

Article

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

Sasha Shahbazi *, Martin Kurdve , Mats Zackrisson , Christina Jönsson and Anna Runa Kristinsdottir

RISE IVF, 43 122 Mölndal, Sweden; Martin.kurdve@ri.se (M.K.); mats.zackrisson@ri.se (M.Z.); christina.jonsson@ri.se (C.J.); anna.runa.kristinsdottir@ri.se (A.R.K.)

* Correspondence: sasha.shahbazi@ri.se; Tel.: +46-70-780-61-25

Received: 18 March 2019; Accepted: 4 April 2019; Published: 11 April 2019



Abstract: To achieve sustainable development goals, it is essential to include the industrial system. There are sufficient numbers of tools and methods for measuring, assessing and improving the quality, productivity and efficiency of production, but the number of tools and methods for environmental initiatives on the shop floor is rather low. Incorporating environmental considerations into production and performance management systems still generally involves a top-down approach aggregated for an entire manufacturing plant. Green lean studies have been attempting to fill this gap to some extent, but the lack of detailed methodologies and practical tools for environmental manufacturing improvement on the shop floor is still evident. This paper reports on the application of four environmental assessment tools commonly used among Swedish manufacturing companies—Green Performance Map (GPM), Environmental Value Stream Mapping (EVSM), Waste Flow Mapping (WFM), and Life Cycle Assessment (LCA)—to help practitioners and scholars to understand the different features of each tool, so in turn the right tool(s) can be selected according to particular questions and the industrial settings. Because there are some overlap and differences between the tools and a given tool may be more appropriate to a situation depending on the question posed, a combination of tools is suggested to embrace different types of data collection and analysis to include different environmental impacts for better prioritization and decision-making.

Keywords: sustainable manufacturing; environmental assessment tool; green lean

1. Introduction

Examining different sustainability definitions associated with industrial systems, such as sustainable manufacturing [1], sustainable production [2] or corporate sustainability [3], the importance of the manufacturing in sustainable development is perceived. However, environmental considerations in manufacturing and performance management systems mostly involve an aggregated top-down approach to the entire plant, that often emanating from a separate environmental department. This approach contrasts with the core areas of old-school production systems, such as productivity, quality, delivery precision and cost efficiency, which are considered via both bottom-up and top-down strategies. Additionally, environmental operations improvement has received insufficient attention i.e., there are many tools and methods to measure, assess and improve quality, productivity and efficiency in manufacturing, while relatively few tools and methods exist that specifically target environmental initiatives on the shop floor [4,5]. Green lean studies have attempted to fill this gap with some tools for environmental initiatives on an operational level [6,7], but a lack of detailed methodologies and selection of practical tools when improving the environmental operations and sustainability performance of manufacturing remains.

This paper reports on the application of four environmental assessment tools: Green Performance Map (GPM), Environmental Value Stream Map (EVSM), Waste Flow Mapping (WFM) and Life Cycle Assessment (LCA), which are commonly used among Swedish manufacturing companies. A short description of each tool is given in Section 2.2. These tools were applied at the same manufacturing process at the same company to solve a particular environmental (and operational) issue related to material efficiency and metal scrap generation of the vehicle frame production process. The authors have earlier applied these tools on several companies of various sizes with different industrial challenges, but none have compared the performance of these tools on the same case. Therefore, the objective of this paper is to help practitioners and scholars to understand the different features of each tool, so in turn (a) right tool(s) can be selected according to particular questions and the industrial settings i.e., variables such as the industrial activity, data accessibility, and staff engagement level and competence. In this paper, these tools are compared to investigate their application and to enable a more precise understanding of the issues involved; however, the intention is not to select a superior tool. Moreover, this study neither deals with material selection nor product design, rather with selecting the best environmental assessment tool for the operational problem posed. Although the empirical focus was on material efficiency and metal scrap reduction, other environmental aspects such as energy use and hazardousness were considered when evaluating, comparing and discussing the tools. Therefore, metal scrap generation in this paper could be seen as an example (demonstrator) for deploying these tools. To fulfill the research objective, two main research questions were posed: (1) what features enables environmental improvements in manufacturing and how those fit into the selected tools? (2) how can these tools be applied in practice?

2. Theoretical Framework

2.1. Moving from Sustainability Concepts to Practical Tools

Although manufacturing companies have been adopting environmental considerations in their production systems since the 1960s [8], environmental improvement thinking and decision-making still most commonly use a top-down approach and environmental data are aggregated for the entire plant on a yearly basis, primarily for the purpose of environmental reporting to authorities and external stakeholders [9], or on a product basis for eco-design purposes, or as an evaluation for marketing. Environmental improvement actions are usually implemented as projects by the environment department and not as an integrated part of continuous improvement activities in work units. However, Cherrafi et al. [10], Dües et al. [11] report tendencies toward a change e.g., in new ISO standards and operative green lean developments.

Environmental assessment and management can be related to different levels of the decision hierarchy [12]. Tools and methods can be linked to a conceptual level with broad and long-term goals, to the supply chain and local industry level, to an operation or a process, or to the lowest level of operational improvements on the shop floor. Previous studies have shown that there are few practical tools appropriate for the operational level that can regularly assess, manage and improve the environmental sustainability of an operation via a bottom-up approach [4,13]. Therefore, developing tools should focus on the operational level and shop floor, where resources are consumed and actual manufacturing is performed, causing a variety of environmental impacts. Bridging the gap between operational and environmental management requires a set of tools to support collaboration between different functions (internal and external), systematic work procedures and problem solving to promote easy learning, and time efficiency [14,15]. These criteria are essential for mutual understanding, intra-organizational communication, improving performance and becoming a learning organization [16]. However, most environmental assessment tools and methods are complex and require expert knowledge of environment management, making it difficult to integrate and apply them into daily continuous improvement work (Kaizen). Studies on green lean manufacturing have (to some degree) bridged this gap by integrating environmental sustainability goals into lean-based

production systems [6,17]. Lean principles, such as continuous improvement (Kaizen), visualization, go-to-gemba (i.e., going to the shop floor where problems occur), simplicity in use and learning, and increased engagement of different functions, have been successfully applied and have improved operations and environmental performance in manufacturing (see e.g., Zokaei et al. [7], Dües et al. [11], Wu et al. [18] and Diane et al. [19]). Therefore, a production system based on an integrated green lean philosophy is likely to have high potential for environmental improvements, as the culture of continuous improvement, engagement and waste elimination are already inherited from lean production [9,20]. This goes hand-in-hand with selected tools which are mainly based on lean principles with focus on shop floor.

Overall, the differences in utility of tools and the overlaps between the available tools in previous literature motivated us to compare the most commonly used environmental assessment tools among large international manufacturing companies located in Sweden (in line with the goal of the study). The selected tools have been previously used by the authors in different studies in several manufacturing companies in Sweden (see e.g., Kurdve et al. [21]) for WFM, Zackrisson et al. [22] for LCA, Shahbazi and Wiktorsson [23] for GPM and Kurdve et al. [24] for EVSM). The selected tools are mainly based on lean principles, have bottom-up approach and are mainly focused on shop floor. Therefore, there are some attributes similar to other tools presented in previous literature, see Table 1. For instance, GPM and WFM are similar to tools developed by Zokaei et al. [7]. Among the selected tools, LCA has a more holistic view of environmental aspects and their impact, is not entirely based on lean principles and is slightly more complicated than the other tools (although screening LCA can be used for simpler use), but it was deliberately selected to broaden the analysis.

Table 1. Similar tools identified in the literature.

Tools Applied	Common Level of Use *	Tools with Some Level of Similarity
LCA	Product level	Chemical Risk Assessment, Eco-strategy Wheel, Energy Mapping
WFM	Line/site level	Material Flow Analysis, Logistic Handling, Material Handling Analysis, Material Energy Waste Map
GPM	Cell level	Material Flow Cost Accounting, System Boundary Map and Green Impact Matrix
EVSM	Line level	Green Big Picture

* All tools might be applied at all levels; however, the table indicates the common level of use.

Previous research on green lean and environmental assessment tools, suggests that a tool benefits from the following essential features to enable environmental improvements in manufacturing:

- Being hands-on and operational [25], supporting collaboration and understanding between different internal and external actors [26,27];
- Being easy to learn and implement, visualization [28], time efficiency, continuous improvement and engagement [29];
- Including root cause analysis [30], be harmonized with ISO 14001 [31,32] and support the go-to-gemba concept [33];
- Being goal-oriented, supporting measurements [34], and being focused on a limited area of influence while supporting systematic work procedures (standardized work) [35].

2.2. Summary of Included Tools

Here, the selected tools are briefly described. A deeper description of each tool is given in the Supplementary Material.

2.2.1. Green Performance Map

The GPM [36] is a hands-on tool based on lean principles and green manufacturing concepts aiming to support team level improvements. The tool follows the input and output model to identify, analyze, assess and visualize a variety of environmental aspects of an operation. The flow of input material is divided into productive materials (which are the primary product material), process materials, energy and water consumption; the flow of output is divided into emissions and noise, consumed water, products and residuals. GPM has been reported to be effective for Swedish manufacturing companies, e.g., by Kurdve and Wiktorsson [37]; Shahbazi and Wiktorsson [23], while is similar to tools used internationally by e.g., Pampanelli et al. [38], Sawhney et al. [39] and Zokaei et al. [7].

2.2.2. Environmental Value Stream Mapping

EVSM [40] not only maps the operation aspects, such as process, information flows, inventory levels and time associated with production (such as lead time and takt time), but also visualizes environmental aspects, such as material and waste flows and energy and water consumption. It also considers correlated environmental impacts according to the company's environmental management system and annual targets. Examples of studies using EVSM include Torres and Gati [41], Müller et al. [42], Posselt et al. [43], Gunduz and Fahmi Naser [44] and Dadashzadeh and Wharton [45], among others.

2.2.3. Waste Flow Mapping

WFM [21] resembles material flow analysis but applied on a micro-level (site, line or cell). This method follows current state analysis principles and includes three phases: (1) mapping of waste generation points and fractions, on-site data collection through observations, interviews, deploying eco-mapping [46] and sorting analysis [47] and logistics and waste-handling data collection; (2) material efficiency analysis for each segment, including waste hierarchy, material segmentation, and root cause analysis to determine the causes of material losses; (3) analysis of efficiency in each waste management sub-process and assessment of waste material handling analysis [48], showing losses in terms of equipment and workers utilization.

2.2.4. Life Cycle Assessment

LCA can be considered the broadest environmental assessment tool with the smallest connection to lean principles among the selected tools. LCA assesses significant environmental aspects and their impact from extraction to production, use and end-of-life phase via a holistic approach with the life cycle perspective. LCA can be deployed in ways ranging from a quick LCA using generic data from databases to a full LCA with a high level of detail. In this study, screening LCA was performed which is relevant to the shop level (in line with other tools) and allows fair comparison of the tools. Input and output data across the system boundaries were collected, validated and normalized. Examples of studies deploying LCA in manufacturing include Cheung et al. [49]; Zhang and Haapala [50]; Thammaraksa et al. [51], among others.

3. Materials and Methods

This research is based on a single case study at a large manufacturing company in Sweden, which provided an in-depth understanding [52]. The selection of the case company was based on the company's environmental management system, environmental goals, reputation and interest in achieving sustainability improvements in operation. Additionally, one of the current environmental goals of this company is to increase resource efficiency. For empirical data collection and analysis, a process of manufacturing vehicle frames (consisting of a pair of beams) was selected. The process uses metal as productive material and generates metal scrap and limited amounts of combustible

waste, including plastic, bio-waste, paper and wood. The operation process includes metal sheet bending, punching, plasma cutting, blasting, phosphating, painting, heat treatment, and shipping to customers. Finished vehicle frames are sent to an in-plant assembly line or shipped to external plants worldwide. The four shift teams with nine operators and a team leader each, three technicians, a production planner, a production manager, the plant environmental manager, a purchaser and a quality controller were consulted in this case.

Data were collected on the material value chain and information flow, as well as scrap volumes, costs and revenues, statistics from an external waste management entrepreneur, final treatment options, and transportation modes; other necessary data were obtained from environmental reports. Empirical data collection involved multiple sources of evidence including participant observations, on-site walkthroughs, archival review, in-depth interviews (between 30–90 min) and discussions with experts, ensuring data triangulation. Two authors spent two weeks in the studied manufacturing process, participated in meetings and morning briefs, reviewed internal environmental and operational reports and discussed and interviewed different functions including internal environmental manager at the factory level, external environmental manager at the enterprise level, operators, team manager, production manager, waste management entrepreneurs, production planner and production technicians. The document reviews helped to realize a basic insight into companies, their overall strategy and environmental targets and current improvement projects. To be able to deploy the tools, a case study focus based on the current environmental and operational problem at the company was selected i.e., material efficiency and metal scrap generation. The case study focus was supposed to provide answers to question including which sub-process has the largest environmental impact? How much scrap is generated in this process and the respective sub-processes and why? And what improvements can be made to move towards circularity, decreasing scrap generation and environmental impact?

In addition to the empirical study, a structured literature review of environmental assessment tools was carried out. The literature search was conducted in both the scientific databases and grey literature. The literature selection method used a keyword search regarding relevant tools, followed by abstract review and full-text reading. The search incorporated the keywords “lean and green” “green lean” and “environmental assessment”, along with combinations with terms “tool”, “approach” and “methods”. The search was focused on papers published between 2005 and 2018 addressing a situation similar to that in the Swedish manufacturing industry; however, papers outside of this scope were also included in the study. This search was compounded with a qualitative upstream and downstream search of the references in the selected articles.

Data collection and analysis were conducted iteratively to ensure the necessary adjustments. The collected data were continuously summarized in case study protocols and project members were consulted. The empirical findings were also compared with existing literature to enhance understanding of the similarities and differences relative to other studies. To ensure validity and reliability, measures suggested by Yin [52] were adopted, including collection of data from a variety of sources, such as observation, document reviews, interviews and discussions using different tools. The validity was further strengthened by peer examination of collected data and results in different time stages by authors, industrial practitioners, project members and research fellows. The structure followed a logical design with a defined problem statement composed by the company and researchers. Figure 1 depicts the research process.

The main implication of this article and the single case study is qualitative and include analytic generalizations [52]. Thus, the replication of achieved results at similar manufacturing companies is expected. Furthermore, the empirical data in this article relate to a large global manufacturing company in the automotive industry located in Sweden; hence, while the results may not be generalizable to completely different industries or to similar manufacturing companies outside of Sweden, it can be assumed that the achieved results represent relevant empirical evidence. In addition, environmental costs, standards and regulations as well as organizational factors such as environmental consciousness

and manufacturing culture, vary greatly over time and across geographic areas. Consequently, results of similar studies could differ over time and in different locations. Additionally, in line with analytic generalization in qualitative research, the single case study represents a case with an opportunity to observe, test and analyze a phenomenon (here environmental assessment tools) that few have studied before [53]. A single case study with an informative approach captures the circumstances and different criteria (see Table 2; Table 4) of an everyday situation (here, manufacturing) [52].

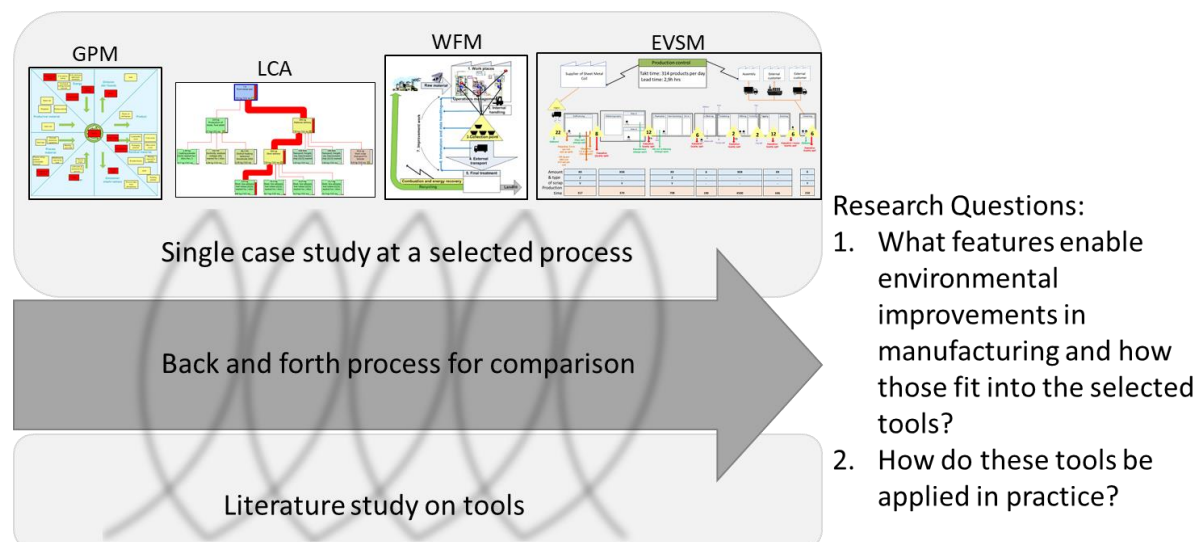


Figure 1. Research process of this study.

4. Empirical Deployment of Tools

This section presents the results and comparison of tools in terms of use experience and features, which are summarized in Table 2. A complete description of tool deployment is given in the Supplementary Material.

4.1. Green Performance Map

GPM was used according to the structure presented by Bellgran et al. [36] to identify and assess various environmental aspects, although with some limitations in quantification. The overall operation process was divided into seven sub-processes to be studied individually in detail. Hence an overall process level GPM as well as seven detailed sub-process GPMs were mapped. Figure 2 illustrates the GPMs at the two levels. This categorization was based on the types of processes, human resourcing and the production layout. The sub-process GPMs and an overall GPM data were then compared, and differences, inputs and outputs were aligned to capture missing information. Collecting quantitative data on costs and environmental aspects was challenging, particularly at a detailed level for sub-processes. For instance, determining the energy consumption at each sub-process was impractical, although the overall number was available. This number for material and scrap-related data was relatively easier to obtain on a sub-process level. It was also challenging to prioritize improvement actions considering the environmental impacts, costs, and resource requirements. From a conventional operations improvement perspective, although GPM improvement reduces cost, it did not improve lean aspects such as production flow, inventory or information flow.

Table 2. Cross-comparison of tools in terms of use experience and features.

Tools	GPM	EVSM	WFM	LCA
Result type	<ul style="list-style-type: none"> • Overview of material and energy flows at process and sub-process level • Qualitative results in the form of environmental aspects for each sub-process 	<ul style="list-style-type: none"> • Focus on the amount, location and type of scrap • Overview of the operation • Information flow regarding production • Supplier and customer information 	<ul style="list-style-type: none"> • Total amount of waste • Cost of waste bins, handling and transport • Sorting degree of different material fractions • Categorization, quantification and localization of scrap 	<ul style="list-style-type: none"> • Quantitative results at the site level in the form of calculated environmental impacts, e.g., climate impacts • Overview of material and energy flows at the site level • Transportation and end-of-life information
Operation level (site, process, cell)	Overall process and sub-process/cell	Entire process from coil to finished frame	Entire process from coil to finished frame	Entire process from coil to finished frame (cradle-to-gate model from site/process and database data)
Environmental aspects included	All flows (mainly those seen on the shop floor)	Specific selected material flows, (in this case metal scrap)	All types of materials and waste, but in this case with a focus on metals	All types of resources, usually with focus on significant environmental impacts 5 days for an expert, excluding most data collection
Time required for data collection and analysis (this study)	2–4 h for an expert 30 man-hours of operators' time	2–4 h for an expert 20 man-hours of operators/technician's time	2 days for an expert 35 man-hours of technician's time	10 man-hours of technician time, in addition to the use of data from other tools
End-of-life scenario	Partially included	Not included	Included	Included
Software demand (price)	No software	No software needed but e.g., Visio recommended for drawings	No software; Microsoft Excel needed for calculations	LCA software (SimaPro/Gabi/Open LCA) and databases
Visualization type	<ul style="list-style-type: none"> • provide quick understanding of processes and correlated environmental aspects • One-page input and output for material and energy flow 	<ul style="list-style-type: none"> • Process flow and one environmental parameter 	<ul style="list-style-type: none"> • Ecomap shows waste generation points • Waste-sorting analysis via pie chart • Waste-handling logistics via spaghetti diagram 	<ul style="list-style-type: none"> • System boundary figure showing process flow • Eco-profile • Environmental impacts at midpoint or endpoint level in absolute or relative terms • Software-dependent graphs
Guidance documents	Handbook available	Reports by the US-EPA	Handbook available	ISO 14044, ILCD Handbook
Ease of learning (knowledge requirements and days)	Easy to learn and implement. Needs <ul style="list-style-type: none"> • Workshop leader • Lean experience • One-day introduction 	Easy to use. Needs <ul style="list-style-type: none"> • Workshop leader • One-week training 	Slightly difficult due to variety of tools. Needs <ul style="list-style-type: none"> • Environmental manager or similar function • One to two days 	Difficult. Needs <ul style="list-style-type: none"> • Expert • Several days
Supporting Go-to-gemba	Takes place at shop floor via walkthroughs	Requires shop floor visit	Requires shop floor visit	Data normally not found at shop floor, but a factory visit is recommended to understand and complement data
Employee engagement	Increased engagement in improvement actions on the shop floor	Increased engagement in improvement actions on the shop floor	Increased engagement in improvement actions on the shop floor	

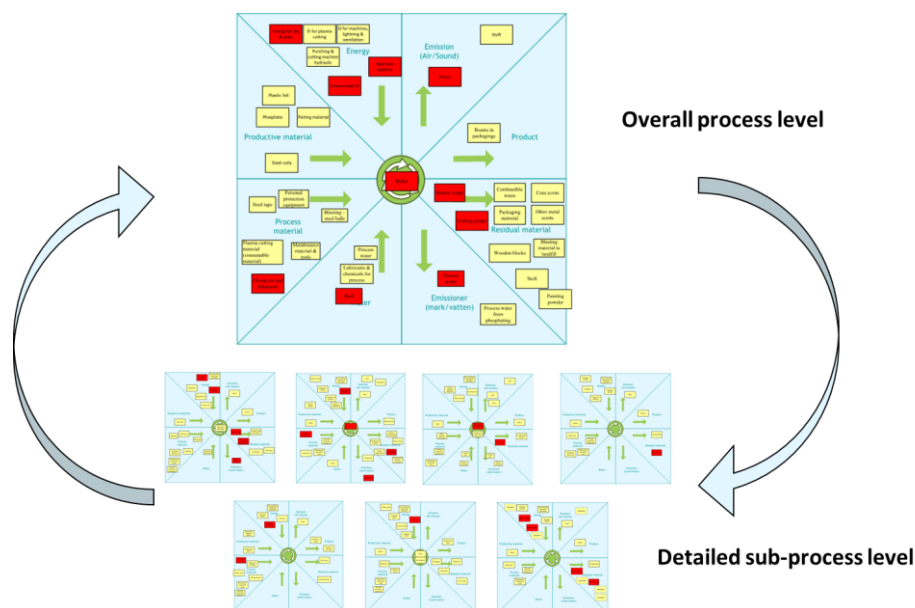


Figure 2. Performance Map Performed in this study at two levels. This figure does not intend to present the identified environmental impact and prioritization, but to present a schematic overview of GPM and how two different levels correlate.

4.2. Environmental Value Stream Mapping

EVSM was conducted following the structure presented by the EPA [40] with a focus on scrap generation. The EVSM also used the same sub-process categorization as the GPM. Based on further investigations, causes of scrap were divided into three categories: (1) design, (2) set up and processing and (3) quality. A notable drawback of using EVSM relates to the number of environmental aspects considered; it was challenging to include an additional environmental aspect (e.g., energy consumption) due to the difficulty of collecting additional data, along with the complexity of visualization. Therefore, Figure 3 depicts only metal scrap generation.

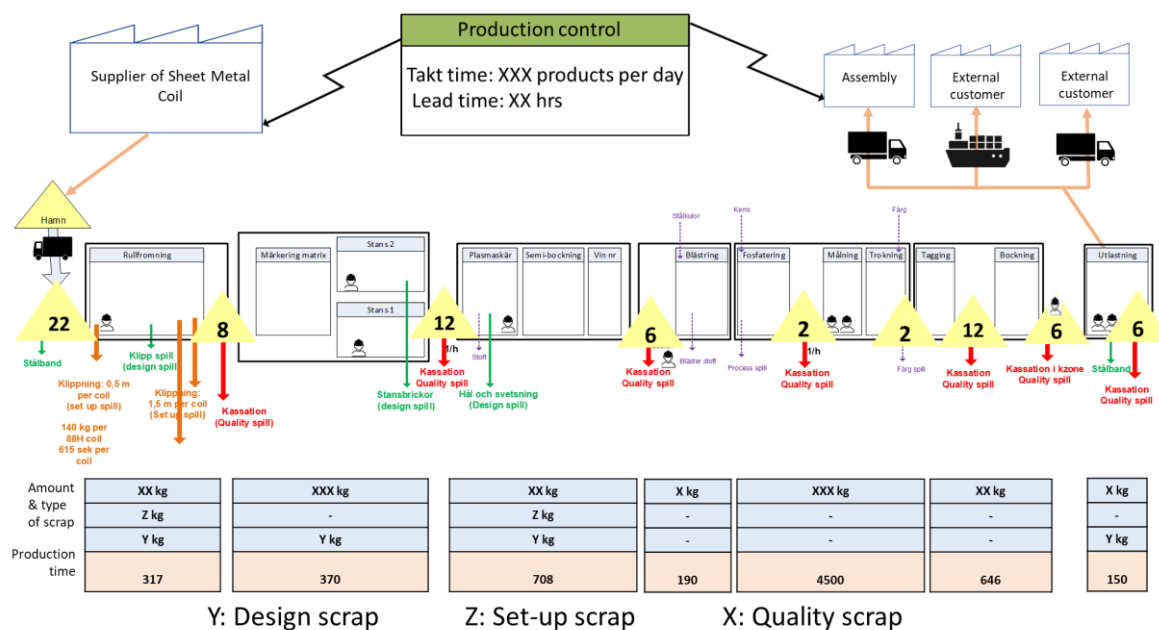


Figure 3. Value Stream Map performed in this study for the productive material. This figure does not intend to present why or how much scrap generated, but to present a schematic overview of EVSM for metal scrap generation.

Design scrap (Y) included designed waste material that is inevitable to avoid, such as holes from a punching machine to fulfill design requirements. Set-up scrap (Z) included scrap due to the machine's set-up or manufacturing processes (technology). Some examples are scrap from a plasma-cutting machine or a from steel-forming machine during the first round of changing the product's specifications to fulfill the process capability. Quality scrap (X) included all scrap due to quality failures, insufficient inspections and human errors. The EVSM also provided a flow analysis with lead time and buffer sizes.

4.3. Waste Flow Mapping

WFM was performed according to Kurdve et al. [21] to study different waste and material flows, with focus on the metal segment. In addition to data from internal waste management, waste management entrepreneurs, quality, maintenance and purchasing systems, data from 2015 and 2016 were also included to analyze an overview of the operation, scrap generation rate, bins and their contents. The process was divided into the same sub-processes as EVSM and GPM. An eco-map was created to understand the machinery, equipment and production flow as well as to localize the different types of waste bins (Figure 4). In addition, bins and containers contents were inspected and analyzed in terms of amount and sorting degree, while quality scrap generation points received extra analysis. Root cause analysis was then performed for the major scrap sources. Moreover, the transportation infrastructure was investigated and waste handling losses were found.

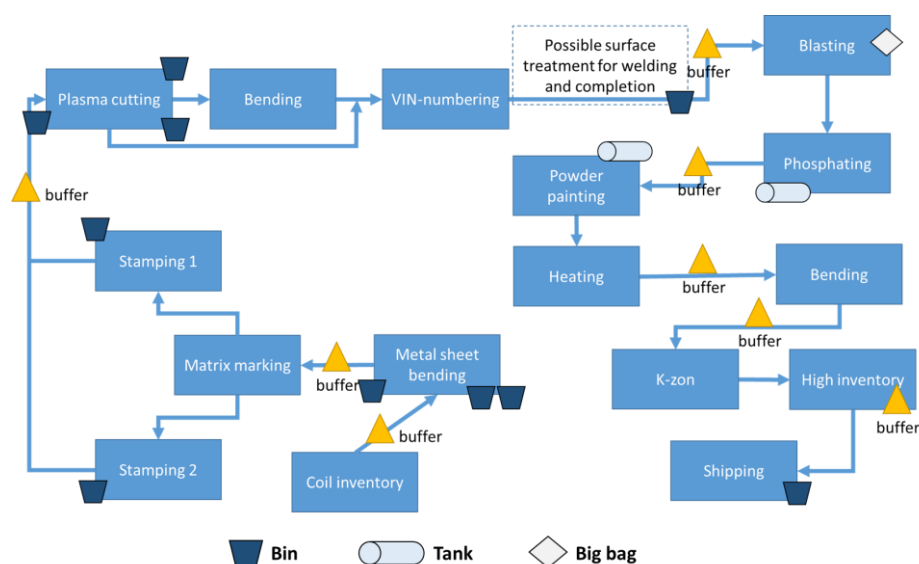


Figure 4. A schematic eco-map overview of the process. This figure only intends to present a schematic overview eco-map.

4.4. Life Cycle Assessment

A screening LCA was conducted for the entire vehicle frame manufacturing process with focus on impacts from the use of materials, energy, water, waste and hazardous materials. The screening LCA involved only the core data on the manufacturing process. Material composition and assumptions about the included phases of the life cycle are specified, but generic datasets from databases were used for all background data. While the LCA consisted of the required four stages: (1) goal and scope, (2) data inventory, (3) impact assessment, and (4) interpretation, the execution was modified from ISO 14044 [54] to benefit from joint data collection. Hence, the first two stages, i.e., goal and scope and data inventory, were performed using previously collected data from GPM, EVSM and WFM. Then additional data were collected to achieve a holistic scope of the environmental aspects. In the interpretation stage, results from other tools were also included to have a system perspective.

Figure 5 depicts the scope of the performed LCA for one vehicle frame, where the functional unit was “one vehicle frame”. The system boundary includes the input material production (cradle) as well as the vehicle frame production and waste handling at the factory (gate). In coherence with the general rules of the EPD system [55], a cut off is done for recycled waste, i.e., the recycled waste belongs to the next product system. This practice allows to add product life cycles without double-counting emissions and resources. Internal and external transportation shown by arrows was included based on the availability of data. The product owner was involved in the interpretation stage but to a lesser degree than usual, instead operational practitioners reviewed the results and supported the interpretation.

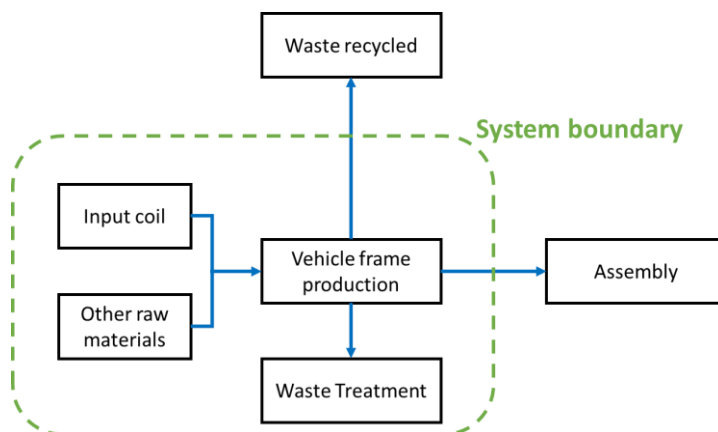


Figure 5. System boundary of performed LCA on the process in this study.

4.5. Comparison on Tool Deployment

Comparing the experience of using the tools, Table 2 shows overlaps and differences in several features. LCA differs the most from the other tools, since (1) it is traditionally focused on products (instead of processes), (2) it usually includes a broader scope of environmental aspects and therefore requires more time, (3) it requires more expertise and knowledge, (4) it is less associated with operational management and lean principles such as go-to-gemba, and (5) it requires specialized software and supporting databases. The overlapping features mainly include: (1) using quantitative and qualitative data (2) visualizing the environmental issues of concern on the same level, (3) including the entire process, although GPM can be used even at the cell or sub-process level, and (4) being based on a handbook or a guide to application.

GPM and LCA can focus on all environmental aspects and costs associated with them, whereas WFM concentrates only on waste and material flows. EVSM can consider various environmental aspects; however, our experience showed that it was cumbersome and confusing to consider more than one at the time. In terms of material and waste flows, EVSM did not include an end-of-life scenario i.e., how waste is treated afterwards such as recycling, reuse, and remanufacturing.

Comparing the tools in term of visualization, EVSM and WFM integrate the manufacturing process with environmental aspects for a better understanding, whereas GPM includes an input-output visualized model and LCA shows the environmental impacts at the site level. Some level of expertise was needed for all the tools, although this was much higher for LCA. Furthermore, fewer resources, including time, man-hours and expertise were required to carry out GPM, EVSM and WFM compared to LCA, i.e., the former tools required a workshop leader and several hours of practice to understand data collection and analytical methods. GPM was more dependent on operators' participation and shop floor walkthroughs than the other tools, even though walkthroughs (go-to-gemba) are essential for EVSM and WFM, but unnecessary for LCA. GPM, EVSM and WFM in addition to go-to-gemba, engage management and employees on daily continuous improvement (Kaizen) of the problem while LCA does not. Using GPM, EVSM and WFM for environmental sustainability improvements in

manufacturing is more in harmony with lean principles than LCA, but those do not result in a holistic product/process view.

In addition, there is a potential risk that if the GPM, EVSM and WFM tools are not supported with an impact assessment when selecting or prioritizing environmental aspects, then the improvement actions will not be focused on the most important matters. It is vital to match the complexity of a given problem with the precision and completeness of a method or tool.

5. Case Results and Discussion

This section reports and discussed empirical results achieved applying the tools in practice with regards to our case study focus: Material efficiency and metal scrap generation. Therefore, this section presents results we achieved using each tool to answer case study questions including which sub-process has the largest environmental impact? How much scrap is generated in this process and the respective sub-processes and why? And what improvements can be made to move towards circularity, decreasing scrap generation and environmental impact?

5.1. Green Performance Map

Analyzing the production process using GPM, helped to identifying different types of environmental aspects and their relative importance based on the company's operational and environmental goals, in both the overall process and detailed sub-process levels. Focusing on only one level would have caused neglecting some environmental aspects. The results suggested five areas to start with improvement actions (labelled with red tags):

- 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 five areas, GPM identified other environmental aspects with less critical impact (labelled with yellow tags), such as waste of painting powder, incorrect sorting, packaging issues, health and safety risk issues, and waste of consumable equipment (e.g., safety gloves and glasses). At the overall operation process level—from coil to shipping to customer—detailed quantitative data on scrap generation could be obtained, but quantitative data related to noise and material consumption remained unobtainable. At the sub-process level, it was even more difficult to obtain quantitative data, for example on material consumption and waste generation, energy consumption and noise made.

According to the GPMs performed on a sub-process level, metal sheet bending and plasma cutting produce the most scrap. This was based on a qualitative speculation, because it was challenging to use GPM for collecting quantitative data on the number of scrapped frames and their environmental impacts. Therefore, the qualitative speculation on the most scrap generation sub-processes turned out to be not entirely correct. It became clear later (via using EVSM) that GPM did not correctly prioritize punching machines as the most scrap generating sub-process (however plasma cutting and metal sheet bending are the third and fourth most scrap generating sub-processes) and did not locate the root cause of scrap generation; for example, scraps generated due to quality failure in surface treatment were identified in the shipping stage, meaning that a pair of vehicle frames that should have been scrapped after the surface treatment, had gone through all the other processes wasting energy and materials as well as production time. Nevertheless, GPM engaged personnel in improvement actions.

5.2. Environmental Value Stream Mapping

Visualizing different material flows on EVSM and then adding energy made the EVSM complicated; therefore, only metal scrap flows were taken into consideration in this tool. However, energy statistics were collected using energy mapping tools. From an environmental perspective with focus on one

aspect—scrap generation—, EVSM helped to understand the type, volume and reasons for scrap generation in each sub-process, i.e., localization (where), quantification (how much), categorization to quality, set up or design scrap (why). This provided a good starting point for improvement measures. The results further determined that quality scrap should be prioritized as it had the highest scrap generation proportion and associated cost; almost all sub-processes generate quality scrap. The most quality scraps were generated by the punching machines (27%), followed by surface treatment (22%), plasma cutting (19%), and metal sheet forming (17%). Surface treatment included blasting, phosphating, painting and paint curing oven. Reasons for scrap generation within these operations were identified afterwards, e.g., half of the frames scrapped after surface treatment had paint lumps. Although the focus was on material, the investigation showed that surface treatment consumes one-third of total plant energy consumption. In addition to environmental data, EVSM also showed traditional production-related data such as takt time, lead time, first time through (95% with 3.5% product reworked and 1.5% scrap) and overall equipment effectiveness (OEE). The process has a high OEE (~80%), however it is expected for such a semi-automated, low-complexity and high-volume process.

5.3. Waste Flow Mapping

To a large extent, the results achieved by WFM overlapped with those from GPM and EVSM, particularly concerning scrap volumes and waste handling at each sub-process. However, WFM also analyzed inefficiencies in waste management and transportation. It indicated a high degree of waste-sorting with an average of 88%, with improvement potential to 95%. Moreover, metal scraps are sent (with lower revenue) to open-loop recycling, resulting in a 100% recycling rate. Figure 6 illustrates the waste-sorting analyses. The pie chart shows the waste segments produced in the studied process with their respective percentages. Data for scrap generation and production rate during the period between 2015 and 2016 were used to estimate the volumes and analyze the root cause. The calculated scrap generation rate is shown in Table 3.

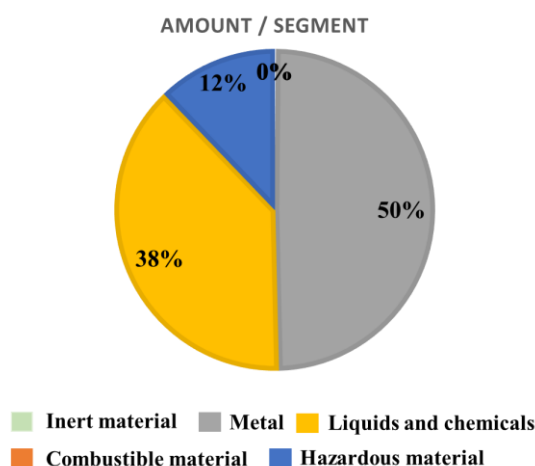


Figure 6. Waste-sorting analyses performed via WFM.

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 mixed metals bins. Other scrap metal collection points contained obsolete material, scrapped equipment and construction material. The metal scraps are transported to the environmental zone by two internal forklifts (one large and one regular), and then from there external transport of scraps is performed on demand every other day by the waste management entrepreneur. Shipping containers off-site typically use half of the maximum load of the truck. It is estimated that the forklifts are used two to three hours per week for waste management purposes. With 144 h of operating time per week, the relative cost is estimated to be 2%

of the annual investment, plus 3 h/week of operator time. The average load of trucks is low, especially for one type of cutting (3.9 tons/truck load). Hazardous material is also internally transported by a forklift to the environmental zone, and phosphating baths are collected in tanks and emptied by pipes to tank truck transport. Some fraction required expensive handling vehicles on site i.e., a suction tank and crane trucks.

Table 3. Metal 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%

5.4. Life Cycle Assessment

LCA used previously collected data via the other tools and complemented them with additional data mainly from environmental data systems. Simapro software and the Ecoinvent database were used to analyze and quantify different environmental aspects including climate impact, eutrophication, acidification and smog. Figure 7 illustrates the climate impacts of the studied 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 CO₂ equivalents are given. As shown in Figure 7, the production phase of steels coil (raw material) has the greatest climate impact. However, concentrating on the manufacturing phase only (vehicle frame production), quality scrap generation has the greatest environmental impact. For instance, both design scrap and quality scrap have greater climate impacts than production of the coating powder. The set-up scrap has slightly lower climate impacts than coating powder production. Energy use during production has a slightly lower climate impact than inbound steel transportation. Conclusions above are consistent for other impact categories of ground-level ozone, acidification and eutrophication.

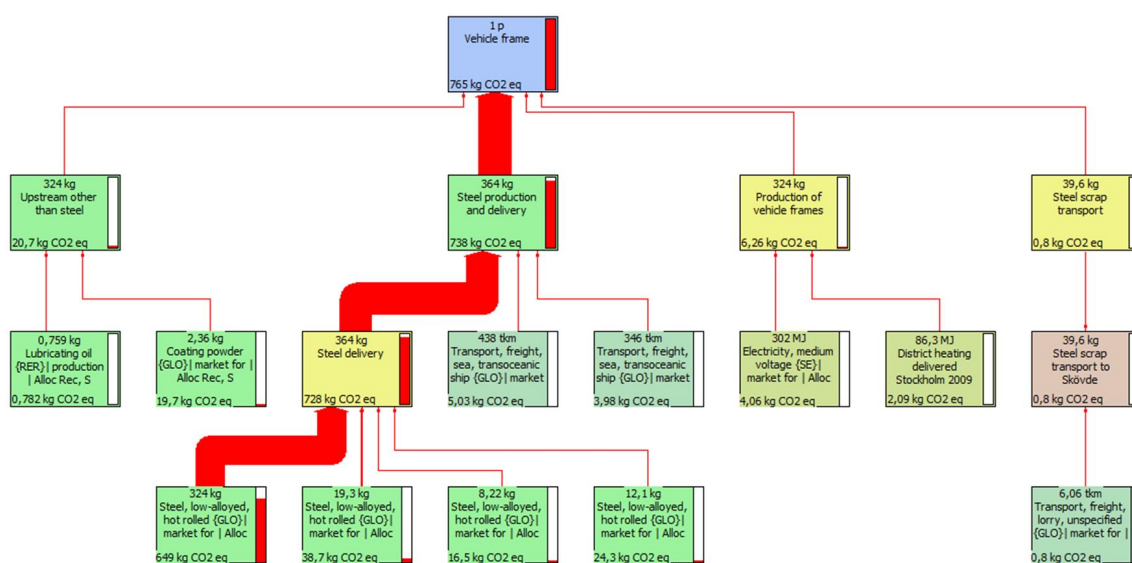


Figure 7. Climate impacts for a frame from cradle to gate.

5.5. Cross Comparison

Comparing the empirical results achieved by applying the tools in practice with regard to our case study focus—material efficiency and metal scrap generation— indicates differences between the tools in both system boundaries (how much of the production system was considered) and which impact category/-ies was/were considered. For example, with regards to transportation: LCA includes transportation and the associated impacts from all operations within the scope; the WFM includes waste management transportation but not inbound material; and GPM and EVSM can include transportation if it is included as an operation in the process or as an environmental aspect. With regard to the impact category, WFM focuses on waste and material flows; LCA and GPM handle many different impact categories; EVSM considers various environmental aspects, but our experience showed that it was cumbersome and confusing to do so while collecting and analyzing data. In addition, EVSM did not include an end-of-life scenario, i.e., how waste is treated afterwards, such as recycling, reuse, and remanufacturing, which directly correlates to environmental impact. Therefore, our experience concludes that with GPM and LCA, different environmental impact categories can be studied, whereas WFM focuses on one impact category (waste), and with EVSM, it is better to focus on one impact category at a time.

As mentioned earlier, this paper does not intend to select one tool as superior to the others. The results suggest that there is no such thing as “one right tool”. Instead, we advocate using a combination of tools, each of which has different strengths and weaknesses, include different types of data collection and analysis, and different information on environmental impacts. Combining tools can lead to better prioritization, decision-making and increased engagement. Based on the predetermined improvement goal, one tool per se might not deliver the desired outcome. Thus, combinations of tools that support each other should be considered e.g., the overall GPM for the entire vehicle frame operation could have been quantified and together with a screening LCA could be used to verify and prioritize the most significant environmental impacts and engage personnel in improvement actions on the shop floor. Because EVSM and WFM were the only methods capable of identifying the root cause of quality scrap generation, one of these methods was necessary for our particular case study. Figure 8 illustrates the integration of environmental assessment tools discussed in this paper, based on four stages of LCA.

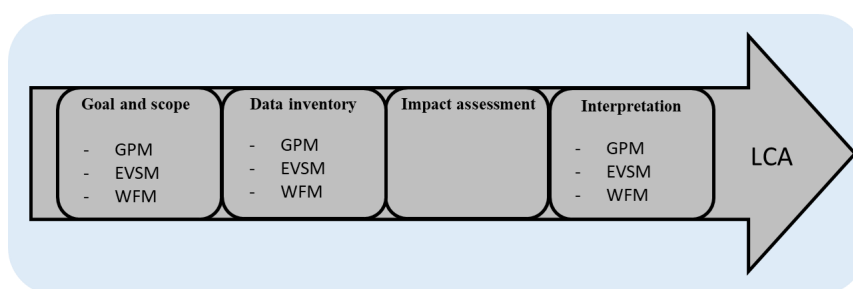


Figure 8. Integration of environmental assessment tools.

Stepping outside the system boundary, a limited LCA investigation focusing on alternatives to the current steel scrap recycling was conducted. Most of the generated scrap is currently transported 165 km for cast iron foundry. 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 CO₂ (see Figure 9), whereas it is 0.8 kg CO₂ for transport to foundry. This can be compared to the climate cost of the ferro-nickel alloy in 39.6 kg of product scrap which is 9.65 kg CO₂. This is significantly greater than the climate cost of extra transport to the steel supplier. Nevertheless, the generic dataset used to model the steel does not exactly match the actual steel quality, so this potential improvement action must be confirmed with actual steel qualities.

Table 4 provides answers to the question posed by the company in this study.

Table 4. Main answers of the industrial questions posed in the case study.

Focus of the Case Study	GPM	EVSM	WFM	LCA
Which sub-process has the most environmental impact?	GPM pinpointed several environmental aspects e.g., scrap generation in metal sheet bending, plasma cutting and k-zone; high energy consumption at hydraulic systems and a pneumatic truck in metal sheet bending; high energy consumption at heat treatment; hazardous ash from blasting and plasma cutting; water waste and chemicals generated from phosphating; and other sustainability issues such as safety risks in surface treatment and high noises from punching machines. However, it was challenging to quantify the environmental aspects and correlating impact.	EVSM concluded that the punching machines produces the greatest number of quality scraps and was thus the most important environmental aspect. However, due to complexity, EVSM did not consider environmental aspects such as noise and water and energy consumption.	According to the WFM, the most scraps are generated from punching machines, plasma cutting, surface treatment, and metal sheet forming. However, quality scraps from the punching machines had the greatest environmental impact. In addition to scrap generation, environmental aspects such as waste segregation, transportation and hazardousness were considered. For instance, 38% of process fluids waste from surface treatment are sent to destruction, which indicates that this process has large environmental impacts and costs.	According to the LCA, from a product life cycle perspective, it was found that steel coil production has by far the greatest environmental impacts (climate impact, eutrophication, acidification and smog). Therefore, scrap generation during production is of large importance. Furthermore, quality and design scraps have greater environmental impacts than energy use in the plant.
How much scrap is generated in the vehicle frame production process and in the respective sub-processes and why?	Metal sheet bending, plasma cutting and k-zone produced the most scrap. However, it was challenging to collect quantitative data and determine environmental impacts, and therefore GPM did not correctly prioritize punching machines. GPM also failed to localize the root cause scrap generation points.	The most scraps are generated from punching machine plasma cutting, surface treatment, and metal sheet forming. EVSM localized and quantified scrap generation throughout the process and identified the reason for the scrap generation at sub-process level.	WFM identified that quality scrap from the punching machine has the greatest environmental aspect. The proportion of scrap generation compared to production was also calculated.	Data on all major waste flows were quantified with LCA; first for the whole process output and then based on their relative impact, improvement potentials are sought. It is not unusual to identify hitherto unknown flows during LCA since mass balances are often used to check inputs with outputs.
What improvements can be made to move towards circularity, decreasing scrap generation and environmental impact?	GPM identified various environmental aspects and pinpointed their origin in the process but not specifically suggest any improvement.	Quality scrap should be improved with a better inspection and logging system.	Waste segregation potentials should be improved.	The comprehensive LCA could find and prioritize the greatest environmental aspects based on their relative environmental impact. The improvement potential for improved metal recycling could also be quantified but a detailed inventory of the process and sub-processes is needed to point out specific process steps to be modified for better material efficiency.

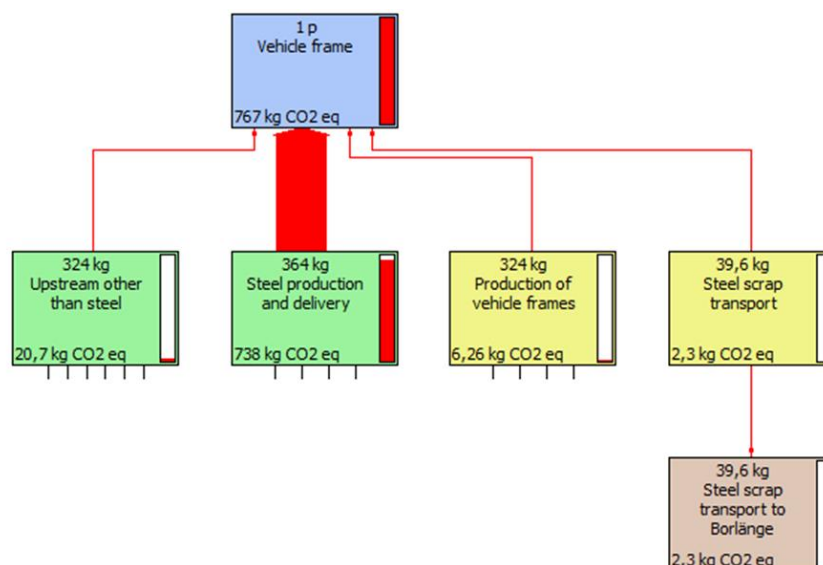


Figure 9. Climate impacts for a frame from cradle to gate for scrap transport to a steel supplier.

6. Conclusions

Previous studies have shown that there is an insufficient use of practical tools and methods on the manufacturing shop floor for regular environmental performance assessment and improvement. Recent studies have shown that the green lean concept has begun to address this gap. Therefore, in this paper, four common environmental assessment tools used in Swedish manufacturing industry –GPM, EVSM, WFM and LCA–were used to assess the environmental aspects of a vehicle frame production process but with a focus on material efficiency and metal scrap generation. These tools were compared in terms of use experience and features as well as results achieved to fulfill the objectives of this study: To help practitioners and scholars to understand the different features of each tool, so in turn, the right tool(s) can be selected according to particular questions and the industrial settings. Although this paper focused on material efficiency and metal scrap generation, other environmental aspects such as energy use, material consumption and chemicals (hazardousness) were also considered when applied the tools.

A literature review revealed that a tool benefits from the following essential features to enable environmental improvements in manufacturing:

- Being hands-on and operational, supporting collaboration and understanding between different internal and external actors;
- Being easy to learn and implement, visualization, time efficiency, continuous improvement and engagement;
- Including root cause analysis, being harmonized with ISO 14001 and supporting the go-to-gemba concept;
- Being goal-oriented, supporting measurements, and being focused on a limited area of influence while supporting systematic work procedures (standardized work)

The results of deploying the selected tools in terms of use experience and feature comparison on the same manufacturing process are presented in Table 2. The tools are compared in different features such as result type, operation level (site, process, cell), resource type, time required for data collection and analysis, end-of-life scenario, software demand (price), visualization type, guidance documents, ease of learning (knowledge requirements and days), and go-to-gemba.

Table 4 presents the application of these tools in a real-time industrial case study with focus on material efficiency and metal scrap generation. According to the results, the tools have overlaps and differences. Each tool has strengths and weaknesses that depend on variables such as the

question posed, expected results, the level of evaluation (site, process or cell), and the accessibility of data. GPM can effectively generate an input-output model, providing a visual overview of environmental problems; EVSM shows selected environmental aspects alongside production-related data and information flows, which enhances understanding; WFM provides a detailed analysis of material and waste flows along the waste management supply chain; LCA can help understand the degree of environmental impact associated with different environmental aspects and therefore is essential for correct prioritization and to avoid sub-optimization. It is also concluded that data collection for the various tools can be performed at the same time, allowing for parallel application of more than one tool with minimal extra time and resource efforts. Combining tools in this way can provide a superior answer to a specific question and better guide and prioritization of shop floor solutions.

The results indicate that there is no such thing as “one right tool” superior to others. Rather, a combination of tools is suggested for different types of data and analysis, and to assess various environmental impacts, which results in better prioritization and decision-making and increasing the effectiveness and efficiency of the operation, environmental performance and the value stream in terms of lean and green. Future research might deploy the tools at more manufacturers with different variables relating to, for example, company size, industry type, product type, and auxiliary and residual material types. Future research can also include SMEs which generally have fewer resources to monitor environmental issues. Additionally, the case study focus was carried out at a company using metal as a primary product material. Future research could replicate this research in other industries that use different primary product materials, such as plastics.

Supplementary Materials: A deeper description of each tool is available online at <http://www.mdpi.com/2071-1050/11/7/2173/s1>.

Author Contributions: The authors contributed in this article as following, conceptualization and methodology, C.J., M.K., M.Z., S.S., investigation, M.K., M.Z., S.S. formal analysis A.R.K., C.J., M.K., M.Z., S.S., validation S.S., M.K., M.Z., discussion and concluding A.R.K., C.J., M.K., M.Z., S.S.

Funding: This research was funded by Mistra Closing the loop II and XPRES.

Acknowledgments: This article is connected to the research project CiMMRec (Circular Models for mixed and Multi material Recycling in Manufacturing extended Loops). The authors acknowledge the funding received for the project from Mistra Closing the loop II and XPRES.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Garetti, M.; Taisch, M. Sustainable manufacturing: Trends and research challenges. *Prod. Plan. Control* **2011**, *23*, 83–104.
2. Veleva, V.; Bailey, J.; Jurczyk, N. Using sustainable production indicators to measure progress in ISO 14001, EHS System and EPA achievement track. *Corp. Environ. Strat.* **2001**, *8*, 326–338.
3. IISD, International Institute for Sustainable Development. *Business Strategies for Sustainable Development*; The International Institute for Sustainable Development in conjunction with Deloitte & Touche and the World Business Council for Sustainable Development: Winnipeg, MB, Canada, 1992.
4. Smith, L.; Ball, P. Steps towards sustainable manufacturing through modelling material, energy and waste flows. *Int. J. Prod. Econ.* **2012**, *140*, 227–238.
5. Bey, N.; Hauschild, M.Z.; Mcaloone, T.C. Drivers and barriers for implementation of environmental strategies in manufacturing companies. *CIRP Ann. Manuf. Technol.* **2013**, *62*, 43–46.
6. Kurdve, M.; Zackrisson, M.; Wiktorsson, M.; Harlin, U. Lean and green integration into production system models – experiences from Swedish industry. *J. Clean. Prod.* **2014**, *85*, 180–190.
7. Zokaei, K.; Lovins, H.; Wood, A.; Hines, P. *Creating a Lean and Green Business System: Techniques for Improving Profits and Sustainability*; CRC Press, Taylor and Francis Group: London, UK, 2013.
8. Noren, G.; Strömdahl, I. *Näringslivets miljöarbete och Sveriges miljömål*; SvensktNäringsliv: Stockholm, Sweden, 2007.

9. Shahbazi, S. Material Efficiency Management in Manufacturing. Licentiate Thesis, Mälardalen University, Västerås, Sweden, 2015.
10. Cherrafi, A.; Elfezazi, S.; Govindan, K.; Garza-Reyes, J.A.; Benhida, K.; Mokhlis, A. A framework for the integration of Green and Lean Six Sigma for superior sustainability performance. *Int. J. Prod. Res.* **2017**, *55*, 4481–4515.
11. Dües, C.M.; Tan, K.H.; Lim, M. Green as the new Lean: How to use Lean practices as a catalyst to greening your supply chain. *J. Clean. Prod.* **2013**, *40*, 93–100.
12. Shahbazi, S.; Wiktorsson, M.; Kurdve, M.; Jönsson, C.; Bjelkemyr, M. Material efficiency in manufacturing: Swedish evidence on potential, barriers and strategies. *J. Clean. Prod.* **2016**, *127*, 438–450.
13. Lindahl, M. Engineering Designers' Requirements on Design for Environment Methods and Tools. Ph.D. Thesis, KTH, Stockholm, Sweden, 2005.
14. Bergendahl, M.N. Stödmeter och samverkan i produktutveckling (Supporting Methods and Collaboration in Product Development). Ph.D. Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 1992.
15. Jönbrink, A.K.; Kristinsdóttir, A.R.; Roos, S.; Sundgren, M.; Johansson, E.; Nyström, B.; Nayström, P. Why use ecodesign in the industry 2013? A Survey regarding barriers and opportunities related to ecodesign. In Proceedings of the EcoDesign 2013 International Symposium, Tokyo, Japan, 4–6 December 2013.
16. Ellinger, A.E.; Daugherty, P.J.; Keller, S.B. The relationship between marketing/logistics interdepartmental integration and performance in US manufacturing firms: An empirical study. *J. Bus. Logist.* **2000**, *21*, 1–22.
17. Iranmanesh, M.; Zailani, S.; Hyun, S.S.; Ali, M.H.; Kim, K. Impact of Lean Manufacturing Practices on Firms' Sustainable Performance: Lean Culture as a Moderator. *Sustainability* **2019**, *11*, 1112.
18. Wu, L.; Subramanian, N.; Abdulrahman, M.D.; Liu, C.; Lai, K.-H.; Pawar, K.S. The Impact of Integrated Practices of Lean, Green, and Social Management Systems on Firm Sustainability Performance—Evidence from Chinese Fashion Auto-Parts Suppliers. *Sustainability* **2015**, *7*, 3838–3858.
19. Mollenkopf, D.; Stolze, H.; Wendy, H.T.; Ueltschy, M. Green, lean, and global supply chains. *Int. J. Phys. Dist. Logist. Manag.* **2010**, *40*, 14–41.
20. Garza-Reyes, J.A. Lean and green—A systematic review of the state of the art literature. *J. Clean. Prod.* **2015**, *102*, 18–29.
21. Kurdve, M.; Shahbazi, S.; Wendin, M.; Bengtsson, C.; Wiktorsson, M. Waste flow mapping to improve sustainability of waste management: A case study approach. *J. Clean. Prod.* **2015**, *98*, 304–315.
22. Zackrisson, M.; Avellán, L.; Orlenius, J. Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles—Critical issues. *J. Clean. Prod.* **2014**, *18*, 1519–1529.
23. Shahbazi, S.; Wiktorsson, M. Using the Green Performance Map: Towards material efficiency measurement. In Proceedings of the 23th EurOMA Conference, Trondheim, Norway, 17–22 June 2016.
24. Kurdve, M.; Wiktorsson, M. *Green Performance Map: Visualizing Environmental KPI's*; European Operations Management Association (EurOMA): Dublin, Ireland, 2013.
25. Baumgartner, R.J. Managing Corporate Sustainability and CSR: A Conceptual Framework Combining Values, Strategies and Instruments Contributing to Sustainable Development. *Corporate Soc. Responsib. Environ. Manag.* **2014**, *21*, 258–271.
26. Simpson, D.F.; Power, D.J. Use the supply relationship to develop lean and green suppliers. *Supply Chain Manag. Int. J.* **2005**, *10*, 60–68.
27. Vachon, S.; Klassen, R.D. Environmental management and manufacturing performance: The role of collaboration in the supply chain. *Int. J. Prod. Econ.* **2008**, *111*, 299–315.
28. Faulkner, W.; Badurdeen, F. Sustainable Value Stream Mapping (Sus-VSM): Methodology to visualize and assess manufacturing sustainability performance. *J. Clean. Prod.* **2014**, *85*, 8–18.
29. Benn, S.; TEO, S.T.T.; Martin, A. Employee participation and engagement in working for the environment. *Pers. Rev.* **2015**, *44*, 492–510.
30. Banawi, A.; Bilec, M.M. A framework to improve construction processes: Integrating Lean, Green and Six Sigma. *Int. J. Constr. Manag.* **2014**, *14*, 45–55.
31. Souza, J.P.E.; Alves, J.M. Lean-integrated management system: A model for sustainability improvement. *J. Clean. Prod.* **2018**, *172*, 2667–2682.
32. Puvanasvaran, P.; Tian, R.K.S.; Suresh, V.; Muhamad, M. Lean principles adoption in environmental management system (EMS)-ISO 14001. *J. Ind. Eng. Manag.* **2012**, *5*, 406–430.

33. Seth, D.; Seth, N.; Dhariwal, P. Application of value stream mapping (VSM) for lean and cycle time reduction in complex production environments: A case study. *Prod. Plan. Control* **2017**, *28*, 398–419.
34. Ruben, B.; Viondh, S.; Asokan, P. State of art perspectives of lean and sustainable manufacturing. *Int. J. Lean Six Sigma* **2018**, *10*, 234–256.
35. Míkva, M.; Prajová, V.; Yakimovich, B.; Korshunov, A.; Tyurin, I. Standardization—One of the Tools of Continuous Improvement. *Procedia Eng.* **2016**, *149*, 329–332.
36. Bellgran, M.; Höckerdal, K.; Kurdve, M.; Wiktorsson, M. *Green Performance Map—Handbook*; Mälardalen University: Eskilstuna, Sweden, 2012.
37. Kurdve, M.; Hanarp, P.; Chen, X.; Qiu, X.; Zhang, Y.; Stahre, J.; Laring, J. *Use of Environmental Value Stream Mapping and Environmental Loss Analysis in Lean Manufacturing Work at Volvo*; Swedish Production Symposium, SPS11; Swedish Production Symposium: Lund, Sweden, 2011.
38. Pampanelli, A.B.; Found, P.; Bernardes, A.M. A Lean & Green Model for a production cell. *J. Clean. Prod.* **2014**, *85*, 19–30.
39. Sawhney, R.; Teparakul, P.; Bagchi, A.; Li, X. En-Lean: A framework to align lean and green manufacturing in the metal cutting supply chain. *Int. J. Enterprise Netw. Manag.* **2007**, *1*, 238–260.
40. EPA. Lean and Clean Value Stream Mapping. 2015. Available online: www.epa.gov/e3 (accessed on 15 December 2018).
41. Torres, A.S.; Gati, A.M. Environmental Value Stream Mapping (EVSM) as sustainability management tool. In Proceedings of the Portland International Conference on Management of Engineering Technology, PICMET 2009, Portland, OR, USA, 2–6 August 2009; pp. 1689–1698.
42. Müller, E.; Schillig, R.; Stock, T.; Schmeiler, M. Improvement of Injection Moulding Processes by Using Dual Energy Signatures. *Procedia CIRP* **2014**, *17*, 704–709.
43. Posselt, G.; Fischer, J.; Heinemann, T.; Thiede, S.; Alvandi, S.; Weinert, N.; Kara, S.; Herrmann, C. Extending Energy Value Stream Models by the TBS Dimension—Applied on a Multi Product Process Chain in the Railway Industry. *Procedia CIRP* **2014**, *15*, 80–85.
44. Gunduz, M.; Fahmi Naser, A. Cost Based Value Stream Mapping as a Sustainable Construction Tool for Underground Pipeline Construction Projects. *Sustainability* **2017**, *9*, 2184.
45. Dadashzadeh, M.D.; Wharton, T.J. A value stream approach for greening the IT department. *Int. J. Manag. Inf. Syst.* **2012**, *16*, 12. [[CrossRef](#)]
46. Engel, H.W. *Ecomapping—A Visual, Simple and Practical Tool to Analyse and Manage the Environmental Performance of Small Companies and Craft Industries*; EcoMapping Network: Brussels, Belgium, 2002.
47. Hogland, W.; Stenlis, J. Assessment and system analysis of industrial waste management. *Waste Manag.* **2000**, *20*, 537–543.
48. Muther, R.; Haganas, K. *Systematic Handling Analysis*; Management and Industrial Research Publications: Kansas City, MO, USA, 2002.
49. Cheung, W.M.; Leong, J.T.; Vichare, P. Incorporating lean thinking and life cycle assessment to reduce environmental impacts of plastic injection moulded products. *J. Clean. Prod.* **2017**, *167*, 759–775.
50. Zhang, H.; Haapala, K.R. Integrating sustainable manufacturing assessment into decision making for a production work cell. *J. Clean. Prod.* **2015**, *105*, 52–63.
51. Thammaraksa, C.; Wattanawan, A.; Prapasongsa, T. Corporate environmental assessment of a large jewelry company: From a life cycle assessment to green industry. *J. Clean. Prod.* **2017**, *164*, 485–494.
52. Yin, R.K. *Case Study Research: Design and Methods*, 5th ed.; SAGE Publications, Inc.: London, UK, 2010.
53. Saunders, M.; Lewis, P.; Thornhill, A. *Research Methods for Business Students*; Financial Times Prentice Hall: Upper Saddle River, NJ, USA, 2009.
54. ISO 14044. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; International Organization for Standardization: Geneva, Switzerland, 2006.
55. EPD®, General programme instructions for the international epd® system. Version 3.0. 2017-12-11. Stockholm, Sweden, 2017.

