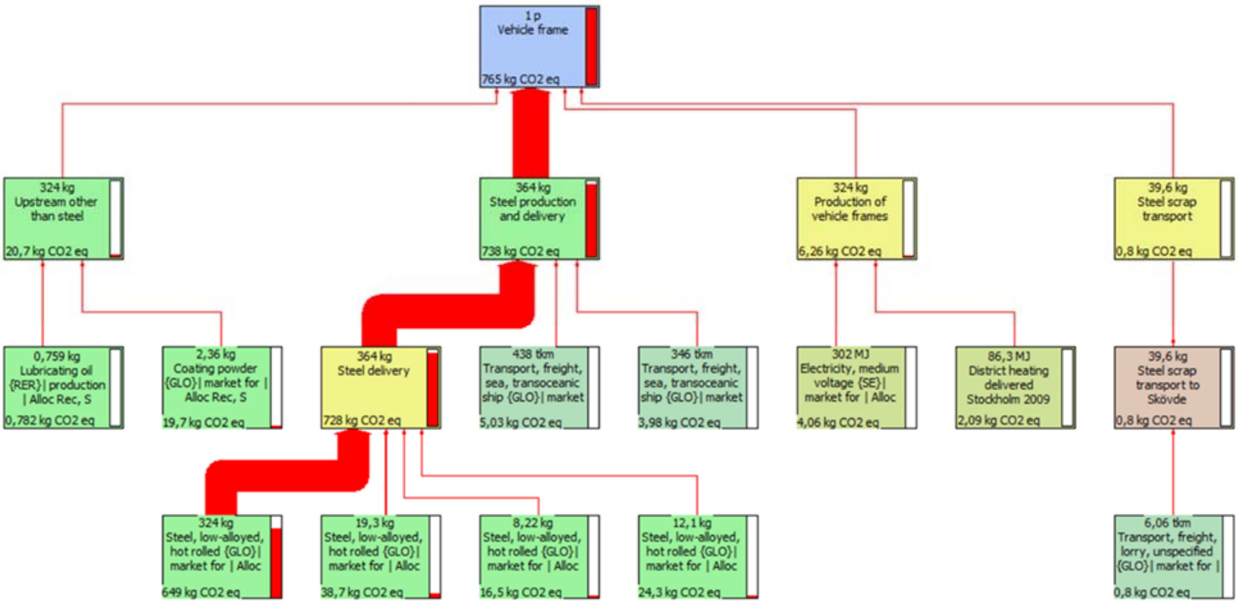


Figure S6. Climate impacts for a frame from cradle to gate (the product name and plant have been excluded).

As shown in Figure S7, manufacturing of the steel coil to be used for production of the vehicle frames generates the greatest climate impact. All the materials used in the manufacturing process are considered in the assessment, although not all result in detectable climate impacts. Design scrap (with 19.3 kg) and quality scrap (with 12.1 kg) have greater climate impacts than production of the coating powder. The set-up scrap (with 8.22 kg) results in slightly lower climate impacts than coating powder production. Energy use during production has a slightly smaller climate impact than inbound steel transportation. The environmental impact calculations for ground-level ozone, acidification and eutrophication all indicate the same conclusion that steel production has the greatest impact.

Stepping outside the system boundary, we conducted a small study focusing on alternatives to the current steel scrap recycling. The generated scrap is currently transported 165 km for use in casting blocks. However, transporting the scrap to a steel supplier (452 km) could result in better use of existing alloy elements. The "climate cost" for the longer transport to the steel supplier is 2.3 kg CO_2 (see Figure S7). This climate cost can be compared with 0.8 kg CO_2 for transport for casting (see Figure S6), whereas the "climate cost" of the ferro-nickel alloy in 39.6 kg of product scrap is 9.65 kg CO_2, which is significantly greater than the "climate cost" for the extra transport to the steel supplier. However, we note that the generic dataset used to model the steel does not match the actual steel quality, so this opportunity for climate gains must be confirmed with actual steel qualities.

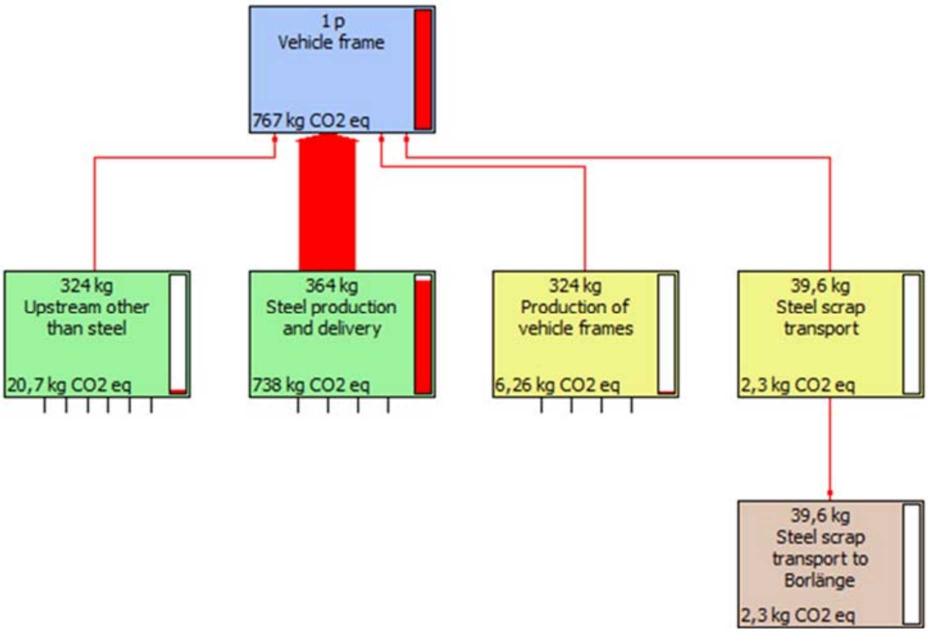


Figure S7. Climate impacts for a frame from cradle to gate for scrap transport to a steel supplier.

Reference

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