Article

A Lean Approach to Developing Sustainable Supply Chains

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Abstract: Corporations and their supply chains have to go through significant changes to become more sustainable as society is pressing for sustainable systems. To this end, it is critical to develop new methodologies to trim away processes and activities that add no value and, thus, derive more sustainable supply chains. Considering the need to have a simple tool that can be used by managers to achieve this goal, in this work, we explore the value stream mapping method (VSM) and extend it to support the design of sustainable supply chains in a more systematic and quantitative way. This work proposes a new generic methodology, called SustainSC-VSM, which allows assessing the supply chain's performance through a set of realistic indicators. These indicators are designed to identify bottlenecks that hinder sustainable operations development and provide guidelines to achieve that goal by following a lean-driven sustainability approach. SustainSC-VSM was tested and validated through its application to a relevant industrial case study, where operational bottlenecks were pinpointed and potential solutions were identified to seek continuous improvement. Although envisioned to be generic and applicable to all supply chains, the indicators should be selected according to the context in study (e.g., services). SustainSC-VSM aims at being a generic and systematic tool to design future value stream maps to achieve a more sustainable supply chain following a lean-driven sustainability approach, through the use of multi-dimensional and multi-disciplinary indicators to identify and solve the supply chain's bottlenecks.

Keywords: supply chain; value stream mapping; sustainability; lean

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1. Introduction

Worldwide stressors, such as climate change and a consciousness of social and environmental responsibilities, along with stronger competition and lower profit margins, have been forcing companies to vigorously act to maintain their competitiveness and to commit to sustainable practices and performance management [1,2]. Both academics and industries are motivated to find the best way to simultaneously include all three aspects of sustainability (economic, environmental and social) to achieve meaningful and beneficial results. Lean management has proven to be a handy and innovative tool to promote continuous improvement, and to be easily adaptable to include sustainability aspects [1]. It is an evolving methodology that targets the highest quality, profitability and customer service level, at the lowest possible costs, in a prompt fashion, through the continuous reduction in waste regarding value-added and non-value-added operations [3]. The unavoidable effect of evolving drivers over the years, such as expanded business networks and customer needs and demands, has motivated the change in focus to the supply chain management level [1,4–6]. “(SCM) encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and logistics management activities” [7]. Lean management has been broadened to include all the actors of the supply chain. In this context, Vonderembse et al. [8] described “lean supply chain” as the “continuous improvement of efforts that target the reduction of waste and non-value-added activities along

the value chain.” Thus, from the sustainability angle, it has been proven that it is impossible to observe environmental and social policies and preserve competitiveness without collaboration among supply chain actors [1,9]. Due to the ongoing interest and need to implement corporate environmental and social policies, combining lean management and sustainability has become more popular. An increasing number of studies have proven that there are clear positive impacts (economic, environmental and social) on the supply chain performance when lean is linked to sustainability [10]. Intensive research has been conducted on the interaction and the pursuit of sustainability, application of lean management and supply chain management practices. Since one of the lean operational goals is to keep or improve the production quality but reduce the use of resources, lean principles lead to more environmentally friendly operations due to lower waste produced and thus lower environmental impact. By reducing the quantity of materials used, the costs are also reduced, and therefore sustainability’s economic facet is likewise addressed. Increasing quality and efficiency leads to water and energy consumption improvements, which also gets reflected in the costs. Henceforth, by implementing the lean principles, one also achieves the main sustainability goals. More and more research has been suggesting the substantial overlap, similarities and synergies between these two concepts and how to use them [11].

Table 1 summarizes the most relevant and popular lean tools developed over the years that attempt to tackle this issue of combining these two concepts: thriving towards sustainability by applying lean principles. Notwithstanding, and as documented in Table 1, many studies have focused on developing tools that are usually based on qualitative models and, more specifically, operations. Improvements towards sustainable supply chains have not been widely explored in the literature and process bottlenecks have been identified in a qualitative way, which leads to missing some important critical points and misleading actions. There is an overall lack of generic, systematic and quantitative approaches to tackle supply chain bottlenecks and point out ways to overcome these matters towards more sustainable supply chains. Therefore, the following research question (RQ) can be formulated and will be answered by this work:

RQ: How can a value stream mapping (VSM) methodology be extended to sustainable supply chain management analysis, so that bottlenecks can be identified and improved in a systematic, accurate and quantitative way?

Henceforth, this work differs from the previous studies in the field by proposing a new methodology called SustainSC-VSM, whose goal is to systematically combine sustainability, lean philosophy and supply chain management into a holistic, quantitative and qualitative methodology. SustainSC-VSM is a systematic tool that measures the supply chain performance and provides guidelines to attain a more sustainable supply chain following a lean-driven sustainability approach by guiding the manager through the steps needed to trim away processes and operations that add no value to the whole value chain. This work introduces the following novel contributions:

- (i) Proposes a new methodology, which integrates the extended VSM (EVSM) [12] methodology with *SustainPro*’s systematic approach [13];
- (ii) Introduces new multi-disciplinary qualitative and quantitative indicators that represent and analyze all facets of sustainability to measure the supply chain performance;
- (iii) Through the use of indicators, the whole supply chain is assessed in terms of the three pillars of sustainability. The assessment of materials and information flows between the supply chain actors is performed;
- (iv) Identifies, in a quantitative way, the supply chain’s bottlenecks, as well as providing potential solutions, prioritization of actions and recommendations to overcome the identified bottlenecks;
- (v) Facilitates creating future value stream maps to attain a (more) sustainable supply chain.

Table 1. Lean tools and contributions towards sustainable development (SD) in chronological order. Adapted and extended from [1,14].

Tool	References	Brief Description
5S	[15]	<ul style="list-style-type: none"> • Encourages a clean and organized work environment (econ, env, soc) • Reduces health and safety risks and space needed for operations (econ, soc) • Increases job satisfaction rate (soc)
Kaizen	[16]	<ul style="list-style-type: none"> • Finds opportunities for continuous improvement and waste reduction (env, econ) • Reduces environmental impacts and health hazards inside or outside the production boundaries (env)
VSM	[17,18]	<ul style="list-style-type: none"> • Applied at the factory level (operations) • Visual tool to improve information and material flows (econ) • Used to obtain a roadmap for improvement by mapping the current and future value streams (track value-added and non-value-added operations) (econ) • Promotes waste elimination (econ, env) • Helps in tracking and eliminating avoidable and/or unnecessary use of resources (econ, env)
Extended VSM (EVSM)	[12]	<ul style="list-style-type: none"> • Extension of the VSM tool to the supply chain context (see points mentioned in lean tool VSM) (econ, env, soc)
Kanban and Visual Factory	[19]	<ul style="list-style-type: none"> • Deals with excessive inventory (the most prejudicial form of waste) (econ, env) • Enables good flow of information and items along the supply chain—some studies mention that it can augment the consumption of energy and water (econ, env) • Visual factory means the use of codes to promote good communication (econ, env, soc) • Facilitates the reduction in waste and good work environment (econ, env, soc)
Visual Management (Andon)	[20]	<ul style="list-style-type: none"> • Based on feedback alerts to control undesirable situations (econ, env, soc) • It provides real-time communication to avoid the propagation of problems along the value chain—associated with effective reduction in waste of resources (econ, env, soc) • Reduction in environmental waste and hazard (econ, env) • It could be used as alert mechanism for environmental management (env)

Table 1. Cont.

Tool	References	Brief Description
Total Productive Maintenance (TPM)	[21]	<ul style="list-style-type: none"> Aims to decrease cycle times and reduce defected production and health risks by proactive maintenance (econ, env, soc) Targets to increase production efficiency to reduce the amount of resources used and to avoid wastes (econ, env) By applying preventive and proactive maintenance, it increases equipment life span and can be used to detect the need for the improvement of technology (econ, env)
Single Minute Exchange of Dies (SMED)	[22,23]	<ul style="list-style-type: none"> Targets the reduction in changeover times by simplifying operations, reduction in or eradication of redundant tasks and work standardization. Systems become more responsive and with lower inventory levels (econ, env) The goal is to reduce the changeover times to “single” digits (econ, env) Potential reduction in emissions and hazardous chemicals (env) Lower manufacturing costs (less equipment downtime), lower inventory levels and better responsiveness to customer demand (econ, env)
Jidoka (Autonomation)	[24]	<ul style="list-style-type: none"> Investigates abnormality, determines root cause and promotes corrective actions (econ, env) Contributes to economic sustainability and waste reduction by eliminating or reducing labor, material and energy usage (costs) (econ, env) Lower health and safety issues (soc)
Just-in-time (JIT)	[25]	<ul style="list-style-type: none"> Provides reduced inventories, increased liquidity and reduced space requirements (econ, env) Lower inventories decreases the environmental impact and economic sustainability (econ, env)
Sustainable-VSM	[26–29]	<ul style="list-style-type: none"> Based upon the VSM tool, extended to include environmental, social and sustainable manufacturing metrics (econ, env, soc) Used to pinpoint value-adding and non-value-adding operations (econ, env)
Green VSM	[30]	<ul style="list-style-type: none"> Extension of the VSM tool context (see points mentioned in lean tool VSM) (econ, env, soc) It has the characteristics of VSM and additional Kaizan features (econ) Uses a preventive strategy regarding processes, products and services (econ, env, soc) Aims at increased overall efficiency and reduced social and environmental risks (econ, env, soc)

Table 1. *Cont.*

Tool	References	Brief Description
Environmental VSM	[31]	<ul style="list-style-type: none"> • Extension of the VSM tool (see points mentioned in lean tool VSM) (econ, env, soc) • It enables the visualization of an integrated structure of the resources usage (econ, env) • Mapping strategy applied to align the economic and environmental aspects in production processes (econ, env)
Energy Value Stream Mapping	[32,33]	<ul style="list-style-type: none"> • Extension of the VSM tool, including energy components (see points mentioned in lean tool VSM) (econ, env, soc) • Identifies the level of energy use and wastage in each step and points out the opportunities for energy savings (non-value-added energy consumption) (econ, env) • Leads to the development of a future value stream map taking into account the energy and cost assessment (econ, env) • Aids the division of operations and process steps into value- and non-value-added activities (econ, env, soc)
EPA Lean and Energy Toolkit	[34]	<ul style="list-style-type: none"> • Implements practical strategies and practices to enhance lean results while cultivating energy efficiency and reduction in greenhouse gas emissions, costs and risks (econ, env)
EPA Lean and Environment Toolkit	[35]	<ul style="list-style-type: none"> • It is developed and used by the EPA to improve environmental results, reduce business costs and risks and identify and eliminate waste (econ, env, soc)

Econ: it contributes to the economic pillar of sustainability; env: it contributes to the environmental pillar of sustainability; soc: it contributes to the social pillar of sustainability.

In summary, SustainSC-VSM aims at being a generic and systematic tool that, following a lean-driven sustainability approach through the use of indicators, identifies and improves the supply chain's bottlenecks. Such tool supports the design of a value stream map that will inform decision makers to achieve a (more) sustainable supply chain.

The remainder of the manuscript is organized as follows. In Section 2, the background literature referring to the tools used to develop the SustainSC-VSM methodology is described. Section 3 describes the methodology proposed in this work. The case study description and the results of the application of the methodology are presented in Section 3. Lastly, key conclusions are drawn and “take-home” messages are formulated in Section 4.

2. Methodology for Lean Design of Sustainable Supply Chains: SustainSC-VSM

The main goal of this work is to propose a new generic and systematic step-by-step methodology to extend the analysis to the sustainable supply chain context, facilitating the identification of bottlenecks in a quantitative way and providing guidelines on the creation of a future value stream map, where lean principles are incorporated alongside pertinent indicators. Thus, it is targeted towards achieving a more sustainable and efficient supply chain. Figure 1 presents the proposed methodology, which is called SustainSC-VSM. This new methodology incorporates two methodologies: (i) extended value stream

mapping (EVSM) and (ii) *SustainPro*, further extending them to the context of sustainable supply chains.

Figure 1. SustainSC-VSM methodology.

SustainSC-VSM based its roots in EVSM because, as described in Table 1, this is a useful tool to identify and screen waste in the supply chain in a qualitative way [12]. Moreover, its straightforwardness and uniform language convert EVSM into a valuable tool for managers that can be used in all kinds of supply chains. However, one of the significant limitations in EVSM analysis is the lack of an available quantitative procedure, which often leads to cumbersome tasks. Moreover, this methodology does not take into consideration the sustainability aspects, and therefore, to tackle this challenge, in the new methodology SustainSC-VSM, EVSM is combined with *SustainPro*.

SustainPro is a framework that incorporates an indicator-based methodology to design new sustainable alternatives in any chemical process [13]. *SustainPro* implements the methodology proposed by Carvalho et al. (2008) [36] and Carvalho et al. (2009a) [37]. *SustainPro* is able to decompose complex systems in smaller parts and assess them quantitatively. However, to cover the whole supply chain and not only the production of chemical processes, *SustainPro* needs to be adapted and extended to include indicators that fit sustainable supply chain purposes. The indicators integrated in SustainSC-VSM are multi-dimensional and multi-disciplinary and are designed to measure supply chain performance and effectively point out its bottlenecks.

The SustainSC-VSM steps are described in the following subsections.

2.1. Step 1: Extended Value Stream Mapping (EVSM)

In this step, the sequence of operations and entities within the supply chain is represented through EVSM [12]. There are eight tasks, and they are described as follows:

Task 1: Identify the product family. A product family encompasses a group of products, which follow very similar process steps. Two products that have the same or similar functionality or features are a potential example.

Task 2: Define a convenient field of view. Due to the often complex nature of the supply chain, Womack and Jones (2002) [12] proposed dividing the entire supply chain into different parts; however, they did not indicate how to do it and they did not propose any quantitative decomposition. To this end, to extend the scope of EVSM, SustainSC-VSM splits the complex structure of the supply chain into smaller areas named open paths, which are proposed in *SustainPro* (see Step 2, path decomposition).

Task 3: Create the work team, including all supply chain entities and companies. Note that this task is not mandatory.

Task 4: Determine the level of detail of the EVSM by setting clear system boundaries. It is essential to note that the EVSM's scale is broader than the VSM, which is limited to facility-level boundaries.

Task 5: Collect the information about the flowrates, lead times and value-added time.

Task 6: Map the backflow from the supply chain's last entity, which triggers the entire production of the upstream process. As mentioned, since the full supply chain is a complex process, it is recommended to map each entity as a single process. The different entities can

be separated into factories, warehouses/cross-docks and retailers. Each entity is defined by its standard symbol, along with the describing data. The required data for each entity are as follows:

- Factory: (i) average time that the flow spends in the raw materials' warehouse; (ii) time that the flow is being processed; (iii) time spent in the final goods warehouse; and (iv) the ratio of defects and every part every interval (EPEI).
- Retailer: demand (daily or weekly) for each product of the family.
- Warehouse: (i) ratio of product defects; and (ii) average time that the product flow stays in the warehouse.

Task 7: Mapping of transportation using predefined symbols. It is essential to distinguish between the expected shipment, including its frequency, and the expedited shipment flow. It is necessary to represent the frequency of the rush or special orders (between the facilities). To clearly describe the shipment characteristics, the following data are required: (i) distance between entities; (ii) time between facilities; (iii) average order of shipment (batch size); and (iv) average ratio of defects of the shipment process. This information is further analyzed in Step 3 of the methodology.

Task 8: Mapping of the transport flows. This information entails: (i) the frequency of the communications; and (ii) the processing time of the information data identified by each production control department.

At the end of this step, the user can comprehensively envision the sequence of all supply chain activities. All activities, with and without value added, are pinpointed following their sequence and connection. Furthermore, after defining the current stream map, all data needed to describe the supply chain operations (see the complete set of data collected in Table 2) are collected as part of this methodology step.

Table 2. Complete set of data to be collected.

Data		
Entity	Path	
Factory/Warehouse	Transport	
Price Utility	Price Utility	Price Product
Energy Consumption	Energy Consumption	Price Raw Material
Inventory	Lead Time	Costumer Demand
Holding Cost	Defective Flow	On Time
Lead Time	Carbon Footprint	Theoretical Flow
Demand	Green Energy Consumption	Due Date for Delivery
Defective Flow	Number of Incidents	Earliest Due Date
Process Capacity	Employees	Variance of Lead Time
Carbon Footprint	Number of Lawsuits	Variance of Demand
Waste	Waste	Variance of Mass Flow
Green Energy Consumption	Lower Salary	Penalty Rate
Number Incidents	Higher Salary	
Employees	Working Hours per Year	
Number of Lawsuits		
Demand Downstream Entity		
Lower Salary		
Higher Salary		
Working Hours per Year		

2.2. Step 2: Path Decomposition

In this step, the supply chain network structure identified in Step 1 is decomposed by breaking it down into smaller areas to simplify the identification of bottlenecks. These smaller areas are determined by applying graph theory [38], which is implemented in SustainPro [13] and incorporated in SustainSC-VSM. Hence, all the mass and energy flow paths are split into open and closed paths for each compound in the process. The closed paths are recycled flows that start and end in the same entity. On the other hand, open paths are flows of a specific compound/part/unit with an entrance and an exit of the system. The “entrance” of a compound is due to one of two events, feed stream or production in a production facility, whereas the “exit” means that the compound gets out of the system or is consumed in a given process of the supply chain. SustainPro is used to identify all the open and closed paths and determine each path’s respective flow compound/part/unit.

2.3. Step 3: Calculate Indicators

As previously discussed, there is a lack of systematization when integrating the different parts of the supply chain to improve operations sustainability. Furthermore, despite the guidelines proposed by [12], which steps are necessary to achieve an improved value stream map is not always evident. Thus, to lead and motivate companies to embrace sustainability, in this work, a new set of indicators is proposed to assess the supply chain paths comprehensively. The proposed indicators cover all three sustainability pillars and create a new information area to ensure optimal coordination between entities to improve performance. The indicators should cover the most popular classification, which divides the indicators into four categories: quality [39,40], time [39–41], cost [39,40,42] and flexibility [39,43]. The indicators are applied to all paths to carry out a comparative analysis and prioritize the retrofit actions to be taken to improve the current value stream map. Noteworthy is that most of the indicators inbuilt in the SustainSC-VSM methodology are generic and applied to the different types of supply chains covering the manufacturing, chemical process-based supply chains and service-based supply chain. The user must select from the list of indicators the ones that translate the activities of the supply chain to be studied. It often occurs that trade-offs among objectives must be made. Furthermore, companies are not recommended to improve all indicators simultaneously, since this will require high resource investment. Therefore, the SustainSC-VSM methodology aims at guiding the managers to carefully prioritize the indicators following their business goals, in order to succeed in devising a more sustainable future state value stream map. The indicators implemented in the SustainSC-VSM methodology are described in detail in the next subsections. A summary list of all indicators introduced in the proposed methodology (SustainSC-VSM) is presented in Table A1 in Appendix A.

Furthermore, the data required to estimate the economic, environmental, social and information indicators (detailed in Tables 3–9) are summarized in Table 2. The data required from the companies are data usually available in the different industries, which therefore makes it possible and easy to calculate the indicators presented in Tables 3–9.

2.3.1. Step 3.1: Economic Indicators

The economic indicators report financial metrics assessing if the company’s resources are being well used to create value and intend to point out other potential ways to create value. In the supply chain management community, it is agreed that accomplishing the strategic goals in any supply chain implies a sound control system, including performance measurements regarding the cost, quality, time and flexibility of the supply chain [39,40]. Therefore, these are the subgroups into which the economic indicators are divided.

Cost

The supply chain cost is one of the most critical aspects of the supply chain’s models. A competitive supply chain requires an in-depth understanding of the distribution cost. To this end, the authors propose a set of relevant indicators to assess the most relevant costs;

they are described in Table 3. It is important to note that some of the indicators are adapted from the relevant literature, while the remaining were devised in this work.

Table 3. Economic indicators: cost.

Indicator	Description	Reference	Equation	Nomenclature
Material Value Added-SC (MVA-SC)	MVA-SC estimates the value generated between the start and the endpoint of a given path. This indicator is expressed in EUR, and, consequently, negative values of MVA-SC identify the need for changes/improvements.	Adapted from [36] to the supply chain context	$MVA - SC = Fop * (P_{Ex} - P_{En})$	Equation (1) Fop —flow open path (kg/h) P_{Ex} —final product selling price P_{En} —price of raw material
Energy Cost-SC (EC-SC)	EC-SC provides the value of energy consumption in a certain path. AF specifies the allocation of the energy consumed per path, estimated in mass or volume according to Equations (3) and (4). As expected, having high values of EC-SC indicates the need for changes/improvements.	Adapted from [36] to the supply chain context	$EC - SC = \sum_{e=0}^E P_{Ut} \times En_e \times AF_e$	Equation (2)
			$AF = \frac{MF}{\sum_p MF}$	Equation (3)
			$AF = \frac{VF}{\sum_p VF}$	Equation (4)
Total Inventory Level Cost (TILC)	Inventory is needed to buffer market and operational uncertainties; however, it often hides inefficient management of supply chain processes. This potentially leads to damages to the supply chain competitiveness due to unnecessary and avoidable costs [44]. The inventory cost represents 33% of the logistics cost [45]. To keep track of this, the Total Inventory Level Factor (TILC) indicator provides information about the most critical paths with regard to inventory costs. When keeping more inventory than necessary, the TILC will present high values, which points out excess costs in this regard.	Developed in this work	$ILC = \sum_{e=0}^E Inv_e * HC_e * Afe$	Equation (5) Inv_e —inventory of entity e HC_e —holding cost of a given SKU and entity e
Entity Inventory Level Cost (EILC)	EILC specifies which entity (or entities) is (are) the most critical in inventory cost, within the identified critical path identified previously by TILC. The closer to 1, the worst the entity performs in terms of inventory costs.	Developed in this work	$EILC = \frac{Inv_e * HC_e * Afe}{\sum_{e=0}^E Inv_e * HC_e * Afe}$	Equation (6) (see nomenclature given in indicator TILC)
Backorder Cost (BC)	Running out of stock potentially leads to the company losing the order. Furthermore, a poor service level might lead the customers to change to a competing company [46]. Hence, monitoring these losses is critical, and this can be achieved by using the BC indicator, which displays the total value of lost sales in a given path. The price of the product suffers an increment due to client compensation. High BC points out inefficiencies.	Developed in this work	$BC = (Dem_c - Fop) \times ((1 + i) \times P_{Ex})$	Equation (7) C —demand of component c Dem_c —demand of component c

Time

The flow of a product usually entails the loss of considerable time going through operations without any value to the client. According to [12], the majority of value streams can be compressed to reduce or even eliminate avoidable processing time. To this end, this subsection proposes three indicators for the purpose of tracking time. The lead time is a pivotal factor in measuring a supply chain's performance since it directly impacts the inventory performance as well as the production forecast [47]. Short lead times provide a very significant competitive advantage. Shortening the lead time might enable the value stream to respond to real orders, rather than inaccurate forecasts, and reduce waste [12].

Furthermore, the lead time also plays a significant role in the bullwhip effect; a long lead time in replenishment orders intensifies information distortion [48]. Moreover, inventory turnover is a standard metric used to show the number of times that the inventory is consumed in a period. It can be improved by applying economies of scale as local

optimization. However, this can lead to the bullwhip effect [48]. To this end, this section proposes a group of indicators to efficiently assess time (see Table 4).

Table 4. Economic indicators: time.

Indicator	Description	Reference	Equation	Nomenclature
Lead Time Factor (LTF)	<i>LTF</i> gives the total lead time of each path. It aims at identifying the critical paths with regard to lead time, which can more easily contribute to a service level problem. High values indicate the need for improvements.	Adapted from [37] to the supply chain context	$LTF = \sum_e^E LT_e$ Equation (8)	<i>LT</i> —lead time of entity <i>e</i>
Operational Lead Time Factor (OLTF)	<i>OLTF</i> identifies the most critical entity (or entities) within the critical paths pointed out by <i>LTF</i> . High values indicate potential bottlenecks with regard to the entity's lead time.	Adapted from [37] to the supply chain context	$OLTF = \frac{LT_e}{\sum_e^E LT_e}$ Equation (9)	(see nomenclature given in indicator <i>LTF</i>)
Inventory Turnover (IT)	<i>IT</i> indicator is used to indicate which inventory takes the longest to empty in a given path. It is only applied to entities with an inventory. High values of <i>IT</i> indicate high lead time, which points to lower agility of the path, and the more noticeable the bullwhip effect.	Adapted from [12] to the supply chain context	$IT = \max\left(\frac{Inv_e}{Dem_e}\right)$ Equation (10)	<i>Dem_e</i> —demand of the downstream process in considered time period <i>Inv_e</i> —largest inventory of entity <i>e</i>

Quality

Measuring quality reflects the capacity of delivering high customer service [40], which means: (i) delivery of minimal defected products; (ii) in the demanded quantity; and (iii) in time [49]. A positive view on the company's service quality can lead to its long-term survival, while failure to achieve this might seriously damage its viability [50]. Furthermore, many supply chain models assume perfect systems, but, in any production system, there are flaws in the production processes as a result of human error and other causes [51]. Therefore, it is also essential to measure the performance of the production equipment. Buchmeister et al. (2012) [52] pointed out that the Overall Equipment Efficiency level (*OEE*) of downstream stages has an important influence on inventory oscillation and order variability. Muthian and Huang (2007) [53] proposed the Overall Throughput Effectiveness (*OTE*) metric to monitor performance at the factory level; this metric is based on *OEE*, which was firstly introduced by Nakajima (1988) [54]. Thus, to keep track of quality, this work proposes a set of metrics to assess all the relevant facets of quality in the supply chain (see Table 5).

Table 5. Economic indicators: quality.

Indicator	Description	Reference	Equation	Nomenclature
Service Level Quantity Factor (SLQF)	To keep track of the orders and the product demand quantities, SLQF informs if the orders are being fully satisfied in terms of the amount. When different from 0, it reports that the service level in terms of quantity is not at its best—that path is not satisfying the customer and thus needs to be improved.	Developed in this work	$SLQF = \frac{Dem_c - Fop}{Dem_c}$	Equation (11) (see nomenclature given in indicators BC and MVA-SC)
Service Level Time Factor (SLTF)	Like SLQF, the SLTF indicator informs about the time as a service level by comparing the actual product delivery time to the expected/planned delivery time specified in the order. Values different from 0 indicate that the path's service level in terms of timely delivery needs improvement.	Developed in this work	$SLTF = \frac{FOP - OnTime}{FOP}$	Equation (12) <i>OnTime</i> —flowrate of the open path delivered according to the scheduled time (see nomenclature given in indicator MVA-SC)
OK-Parts (OP)	OP keeps track and raises awareness of the defected products in the value stream. It gives the ratio of product flow that successfully reaches the costumers with a suitable quality compared to the total amount produced. The lower the OP value, the worse the quality performance of the path.	Developed in this work	$\prod_{e=0}^E \left(1 - \frac{OP = Def_e * Afe}{Fop} \right) * 100$	Equation (13) <i>Def_e</i> —defective flowrate of entity <i>e</i> (see nomenclature given in indicators EC-SC and MVA-SC)
Overall Throughput Effectiveness (OTE-SC)	To go a step further, in this work, we propose the OTE-SC metric to compare actual productivity to the maximum achievable productivity for a given path. Low values of OTE-SC indicate low production performance and the need to improve the production yield.	Adapted from [53] to the supply chain context	$OTE - SC = \frac{Fop}{TFop} * 100$	Equation (14) <i>TFop</i> —theoretical flow of an open path working at full yield (see nomenclature given in indicators EC-SC and MVA-SC)

Flexibility

Flexibility is the aptitude to respond to quick changes in supply or demand [40]. Beamon (1999) [39] stated that supply chains' flexibility should be evaluated with regard to four aspects: volume, delivery, mix and new product. Nevertheless, these aspects are not always a concern for all supply chains since they are product-dependent. Furthermore, [55] singled out time and volume flexibility as a common source of disagreement among buyers and suppliers. Hence, this work covers volume flexibility and time flexibility. Volume flexibility is needed to overcome customer order oscillations, and time flexibility is critical to fulfilling rush or special orders [39] (see Table 6).

Table 6. Economic indicators: flexibility.

Indicator	Description	Reference	Equation	Nomenclature
Flexibility Volume Factor (FVF)	<i>FVF</i> assesses if the company can adapt its production to demand variation in terms of quantity. Low values of <i>FVF</i> indicate a low capacity to adjust production to demand variations.	Developed in this work	$\min \left(\frac{FVF = Cap_e - Dem_e}{Cap_e} \right)$ Equation (15)	<i>Cap_e</i> —process capacity of the entity <i>e</i> of a given path (see nomenclature given in indicator IT)
Flexibility Time Factor (FTF)	<i>FTF</i> quantifies the company’s capability to adapt production to meet demand changes regarding time. The lower the value of <i>FTF</i> , the lower the company’s capacity to respond to changes in deadlines.	Adapted from [39] to the supply chain context	$\frac{FTF = (DDD - EDD)}{(DDD)}$ Equation (16)	<i>DDD</i> —due date for delivery <i>EDD</i> —earliest due date for which delivery can be made (see nomenclature given in indicator LTF)

2.3.2. Step 3.2: Environmental Indicators

Several quantitative performance metrics have been established to estimate the impact of the supply chain in the environment, such as GHG emissions, material recycling, waste production and energy use, among others [56]. In this work, the most critical environmental indicators identified in the literature [57] were collected and combined into the indicators presented in Table 7.

Table 7. Environmental indicators.

Indicator	Description	Reference	Equation	Nomenclature
Carbon Emissions (CE)	<i>CE</i> quantifies the CO ₂ emissions for each open path. High values of <i>CE</i> indicate the need to adopt more energy-efficient equipment and facilities and/or optimize the supply chain operations.	Developed in this work	$CE = \sum_{e=0}^E AF_e \times CDE_e$ Equation (17)	<i>CDE_e</i> —carbon dioxide emissions emitted by entity <i>e</i> (see nomenclature given in indicator EC-SC)
Waste Factor (WF)	<i>WF</i> measures the material waste disposal in the open paths. High values of <i>WF</i> point out a need for improvements and potential opportunities to reduce waste of resources and reduce operating costs by increasing material recycling.	Developed in this work	$WF = \frac{\sum_{e=0}^E W_e * AF_e}{Fop}$ Equation (18)	<i>W_e</i> —material waste from entity <i>e</i> (see nomenclature given in indicators MVA-SC and EC-SC)
Sustainable Energy (SE)	To motivate companies to commit to using more sustainable energy sources, <i>SE</i> measures the ratio of sustainable energy on the total energy consumed in the supply chain operations. The lower the ratio, the higher the need to adopt more environmentally friendly sources of energy.	Adapted from [58] to the supply chain context	$SE = \frac{\sum_{e=0}^E Gen_e * Af_e}{\sum_{e=0}^E En_e * Af_e} * 100$ Equation (19)	<i>Gen_e</i> —consumption of green energy by entity <i>e</i> <i>En_e</i> —consumption of energy by entity <i>e</i> (see nomenclature given in indicator EC-SC)

Table 8. Social indicators.

Indicator	Description	Reference	Equation	Nomenclature
Labor Equity (LE)	To assess the labor market, <i>LE</i> describes the distribution of employee compensation. The closer the <i>LE</i> ratio is to one, the better the distribution of equity.	Adapted from [60] to the supply chain context	$LE = \min \left(\frac{LS_e}{HS_e} \right)$	Equation (20) <i>LS_e</i> —lowest salary of a given entity <i>e</i> <i>HS_e</i> —highest salary of a given entity <i>e</i> including all benefits
Fatal Accident Rate (FAR)	<i>FAR</i> is a statistical method that reports the number of fatal incidents [61] of an activity based upon the total number of employees working their entire lifetime. The higher the FAR, the bigger the need to improve procedures and/or change the operations. <i>FAR</i> was firstly proposed by the British chemical industry and here adjusted to the supply chain context.	Adapted from [61] to the supply chain context	$FAR = \frac{\sum_{e=0}^E Ninc_e * 10^8}{\sum_{e=0}^E NE_e * Wh_e}$	Equation (21) <i>Ninc_e</i> —number of incidents in entity <i>e</i> <i>NE_e</i> —number of employees that work in entity <i>e</i> <i>Wh_e</i> —working hours per year in entity <i>e</i>
Corruption (C)	<i>C</i> is an attempt to quantify the effect of corruption on the social sustainability of an enterprise. The higher the <i>C</i> , the greater the need to change policies to fight corruption [59].	Developed in this work	$C = \sum_{e=0}^E Nls_e$	Equation (22) <i>Nls_e</i> —number of lawsuits in entity <i>e</i>

2.3.3. Step 3.3: Social Indicators

Metrics of the social performance show the company's policies towards its stakeholders (e.g., suppliers, employees). These indicators provide information about its employment situation and its relationship with private and public institutions or community groups [37]. However, there is still a lack of agreement in the literature regarding the best approach to evaluate social sustainability [59]. Nonetheless, the authors of [59] identified four elements that stakeholders find worthy of protection: (i) labor practices, (ii) human rights, (iii) product responsibility and (iv) society. The indicators proposed in this work cover all the topics mentioned above and are defined in Table 8.

2.3.4. Step 3.4: Information Indicators

Information indicators aim to represent a new sustainability angle to assess the effectiveness of coordination among the supply chain members and the potential benefits of implementing information-sharing policies. The performance of the supply chain highly depends on the quality of the information. The information flows directly impact the inventory levels, shipments and the production schedules [48]. Furthermore, information distortion can lead to the presence of the bullwhip effect. Lee et al. (2004) [48] referred to the bullwhip effect as “the phenomenon where orders to the supplier tend to have a larger variance than sales to the buyer (i.e., demand distortion), and the distortion propagates upstream in an amplified form (i.e., variance amplification)”.

Sabato and Bruccoleri (2005) [62] showed that reducing lead time variability is, in some cases, more effective in removing the bullwhip effect than lowering the average lead time.

Table 9. Information indicators.

Indicator	Description	Reference	Equation	Nomenclature
Variability of Lead Time (VLT)	VLT aims at monitoring the lead time variability. High values indicate the need to improve the information flow's stability across a given path within the supply chain.	Developed in this work	$VLT = \frac{\sigma_{LTF}}{LTF}$ Equation (23)	σ_{LTF} —standard deviation of the lead time factor of a given path LTF—lead time factor of a given path
Bullwhip Effect (BE)	BE gives information concerning the demand variation in the more upstream process of a certain path to promote information sharing and prevent the bullwhip effect. The original equation used to quantify the bullwhip magnitude has been adapted to fit with the open path context. Since the more considerable order quantity variations are located in the most upstream process [48], each path only focuses on the demand increase of the first entity considered in the analysis.	Adapted from [63] to the open path context	$BE = \frac{\sigma_{Fop}}{\sigma_{Dem}}$ Equation (24)	σ_{Fop} —variance of the orders of the first entity of a given path σ_{Dem} —demand of flow of a given path

The proposed indicators aim to prevent the bullwhip effect and ensure coordination among the supply chain members to reduce the variability of the lead time. These indicators are described in Table 9.

2.4. Step 4: Bottleneck Identification and Potential Solutions

The indicators defined above are applied to each path, and based on their values, the managers can potentially identify the most critical areas of the supply chain. In Table 10, a few guidelines and recommendations are suggested to improve each indicator separately and improve the supply chain's overall sustainability.

Table 10. Recommendations to improve each indicator estimated through the SustainSC-VSM methodology.

Indicator	Recommendations
MVA-SC	Redesign the production process, for example, by applying process intensification and/or process integration.
EC-SC	Invest in equipment and vehicles that are more efficient, as well as investing in continuous heat integration.
TILC EILC	Decrease the level of production and demand uncertainty. The production uncertainty can be reduced by implementing more robust production processes. Demand uncertainty can be decreased by identifying a significant buffer near the end customer to protect the supply chain from market uncertainties or by applying a production leveling technique ("heijunka").
BC	Improve supply chain coordination and inventory management policies.
LTF OLTF	Ideally, all activities should be located at the same place near the end customer. This is often not possible, so the recommendation is to find facilities that share material flows and locate them as close as possible. Using "just in time" methods such as pull systems or process synchronization also shortens the lead time.
IT	Reduce the inventory by gradually ensuring not compromising the service level or reducing the batches' size and increasing the pick-up frequency.
VF TF	Redirect the flow of material to another path with a lower workload, or boost the work capacity acquiring newer and more effective equipment.
OK-P	Implement failure prevention techniques ("poka yoke") to reduce scrap and rework in every facility's production processes.

Table 10. Cont.

Indicator	Recommendations
SLQF SLTF	Improve the information sharing between the supply chain members to know the capacity constraints and each supplier's inventory management. According to the collected information, find out how to deliver the required orders in the proper quantity and time.
OTE-SC	Implement <i>kaizen</i> workshops to decrease the production uncertainty (technical, organizational and quality losses, and changeover times).
VLT	Homogenize all the processes of the value stream to gain stability and ensure consistent results over time.
BE	Adopt a centralized multi-echelon inventory control system since it presents a superior performance over independently operating site-based inventory.
CE	Implement more energy-efficient equipment, vehicles and facilities; and/or optimize the supply chain operations.
WF	Reengineer the production process to be more efficient and promote recycling policies.
SE	Improve energy efficiency and invest in renewable and sustainable energy sources.
LE	Improve the lowest salary and/or reduce the highest salary—decrease salary disparity.
FAR	Improve labor conditions by implementing robust security policies and provide training to the employees.
C	Organize workshops to raise awareness among managers and promote transparent communication of information.

Noteworthy is that, based on Step 4, it is then possible to follow the recommendations and overcome the identified bottlenecks, therefore leading the user to the future value stream map (Figure 1).

3. Results

To validate the SustainSC-VSM methodology, as presented in Figure 1, Section 2, a case study of the supply chain of a heat exchanger manufacturer is used (adapted from Persson (2011) [64]). The case study presented in Figure 2 was selected as a good representative supply chain since (i) it refers to a relatively large company in Denmark and Nordic countries with an international supply chain; (ii) it has a discrete flow, which shows the applicability of SustainSC-VSM to the manufacturing and services sectors; and (iii) the data collected are real and complete.

Figure 2. Case study of the supply chain of a heat exchangers manufacturer. Adapted from Persson (2011) [64].

Raw materials such as stainless steel, copper and other metals are obtained from different suppliers (1a, 2a and 3a, respectively) and transported to the main central manufacturing component unit in Ronneby, Factory A (1, 2). The critical components are subsequently distributed to the three supply units: Ronneby (4), Italy (5) and China (6). Connections are setup locally for each supply unit (3, 7, 8). Distribution centers supply the U.S. (13) and the after-market (10, 12). The remaining companies and end customers are supplied by all supply units but not through the distribution centers (11, 14, 15).

Streams 18, 19 and 20 represent the final products (heat exchangers) when they are sold to be implemented in the physical plant.

A critical component used in the end product manufacture is produced in the component unit in Ronneby. Its production process is divided into two parts: one part that supplies the Ronneby supply unit in a make-to-order (MTO) environment, and the second part produces the component in a make-to-stock (MTS) environment (forecast-based). Moreover, the supply units (Ronneby S.U. and Italy S.U.) are produced in an MTO environment. In this work, the case study is framed around the whole network. However, it only includes the “after-market” and the “U.S. market” as customers. Therefore, the flows were adapted to reflect this. Although this simplification somewhat changes the final results, it is sensible to accept the obtained results as valid, since the supply chain structure is already quite complex.

3.1. Step 1: Extended Value Stream Map

The supply chain structure presented in Figure 2 should be decomposed into three EVSMs since it has three known customers. However, due to space constraints, we will focus on the detailed representation and analysis of the after-market and the U.S. market EVSMs, as presented in Figures 3 and 4.

The Italian factory is located in Monza [65], and the distribution center is located in Denmark [66].

The required data to produce the EVSMs are summarized in Tables 11 and 12 and they were collected as follows:

- The distances between the different units were obtained by using Google Maps;
- The data needed for the complete description of the data boxes (EPEI, defects, inventory days, batch and demand) of the EVSM were collected from the Alfa Laval sustainability report [67];
- The demand was estimated based on the Alfa Laval sustainability report [67] and by applying some assumptions, such as: (i) the heat exchangers represent 40% of the sales in the equipment divisions, and (ii) the after-market represents 35 % of the total market share.

Figure 3. EVSM representation of the after-market developed in this work. Blue: supplier stage; green: manufacturing stages; orange: distributor stage; yellow: retailer stage. The EVSM was created in the Lucidchart software [68].

Table 11. Summary of the data regarding the entities.

Data Boxes	TIME				Total	EPEI	Defects	Steps
	Rm (Days)	WIP (Days)	FG (Days)	Value Added (s)				
Ronneby C.U.	4	1.8	1.5	2346	7.3	3 days	3.42%	30(6)
Ronneby S.U.	0.8	2.5	2.3	1600	5.6	2 days	4.13%	26(5)
Italy	2.2	2.6	1.8	1789	6.6	2 days	2.13%	26(5)
Distribution C.		1.2		0	1.2		0.03%	4(0)

Table 12. Summary of the data regarding transportation.

Transportation	Time	Distance (km)	Batch	Defects	Frequency	Steps
Supplier Steel	0.2 days	95	150 coils	3.90%	Weekly	1
Supplier Copper	0.3 days	120	150 coils	4.31%	Weekly	1
Sup Connections IT	02 days	70	5 pallets (75 u/p)	1.98%	Weekly	1
Sup Connections RO	0.4 days	150	15 pallets (50 u/p)	1.40%	2× Week	1
Ronneby C.O-IT	2.4 days	2122	10 pallets (50 u/p)	2.01%	Weekly	1
Ro C.U. -Ro S.U.	0.1 days	1	5 pallet (50 u/p)	0.50%	Daily	1
Ro S.U.- Distributor	0.6 days	444	15 pallets (25 u/p)	2.02%	4× Week	1
Italy-Distributor	1 day	1357	15 pallets (25 u/p)	1.01%	Weekly	1
Distributor-Market	0.8 days	703	15 pallets (25 u/p)	1.56%	Daily	1

The production control entities are the offices where the information flows are managed in the supply chain (all data are shared electronically between entities). As previously mentioned, the share of the component unit that serves Italy S.U. works in an MTS environment. The supply unit and the part of the component unit that serves Ronneby S.U. works in an MTO environment. Thus, the supply units only schedule batches in response to a confirmed order. Furthermore, the data reported in Table 13 were estimated in resemblance to the EVSM described in [12] and considering the supply chain description presented in [64]. The EVSM representation of the after-market was developed in this work, depicted in Figure 3. The nature and the frequency of the information flow are detailed in Table 13. Note that the information flows in Figure 3 are linked to the number presented in the first column.

Table 13. Description of the EVSM's information flow.

Number	Information Flows	Frequency	Description Flow
1	Costumer-PCCostumer	Daily	Consumption Information
2	Distribution-PCCostumer	Daily	Shipping Release
3	PCCostumer-Distribution	Daily	Orders
4	PCCostumer-PCRonneby	Daily	Orders/Consumption Information
5	Italy-PCRonneby	Weekly	Shipping Release
6	PCRonneby-Italy	Weekly	Orders
7	PCRonneby-Connections	2× Week	Source Stocked Product
8	Ronneby S.U.-PCRonneby	4× Week	Shipping Release
9	PCRonneby-Ronneby S.U.	4× Week	Orders
10	PCRonneby-copper	Weekly	Source Stocked Product
11	PCRonneby-steel	Weekly	Source Stocked Product
12	PCRonneby-Connections	Weekly	Source Stocked Product
13	Ronneby C.U.-PCRonneby	Daily	Shipping Release
14	PCRonneby-Ronneby C.U.	Monthly	Forecast

Figure 4. The EVSM of the U.S. customer market developed in this work. Blue: supplier stage; green: manufacturing stages; orange: distributor stage; yellow: retailer stage. The EVSM was created in the Lucidchart software [68].

The material flows of the EVSM presented in Figure 3 are described as follows:

- i. The steel and copper suppliers send a weekly shipment of 150 coils to the Ronneby C.U.;
- ii. The component unit is manufactured in the Ronneby C.U.;
- iii. A fraction of the finished items are sent to the Italy S.U. by truck, and the others are sent to the Ronneby S.U. by milk run;
- iv. The heat exchangers are manufactured in each supply unit. The heat exchangers are made of the component unit, which was sent earlier from the Ronneby C.U., and a connection component, which was acquired from a local supplier;
- v. Once the heat exchangers are manufactured, the supply units' factories send the finished product to the distribution center in Denmark;
- vi. The finished goods are distributed to all the retailers in the distribution center.

The information flows of the EVSM presented in Figure 3 are described as follows:

- i. All retailers send daily information on the sales to the office of customer production control;
- ii. All data are processed in the production control office, and the shipment orders are sent to the distribution center;
- iii. The distribution center sends the shipments' confirmation back to the office of customer production control;
- iv. The office of customer production control also sends the consumption data and the orders to the production control;
- v. The information is then processed in Ronneby's production control office, and orders are sent to the supply units located in Ronneby and Italy;
- vi. The Ronneby and Italy supply units send weekly and daily confirmation of the shipments, respectively;
- vii. The Ronneby production control office also sends daily material requirements to the suppliers;
- viii. The Ronneby production control office sends the monthly production forecast to the Ronneby C.U.

The EVSM of the U.S. customer market developed in this work is represented in Figure 4. The distribution center is located in Indianapolis, where Alfa Laval has a distribution center that supplies the U.S. market (<https://www.alfalaval.com/globalassets/images/misc/partnerdays/alfalavalpartnerdays2018-programme.pdf>, accessed on 1 January 2021).

The data presented in this step aim to depict the supply chain operations in a consistent and straightforward manner. The EVSM representation identified all the activities in accordance with their sequence and relationships.

Furthermore, as previously mentioned, the supply chain's structure and the production approach of each entity were obtained from Persson (2011) [64] and Alfa Laval's sustainability report [67]. However, in the sustainability report, the given figures include all company operations, mostly not relevant to this work. Thus, some assumptions were needed to be made to collect the required data.

The total inventory, lead time, demand, defective flow and inventory required for the EVSM are presented in Tables 12 and 13. Tables 14 and 15 summarize the details for each entity and transport flows. The sources of information used are detailed in Appendix B, Section 3. A summary of the data regarding the open paths is shown in Table 16.

Table 14. Data of entities and the respective transportation flows.

Factories/Warehouse	Ronneby C.U.	Italy	Ronneby S.U.	Danish Distributor	EEUU Distributor
Price Utility (EUR/MWh)	80.00	170.00	80.00	100.00	61.90
Energy Consumption (MWh/year)	6550	4100	4750	1000	800
Inventory Total (units)	3300	1450	1850	450	675
Holding Cost (EUR/unit)	9	11	12	22	20
Lead Time (days)	7.3	6.6	5.6	1.2	4.5
Demand (units/day)	375	225	300	375	150
Defective Flow (kg/year)	9975.00	6508.33	25,697.78	933.33	30.00
Process Capacity (units/day)	400	250	305	500	300
Carbon Footprint (tones/year)	5245	3875	3245	635	425
Waste (kg/year)	23,000	13,500	28,750	933.33	30
Green Energy Consumption (MWh/year)	400	0	249	0	0
Number Incidents	1	0	2	1	0
Employees (people)	740	320	524	60	50
Number of Lawsuits	1	0	1	0	0
Largest Inventory (units)	1500	585	750	450	675
Lowest Salary (EUR/year)	21,000	19,000	23,000	23,000	24,000
Highest Salary (EUR/year)	68,000	66,000	70,000	85,000	76,000
Working Hours (year)	1607	1752	1607	1411	1770

Table 15. Data related to transport flows.

Transport	Sup Steel	Sup Copper	Sup Con IT	Sup Con RO	Ro C.O-IT	Ro C.U. -Ro S.U.	Ro S.U.-Danish D.C.	It-Danish D.C.	Danish D.C.-After-Market	It-U.S. D.C	U.S. D.C.-U.S. Market
Price Utility (EUR/MWh)	102	102	109.3	102	102	102	102	109.3	110	67	67
Energy Consumption (MWh/year)	12.4	15.7	9.1	39.2	276.9	0.7	231.8	177.1	458.7	959.3	561.5
Lead Time (days)	0.2	0.3	0.2	0.4	2.4	0.1	0.6	1	0.8	12.8	1.8
Defective Flow (kg/year)	8775	2873.3	264	1960	1172.5	1166.7	5027.6	628.4	4853.3	9510	2940
Carbon Footprint (ton CO ₂ /year)	112.75	42.2	12.92	179.6	652.96	4.9	2331.7	445.4	5768.5	5816.4	3402.4
Green Energy (MWh/year)	0	0	0	0	0	0	0	0	0	0	0
Number of Incidents	0	1	0	0	1	1	1	0	1	0	0
Employees (people)	1	1	1	1	1	1	1	1	2	3	2
Number of Lawsuits	0	1	1	0	0	0	0	0	0	0	0
Waste (kg/year)	8775	2873.3	264	1960	1172.5	1166.7	5027.6	628.4	4853.3	9510	2940
Lowest Salary (EUR/year)	17,000	20,000	18,000	16,000	17,000	18,00	19,000	22,000	26,000	26,000	19,000
Highest Salary (EUR/year)	50,000	56,000	56,000	45,000	36,000	44,000	50,000	55,000	84,000	75,000	66,000
Working Hours (year)	1607	1607	1752	1607	1607	1607	1607	1752	1411	1770	1770

Table 16. Data related to the open paths.

Path	OP1	OP 2	OP3	OP4	OP5	OP6	OP7	OP8	OP9
Price of Product (EUR/kg)	140	140	140	140	140	140	140	140	140
Price of Raw Material (EUR/kg)	2.1	2.1	5.68	5.68	3.50	2.6	140	140	140
Customer Demand (kg/year)	180,000	45,000	55,000	13,500	142,500	35,000	250,000	62,222	150,500
On Time (kg/year)	180,000	45,000	50,000	10,000	125,000	34,000	230,000	61,000	146,000
Theoretical Flow (kg/year)	210,000	52,000	61,500	15,500	160,000	37,500	275,000	67,500	170,000
Due Date for Delivery (days)	15	18	15	19	6	9	9	11	28
Earliest Due Date (days)	13	14	13	14	5.6	5	8	7	24
The Variance of Lead Time (days)	2.2	2.6	1.2	1.5	2.2	0.8	2	2.2	4
The Variance of Demand (kg/y)	10,000	5000	4000	1000	6000	5000	50,000	10,000	7500
The Variance of Flow Path (kg/y)	10,500	5550	4800	1050	7000	5100	65,000	11,500	8800
Penalty Rate	0.1	0.15	0.1	0.15	0.1	0.15	0.7	0.7	0.6

3.2. Step 2: Path Decomposition

SustainPro [13] was used to generate the open paths for the two EVSMs previously mentioned. The reader is referred to Carvalho et al., 2008 [36,69] for details on *SustainPro*'s inbuilt methodology used for path decomposition. Thus, network decomposition was applied, and a total of 15 open paths were obtained, representing the whole supply chain. However, since this study, as mentioned before, focuses solely on the paths related to the after-market and the U.S. customer market, only the corresponding open paths will be analyzed. This totals to nine out of the fifteen open paths identified, as presented in Table 17. The path decomposition for the nine open paths is presented in Table 17, where each path is linked to a component and a flow which forms the flow-path.

Table 17. Path decomposition of the EVSM representing the U.S. customer market.

Open Path	Component	Flow (kg/y $\times 10^3$)	Description
1	Steel	180	(Steel Supplier $\rightarrow$ Ronneby C.U. $\rightarrow$ Ronneby S.U.)
2	Steel	45	(Steel Supplier $\rightarrow$ Ronneby C.U. $\rightarrow$ Italian S.U.)
3	Copper	53.3	(Copper Supplier $\rightarrow$ Ronneby C.U. $\rightarrow$ Ronneby S.U.)
4	Copper	13.3	(Copper Supplier $\rightarrow$ Ronneby C.U. $\rightarrow$ Italian S.U.)
5	Connections	140	(Connections Supplier $\rightarrow$ Ronneby S.U.)
6	Connections	35	(Connections Supplier $\rightarrow$ Italian S.U.)
7	Heat Exchanger	248.9	(Ronneby S.U. $\rightarrow$ Danish distribution center $\rightarrow$ after-market)
8	Heat Exchanger	62.2	(Italian S.U. $\rightarrow$ Danish distribution center $\rightarrow$ after-market)
9	Heat Exchanger	150	(Italian S.U. $\rightarrow$ Indianapolis distribution center $\rightarrow$ after-market)

3.3. Step 3: Calculation of the Indicators

In this section, the indicators included in the SustainSC-VSM methodology are estimated for all the open paths. As mentioned in the detailed description of the indicators presented in Section 2, Step 3.1, the indicators EILC (Entity Inventory Level Cost) and OLTF (Operational Lead Time Factor) characterize the supply chain's entities. Thus, Tables 18 and 19 summarize the indicators with regard to EILC and OLTF. In contrast, Table 20 summarizes the remaining indicators' values, which correspond to the U.S. market and the after-market open paths. As observed, the worst paths regarding the *EILC* and *OLTF* indicators are OP1 and OP9, respectively. The most critical open path with regard to inventory is OP1 (see Table 18); thereby, the EILC indicator is applied only to this path. In terms of the lead time, the most critical is OP9.

Table 18. EILC indicator of open path 1 in the entities regarding inventory. Values highlighted in red represent the worst performance.

Open Path 1	EILC
Ronneby C.U.	0.741
Ronneby S.U.	0.259

Table 19. OLTF for the critical open path 9 regarding entities concerning lead time. Values highlighted in red represent the worst performance.

Open Path 9	OLTF
Italian S.U.	0.257
It S.U.-Indianapolis Distribution center	0.498
Indianapolis Distribution center	0.070
Indianapolis Distribution center -U.S. market	0.175

Table 20. Values of the indicators for all open paths. Values highlighted in red represent the worst performance.

		OP1	OP2	OP3	OP4	OP5	OP6	OP7	OP8	OP9	
Economic	Cost	MVA	EUR 24,822,000	EUR 6,205,500	EUR 7,163,733	EUR 1,790,933	EUR 19,110,000	EUR 4,809,000	- EUR	- EUR	- EUR
		EC	EUR 434,374	EUR 205.537	EUR 129,682	EUR 61,145	EUR 89,493	EUR 80,837	EUR 296,007	EUR 191,388	EUR 493,554
		TILC	EUR 24,751	EUR 6931	EUR 7334	EUR 2054	EUR 4995	EUR 1827	EUR 16,800	EUR 5228	EUR 13,505
		B	- EUR	- EUR	EUR 256,667	EUR 26,833	EUR 154,000	- EUR	EUR 264,444	- EUR	EUR 112,000
	Time	LTF	13.20	16.50	13.30	16.60	6.00	6.80	8.20	9.60	25.70
		IT	4.00	4.00	4.00	4.00	2.50	2.60	2.50	2.60	4.50
	Flexibility	VF	0.02	0.06	0.02	0.06	0.02	0.10	0.02	0.10	0.10
		TF	0.13	0.22	0.13	0.26	0.07	0.44	0.11	0.36	0.14
	Quality	SLQF	0.000	0.000	0.03	0.01	0.01	0.000	0.00	0.00	0.00
		SLTF	0.000	0.000	0.06	0.25	0.11	0.03	0.08	0.02	0.03
		OK-P	88.5%	89%	88.2%	88.6%	94.5%	97.1%	92.2%	95.1%	90.8%
		OTE	85.7%	86.5%	86.7%	86.0%	87.5%	93.3%	90.5%	92.2%	88.2%
Information	VLT	0.17	0.16	0.09	0.09	0.37	0.12	0.24	0.23	0.16	
	BE	1.05	1.11	1.20	1.05	1.17	1.02	1.30	1.15	1.17	
Environment	CE	4241.45	1748.29	1261.65	519.24	885.21	452.91	6668.55	2035.46	8780.47	
	WF	0.17	0.18	0.17	0.19	0.06	0.05	0.09	0.07	0.22	
	SE	0.06	0.03	0.06	0.03	0.05	0.00	0.03	0.00	0.00	
Society	LE	0.31	0.29	0.31	0.29	0.33	0.29	0.27	0.27	0.29	
	C	2	1	3	2	1	1	1	1	0	
	FAR	197	114	246	171	237	0	537	308	0	

3.4. Step 4: Bottleneck Identification and Potential Solutions

In this section, the supply chain's bottlenecks are identified and analyzed. Moreover, some suggestions are provided to tackle these bottlenecks. The indicators are grouped in the same order as presented in the description of the methodology in Section 2.

3.4.1. Economic Indicators

The economic indicators are analyzed in Table 21 to identify the potential creation of wealth for the customer and assess the organization's resource effectiveness in the supply chain. The higher the performance, the greater the level of competitiveness of the supply chain.

Table 21. Identification of bottlenecks based on the economic indicators, and suggestions to overcome these bottlenecks.

Material Value Added (MVA-SC)	The supply chain is working in the right conditions: no negative MVA-SC values have been limited improvements.
Energy Cost (EC-SC)	OP9 seems to be the most critical path in terms of energy consumption (heat exchangers' distribution from Italy to the USA market). It indicates the possibility of opening or using an existing factory in the U.S. to manufacture the components currently produced in Italy. This would also entail a change in the raw materials' suppliers. Still, it would reduce the transportation costs as the material to transfer will not be the final product, but its components would reduce energy consumption.
Total Inventory Level Cost (TILC) and Entity Inventory Level Cost (EILC)	OP1 is the most expensive path in terms of inventory. EILC indicates that the Ronneby C.U. factory has the largest inventory cost in OP1. This is due to the centralized production of component units, which gives the biggest circulation of flow through the Ronneby C.U. entity. Thus, to avoid this bottleneck, a change from the current MTS policy to MTO would be appropriate to reduce unnecessary inventory.
Backorder Cost (BC)	OP7 is identified as being the most expensive in terms of losses for not meeting the demand requests. This indicator's assessment should be a priority since the most competitive market with lower customer loyalty is the after-market (see the penalty rate in Table 15). Back-ordering can jeopardize the economic feasibility of the supply chain. OP3 and OP5 are pointed out as the second and third worst open paths with regard to back-ordering. These results indicate the need for a detailed analysis of the Ronneby S.U. entity, since OPs 7, 3 and 5 have the Ronneby S.U. facility in common.
Lead Time Factor (LTF) and Operational Lead Time Factor (OLTF)	OP9 is the most critical path in terms of LTF. This is associated with the distribution of heat exchangers from Italy to the U.S. customer market. Analyzing OP9's OLTF, it is clear that this is the path that carries the most significant bottleneck concerning lead time (Table 20). According to the EC-SC indicator, it would be beneficial to study the use of the facilities that Alfa Laval has in the U.S. to produce the components that are being produced in Italy (lower transportation time).
Inventory Turn (IT)	OP9 is the most severe in terms of inventory turns—the distribution center appears to be the bottleneck. There is only one weekly shipment from Italy to Indianapolis due to the great distance between these entities. Thus, each order batch is large and takes a long while to be consumed. Adopting the proposed solutions in the EC-SC and LTF indicators would allow for more regular supplier shipments with a lower order batch, thereby reducing the non-value-added time and improving economic performance. If not possible to change the production location, implementing techniques such as a pull system to link the downstream process's demand with the production of the upstream process would also reduce inventory time.
Flexibility Volume Factor (FVF)	OPs 1, 3, 5 and 7 have the lowest volume flexibility of the supply chain. These paths share the Ronneby S.U. factory, which seems to be the bottleneck. This bottleneck indicates a very tight production schedule, which translates into losses due to back-ordering (Table 20 and BC analysis). To tackle this, balancing the supply unit factories' workload seems to be the best option: (i) transfer a share of the production volume to the Italian supply unit factory, or (ii) invest in new equipment to increase effectiveness of the Ronneby S.U.

Table 21. *Cont.*

Flexibility Time Factor (FTF)	OP5, followed by OP7, OP1 and OP3, is the most critical path in terms of time flexibility. This is closely related to the very limited volume flexibility of the Ronneby S.U. Thus, the measures stated above (analysis of BC and FVF) should be implemented to solve this threat to the supply chain's overall sustainability.
Service Level Quantity Factor (SLQF) and Service Level Time Factor (SLTF)	OP3 has the worst delivery performance in terms of the quantity. OP4 is the most critical path in terms of time service level and the second worst in quantity service level. Both OP3 and OP4 share the same copper supplier (see EVSM, Figure 3). This is the source of the low service level, which indicates that it would be beneficial to look for new suppliers to ensure a steady flow of raw material.
Ok-Parts (OP)	OP3, followed by OP1, OP2 and OP4, is the most critical path in manufacturing quality (see Table 20). All these paths flow through the Ronneby C.U. factory and are the upstream paths in the supply chain (see EVSM, Figure 3). The most upstream entities should launch a <i>kaizen</i> project to implement the <i>jidoka</i> and <i>poka yoke</i> (mistake-proofing processes) approaches to reduce the scrap and the rework.
Overall Throughput Effectiveness (OTE-SC)	OP1 has the lowest overall throughput effectiveness in the supply chain, which is probably caused by quality losses. Still, a more in-depth study should be led to assess the technical losses (machinery breakdowns) and organizational losses (lack of resources to manufacture). Each facility should improve their productivity and efficiency (total productive maintenance (TPM)).

3.4.2. Information Indicators

The information indicators are analyzed in Table 22 to identify potential improvements regarding the coordination of information and material flows.

Table 22. Identification of bottlenecks based on the information indicators and suggestions to overcome these bottlenecks.

Variability Lead Time (VLT)	OP5 has the most considerable relative variance in the supply chain. This uncertainty weakens the production performance of the Ronneby S.U. factory, leading to organizational losses—it requires re-scheduling and forces the Ronneby S.U. factory to keep a large inventory. It would be beneficial to set up well-defined standards to prevent these time fluctuations. If not possible, the Ronneby S.U. factory should look for a new supplier to ensure a steady flow of raw materials.
Bullwhip Effect (BE)	OP7 is the most critical path with regard to material distortion. The after-market seems to be an unsteady market, so many unforeseen deviations trigger rush orders, causing a malfunction in the supply chain. Two options are suggested to improve information performance: (i) to implement a vendor-managed inventory (currently the customer production control sends orders to the Ronneby production control, Figure 3); and (ii) to increase the inventory units in the distribution center to protect it against the uncertainties of the market demand.

3.4.3. Environmental Indicators

The environmental indicators are assessed and discussed in Table 23 to identify the bottlenecks regarding the supply chain's environmental performance.

Table 23. Identification of bottlenecks based on the environmental indicators, and suggestions to overcome these bottlenecks.

Carbon Emission (CE)	OP9 has the most considerable carbon footprint in the supply chain. The transportation flow from the Italy S.U. has a significant impact on the CE; thereby, it is strongly recommended to adopt the solution mentioned above. Apart from moving the supply unit's production, it is suggested to improve the equipment efficiency, especially the vehicles that account for the largest share of carbon emissions (see Table 15).
Waste Factor (WF)	OP9 is again identified as the bottleneck in terms of material waste. This fact supports the conclusions drawn in the EC, TLF, IT and WF indicators. An additional critical factor which significantly impacts the waste generation is the production performance in terms of quality. The higher the scrap, the higher the waste. Hence, quality improvement should also reduce the supply chain's environmental impact.
Sustainable Energy (SE)	OP6 and OP8 do not consume any renewable energy. Analyzing the indicators and the related data, two concerns appear: (i) Italy's factory is the only one that does not use renewable energy; and (ii) all transport energy comes from fossil energy. Due to the fact that transport represents a significant share of the energy consumption, it is required to (i) reduce the transport in the supply chain (adds value to the customer); and (ii) invest in "greener" means of transportation (e.g., hybrid vehicles or trains).

3.4.4. Social Indicators

Finally, to achieve a more socially sustainable supply chain, the social indicators are analyzed to improve its performance. They are presented and discussed in Table 24.

Table 24. Identification of bottlenecks based on the social indicators, and suggestions to overcome these bottlenecks.

Labor Equity (LE)	OP8 and OP7 are the most critical paths with regard to labor equity. This means that they report the most significant differences between the lowest and highest salaries (EUR 26 k and EUR 84 k) of the supply chain. Raising the lowest wage should be on the supply chain management agenda to reduce the gap of wealth distribution and, in this way, increase the workers' motivation.
Corruption (C)	OP3 has the worst performance regarding corruption. All entities of this path have broken the law, as well as dismissed the business ethic code. It represents a non-sustainable social performance that would probably damage the entire supply chain and its image. Therefore, measures must be implemented to raise awareness among workers about the importance of fair competition. Additionally, an internal audit program would help to review the current standards to decrease these figures significantly.
Fatal Accident Rate (FAR)	OP7 is reported as having the highest fatal accident rate in the supply chain. This path is the most dangerous, and workers are prone to suffer an accident while carrying out their tasks. This must be considered as unacceptable for all the companies. Enhancing workforce protection policies and raising awareness among workers must be a priority in order to reduce the number of accidents.

The presented indicators point out all the significant supply chain bottlenecks. The indicators provide sufficient and adequate information to guide the development of the future state of EVSM. It is important to note that, as presented in Figure 5, OP9 is the one that shows the highest number of critical points. Therefore, the recommendation is that this path should be the one to be tackled first.

Figure 5. Critical points identified per open path.

In summary, the main outcomes/achievements of applying the SustainSC-VSM methodology to the case study are as follows:

- (i) It leads to the identification of hot spots (e.g., flow of steel from supplier to the component unit in Ronneby and its transport to the Ronneby supply unit seem to be a critical point due to high levels of inventory);
- (ii) It provides suggestions to overcome these hot spots (e.g., change current MTS policy to MTO in order to reduce unnecessary inventory);
- (iii) It guides the user towards the development of the future state of the value stream map based on the suggestions provided, allowing the development of a more sustainable supply chain.

4. Conclusions

A novel methodology (SustainSC-VSM) is proposed in this work and it aims at being a systematic tool to design the future value stream map that will support the attainment of a (more) sustainable supply chain. This follows a lean-driven sustainability approach where a set of indicators is used to identify and solve the supply chain's bottlenecks. SustainSC-VSM is based upon: (i) the lean viewpoint of zero wastes, smooth flow and adding value for the customer; (ii) the sustainability concepts, cutting the use of unnecessary resources; and (iii) the coordination of information to improve overall performance. Furthermore, guidelines to tackle the bottlenecks identified are also given. This methodology was tested and validated through its application to a relevant and real industrial case study. The indicators provided sufficient and adequate information to guide the user through the identification of the bottlenecks, and along with the provided recommendations, it was possible to derive the future state of the value stream map. Therefore, SustainSC-VSM proved to be an efficient tool to enhance the overall supply chain's performance and sustainability.

SustainSC-VSM has many managerial benefits. (a) It allows visually mapping the operations of the supply chain in a sustainable perspective. (b) It turns VSM into being applicable to supply chains and increases the confidence in the bottlenecks' identification. VSM is usually a visual and qualitative tool and SustainSC-VSM allows the decision makers, through a set of indicators, to clearly identify and prioritize actions towards a more sustainable supply chain. (c) Decision makers can use SustainSC-VSM in any sector and easily eliminate indicators that do not fit their purposes or add additional indicators that are relevant for their core business. (d) SustainSC-VSM decomposes complex supply

chains in paths, which allows managers to clearly identify problems in complex systems, which are usually not comprehensive due to their complexity. (e) The proposed indicators are also a powerful tool for supply chain managers to quantify the improvements they have made. This will allow them to monitor their sustainability performance and also to communicate internally and with their stakeholders about the improvements achieved.

Although validated on a manufacturing case study, the proposed methodology is flexible and adaptable to other industries and sectors. Suggestions for further research include the analysis of additional case studies, so that some additional guidelines can be developed for the inclusion or exclusion of indicators according to the type of supply chain (service-based, chemical-based, etc.). Moreover, multicriteria decision analysis methodologies could be employed in order to explore potential trade-offs among indicators. This would provide a simpler way to communicate with the decision maker.

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Abbreviations

AF—	Allocation factor [mass or volume allocation]
AHP—	Analytic Hierarchy Process
BC—	Backorder Cost indicator (EUR)
BE—	Bullwhip Effect [ratio]
C—	Corruption [Number of lawsuits]
Cap—	Capacity
CDE—	Carbon Footprint [ton CO ₂]
CE—	Carbon Emissions [ton CO ₂]
C.U.—	Component Unit
DDD—	Delivery Due Date
Def—	Defective flow
Dem _c —	Demand of compound c
Dem _e —	Demand of Entity e
e—	Entity
E—	Total number of entities in a given path
EC—	Energy Cost [EUR]
EDD—	Earliest Due Date
EE-VSM—	Energy and Environment VSM
EILC—	Entity Inventory Level Cost
En—	Energy consumed in each entity of the path
EPA—	Environmental Protection Agency
EPEI—	Every Part Every Interval
EVM—	Environmental VSM
EVSM—	Extended Value Stream Map
FAR—	Fatal Accident Rate [Event/ (workers*time)]
FG—	Finished Goods

<i>Fop</i> —	Flow of the open path
<i>FTF</i> —	Flexibility Time Factor [ratio]
<i>FVF</i> —	Flexibility Volume Factor [ratio]
<i>Gen</i> —	Green Energy
<i>HC</i> —	Holding Cost
<i>Hs</i> —	Highest Salary
<i>Inv</i> —	Inventory
<i>IT</i> —	Inventory Turn [time units]
<i>JIT</i> —	Just in Time
<i>KPI</i> —	Key Point Indicator
<i>LE</i> —	Labor Equity [ratio]
<i>LS</i> —	Lowest Salary
<i>LT</i> —	Lead time
<i>LTF</i> —	Lead Time Factor [time units]
<i>MVA</i> —	Material Value Added [EUR]
<i>MF</i> —	Mass flow
<i>Ne</i> —	Number of Employees
<i>Ninc</i> —	Number of Incidents
<i>Nls</i> —	Number of Lawsuits
<i>OLTF</i> —	Operational Lead Time Factor [dimensionless]
<i>OEE</i> —	Overall Equipment Efficiency
<i>OP</i> —	OK-Parts indicator [%]
<i>OTE</i> —	Overall Throughput Effectiveness [%]
<i>p</i> —	Path
<i>P</i> —	Total number of paths passing in that entity
<i>P_{Ex}</i> —	Price of the product when leaving the supply chain
<i>P_{En}</i> —	Price of the raw material or the product before the value-added chain
<i>P_{Ut}</i> —	Price of the utility (fuel, electricity, etc.) []
<i>Rm</i> —	Raw mMaterial
<i>SC</i> —	Supply Chain
<i>SE</i> —	Sustainable Energy [%]
<i>SKU</i> —	Stock Keeping Units
<i>SLQF</i> —	Service Level Quantity Factor [dimensionless]
<i>SLTF</i> —	Service Level Time Factor [dimensionless]
<i>SSCM</i> —	Sustainable Supply Chain Management
<i>SMED</i> —	Single Minute Exchange of Dies
<i>S.U.</i> —	Supply Unit
<i>TFop</i> —	Theoretical Flow of Open path
<i>TILC</i> —	Total Inventory Level Cost [EUR]
<i>TOC</i> —	Theory of Constraints
<i>TPM</i> —	Total Preventive Maintenance
<i>VF</i> —	Volume flow
<i>VLT</i> —	Variability Lead Time [time units]
<i>VSM</i> —	Value Stream Map
<i>W</i> —	Waste
<i>WF</i> —	Waste Factor [ratio]
<i>Wh</i> —	Working Hours
<i>WIP</i> —	Work in Progress

Appendix A. Indicators

Table A1. Summary of all indicators proposed in the SustainSC-VSM methodology.

Indicator	Description	Units
Material Value Added	Value added in the supply chain per path	Euro
Energy Cost	The cost of energy consumption per path	Euro
Total Inventory Level Cost	The cost of the inventory per path	Euro
Entity Inventory Cost	The percentage of cost that represents each entity	Ratio
Backorder	The total value of lost sales per path	Euro
Lead Time Factor	The total lead time per path	Time
Operational Lead Time Factor	The percentage of time that represents each entity	Ratio
Inventory Turns	The inventory that takes longer to empty per path	Time
Service Level Quantity Factor	The accomplishment of the delivered quantity per path	Ratio
Service Level Time Factor	The accomplishment of the delivered time per path	Ratio
OK-Parts	The quality of the delivered product per path	Percentage
Overall throughput effectiveness	Comparing actual to maximum attainable productivity p.e.p.	Percentage
Volume Flexibility	The capacity to adapt to volume demand changes per path	Ratio
Time Flexibility	The capacity to adapt to time demand changes per path	Ratio
Carbon Emission	The CO ₂ emissions into the environment per path	Tons CO ₂
Waste Factor	The disposal of waste material per path	Ratio
Sustainable Energy	The ratio of renewable energy used per path	Percentage
Labor Equity	The distribution of employee compensation per path	Ratio
Fatal Accident Rate	Statistical method that reports the number of incidents per path	Inc/(Em*Time)
Corruption	The total number of lawsuits per path	Lawsuits
Variability of lead time	The variability of the Lead Time Factor per path	Time
Bullwhip Effect	The demand variation of the first entity per path	Ratio

Appendix B. Data Collection

The following data are composed of the information collected in order to apply the SustainSC-VSM methodology to the presented case study.

Price of Utilities: For entities, the data were obtained from (<https://www.argusmedia.com/metals-platform/priceindex>) (accessed on 24 February 2021). for European electricity prices and from (https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_03) for the USA electricity price (accessed on 24 February 2021). For transport flows, the fuel (gasoline) prices come from (<http://www.globalpetrolprices.com>) (accessed on 24 February 2021).

Energy Consumption: The consumption was estimated from the annual report (92.381 MWh) and the Alfa Laval ratio (EUR 1 million of value added/300 MWh) [67]. For transport flows, the energy consumption was determined assuming the average fuel consumption of a truck (17.4l/100 km) [70].

Holding Cost: The holding cost was estimated considering the premise: the more complex the component, the higher the cost, and from the annual figures of the inventory cost (SEK 258 million) [67].

Green Energy: For entities, the consumption of green energy was estimated from the annual report of the company (827 MWh) [67]. The annual report figures consider all the divisions of Alfa Laval; therefore, the data are just a fraction of the report figures. For transport flows, it was assumed that all the trucks are gasoline engine vehicles; therefore, the green energy is estimated as 0 in all the transport paths.

Employees: The number of employees was estimated from the annual report figures of the company [67]. The annual report figures consider all the divisions of Alfa Laval (16.468 employees); therefore, the data are just a fraction of the total number. In the allocation of employees in each factory, the amount of flow and the nature of the entity were considered. For example, a factory requires more employees than a distribution center.

Capacity: The process capacity of each facility was estimated from the data of the demand. The higher the demand for an entity, the higher the process capacity of the entity.

Carbon Footprint: For entities, the carbon footprint of the entities was estimated using two sources of information:

- The annual report (34.440 tons CO₂ manufacturing) [67];

- The ratio between transport and production emissions (49.777 tons CO₂ transport/34.440 tons CO₂ manufacturing) [67].

For transport flow, the data of the carbon footprint were estimated using the ratio (105.5 g/(tonne*km)) [67].

Waste:

The defective flows are all the parts/final products that had quality problems and that, therefore, will be waste. Waste is considered as all the parts and final products that are not able to be reprocessed and all other material flows of production or packaging that will be waste. Therefore, waste includes the defective flows.

For entities, the waste was determined adding the defective flow and a complementary mass flow of material disposal which was assumed, since there were no data available.

For transport flows, the waste values match with the defective flow values because the only source of waste is the defects that may occur during the transport. Packaging waste has not been considered.

Lawsuits, Salaries and Incidents: The number of lawsuits, the salaries and the numbers of incidents were assumed, since there were no data available. The number of incidents makes reference to major injury accidents.

Working Hours: Finally, the number of worked hours per year was obtained from (<https://data.oecd.org/emp/hours-worked.htm>) (accessed on 24 February 2021).

Price of Product and Raw Materials: The price of the steel and copper is from (<https://www.argusmedia.com/metals-platform/priceindex>) (accessed on 24 February 2021). The final price of the heat exchanger was estimated from an Alfa Laval catalogue (<https://pdf.directindustry.com/pdf/alfa-laval/heating-cooling-systems/16602-769212.html>) (accessed on 24 February 2021).

Customer Demand, On-Time Flow and Theoretical Flow: The customer demand, the on-time flow and theoretical flow were estimated from the values of the flow of each path.

Delivery Due Date and Earliest Due Date: The delivery and earliest due dates were estimated from the Lead Time Factor.

Variance of Lead Time, Demand and Flow Path: The variances of lead time, demand and flow path were assumed since there were no data available. The mean value was used as a reference on the assumptions.

Open Paths:

Price of Product and Raw Materials: The price of the steel and copper is from (<https://www.argusmedia.com/metals-platform/priceindex>) (accessed on 24 February 2021).

The final price of the heat exchanger was estimated from an Alfa Laval catalogue (<https://pdf.directindustry.com/pdf/alfa-laval/heating-cooling-systems/16602-769212.html>) (accessed on 24 February 2021).

Customer Demand, On-Time Flow and Theoretical Flow: The customer demand, the on-time flow and theoretical flow were estimated from the values of the flow of each path.

Delivery Due Date and Earliest Due Date: The delivery and earliest due dates were estimated from the Lead Time Factor.

Variance of Lead Time, Demand and Flow Path: The variances of lead time, demand and flow path were assumed since there were no data available. The mean value was used as a reference on the assumptions.

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