TÉCNICO LISBOA

A new methodology to identify supply chains sustainability bottlenecks

Eduardo Pereda Pons

Thesis to obtain the Master Science Degree in

Industrial and Engineering Management

Supervisor: Prof. Ana Isabel Cerqueira de Sousa Gouveia Carvalho

Jury

Chairperson: Prof. Ana Paula Ferreira Dias Barbosa Póvoa

Supervisor: Prof. Ana Isabel Cerqueira de Sousa Gouveia Carvalho

Member of the Committee: Prof. Tânia Rute Xavier de Matos Pinto Varela

June 2015

Abstract

The world globalization has been creating a very strong competition amongst companies. To maintain their market position, companies need to guarantee that all their activities are performed with high efficacy and efficiency standards, allowing not only a business profit but also a good company image among their stakeholders. Such reputation is not definitely related only to the service level and the economic performance but also to the way environmental and social aspects are treated within the companies' strategy.

This thesis explores these concerns and presents a simple and systematic methodology (SustainSC-VSM) for supply chain analyses. SustainSC-VSM is composed of a value stream map and a complementary analysis which is based on the *Sustain-Pro* methodology. SustainSC-VSM will screen and identify the main bottlenecks, regarding sustainable factors (economic, environmental and social) in any supply chain. Moreover, SustainSC-VSM proposes an information factor in order to improve the coordination among the supply chain actors and their sustainable performance. A set of new indicators is applied during the analysis; these indicators aims to identify the bottlenecks in terms of sustainability of the supply chain. The analysis of these indicators points out the issues to be improved, when the future state Value Stream Map is designed. A set of best practises is also presented as a guideline to undertake this last step. A case study is presented to highlight the applicability of the developed methodology. The obtained results point out the direction to harmonize business efficiency standards and sustainability in the supply chain.

Key words

Supply Chain; Sustainability; Value Stream Mapping; Indicators; *Sustain-Pro*; Lean

Acknowledgements

I would like to thank Dr. Ana Carvalho, and Dr. Ana Povoa for giving me the opportunity to work on this thesis. I am really satisfied with all the acquired knowledge because I strongly believe that this knowledge would be very useful for my career. I specially want to thank Dr Ana Carvalho for her guidance during the thesis and her efforts to help me to pursue my future plans. I also want to thank all the members of the jury to make the effort to correct my thesis in a record time to help me to pursue my future plans.

I want to thank my parents for their emotional support during the thesis and their faith in me. I also would like to thanks my brother for their wise councils and their willingness to help me to overcome the obstacles that came up while I was doing the thesis.

Finally, I want to express my appreciation to all the new people that I've met in Lisbon especially Franc, my Erasmus buddy, for enjoying with me this fantastic experience

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Nomenclature

AF- Allocation factor (mass or in volume allocation)

AHP- Analytic Hierarchy Process

BC- Backorder Cost indicator

BE- Bullwhip Effect

BSC- Balance ScoreCard

C- Corruption Indicator

Cap- Capacity

CDE- Carbon Footprint

CE- Carbon Emission indicator

CO- Component Unit

CSR- Corporate Social Responsability

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 Consumption indicator

EDD- Earliest Due Date

EILC- Entity Inventory Level Cost

En- Energy consumed in each entity of the path

EPEI- Every Part Every Interval

EVSM- Extended Value Stream Map

FAR- Fatal Accident Rate indicator

FG- Finished Goods

Fop- Flow of the open-path

FTF- Flexibility Time Factor

FVF- Flexibility Volume Factor

Gen- Green Energy

HC- Holding Cost

Hs- Highest Salary

Inv- Inventory

IT- Inventory Turn indicator

JIT- Just in Time

KPI- Key Point Indicator

LE- Labour Equity indicator

Ls- Lowest Salary

LT - Lead time

LTF - Lead Time Factor indicator

MVA- Material Value Added indicator

MF - Mass flow

NGOs- Nongovernmental Organisations

Ne- Number Employees

Ninc- Number Incidents

Nls- Number Law Sues

OLTF- Operational Lead Time Factor indicator

OEE- Overall Equipment Efficiency

OP- OK Parts indicator

OTE- Overall Throughput Effectiveness indicator

p – Path

P - Total number of paths passing in that entity

P_{Ex} - Price of the product when leaving the supply chain

P_{En} - Price of the raw material or the product before the value added chain

P_{Ut} - Price of the utility (fuel, electricity, etc)

Rm- Raw Material

SC- Supply Chain

SCM- Supply Chain Management

SCOR- Supply Chain Operation Reference Model

SE- Sustainable Energy indicator

SKU- Stock Keeping Units

SLQF- Service Level Quantity Factor indicator

SLTF- Service Level Time Factor indicator

SSC- Sustainable Supply Chain

SSCM- Sustainable Supply Chain Management

SU- Supply Unit

TBL- Triple Bottom Line

TFop- Theoretical Flow of Open-Path

TILC- Total Inventory Level Cost indicator

TQM- Total Quality Management

TOC- Theory of Constraints

TPM- Total Preventive Maintenance

TPS- Toyota Production System

VF - Volume flow

VLT- Variability Lead Team Indicator

VSM- Value Stream Map

W- Waste

WCED- World Commission on Environment and Development

WF- Waste Factor indicator

Wh- Working Hours

WIP- Work In Progress

1. Introduction

1.1 Contextualization

Supply chains have become a strategic aspect that companies have to consider if they want to achieve a good position in the global market. Therefore, in order to strive, supply chains have to embrace sustainability, extending their focus from a specific process to a general positioning, which considers the involvement of all supply chains' stakeholders (community, employees, consumers, etc). Considering these aspects, supply chains and consequently organizations, will achieve a competitive advantage (Levesque, 2012). In this context environmental and social concerns appear as key issues that will allow companies to achieve their sustainability. To achieve this goal companies have frequently adopting lean manufacturing practices (Abdulmalek and Rajgopal, 2007).

Lean production can be defined as a multi-dimensional approach that encompasses a wide variety of management practices in an integrated system, which includes just-in-time, quality systems, work teams, cellular manufacturing, supplier management, among other (Shah and Ward, 2003). These practices are generic and have been applied in many different sectors such as automotive, electronics, white goods, and consumer products (Abdulmalek and Rajgopal, 2007). In order to implement this technique some methods have been developed and presented on the literature. The most common lean manufacturing methods are cellular manufacturing, Just-In-Time (JIT), Kanbans, Total Preventive Maintenance (TPM), setup time reduction, Total Quality Management (TQM) and 5S (Dotoli, et.al., 2011). To effectively implement the aforementioned methods into companies' daily routines, several tools have been developed to help practitioners in this task. One of the tools available and frequently used is the Value Stream Mapping (VSM).

Value Stream Mapping is a simple and effective tool to identify and eliminate waste, hence enhancing the overall production control (Dotoli, et.al., 2011). While some developed tools focus on optimizing individual operations in the supply chain, applying the VSM implies working on the big picture and not individual process (Abdulmalek and Rajgopal, 2007). Consequently, VSM allows visualizing the information flow and the material flow of the entire supply chain.

1.2 Problem's characterisation

Supply chains are clearly a fundamental factor to assess a company's performance, however, performance models of supply chains lack of inclusiveness due to the inherent complexity (Beamon, 1999). In addition, identifying the supply chain bottlenecks is commonly not a straightforward process and creating the future VSM might be a difficult task. To address this issue, developing a new model seems unquestionably convenient.

Several studies have designed the future state (new improved value map) using the questions prescribed by Rother and Shook (1999) in a straightforward manner, this means using only the manual approach. However, in some cases, defining the future state for a process may be difficult using only the value stream map. Moreover, mapping a complex manufacturing system and identifying its critical issues is commonly not straightforward process and it might be time consuming (McManus and Millard, 2002). Some authors have presented improved versions of the VSM analysis, which incorporates other features. McDonald et.al (2002) and Abdulmalek and Rajgopa (2007) used simulation processes and Dotoli, et.al. (2011) used analytic hierarchy procedures to test the new alternatives proposed by the VSM analysis. However, the aforementioned works were all focused on a facility level analysis.

To fulfil this research gap one question arises:

-Which is the best procedure to extend the scope of the VSM in order to embrace a sustainable supply chain in a systematic way?

Summarizing,- this thesis aims to present a new systematic methodology, which will turn the VSM analysis into a systematic procedure, which analysis the entire supply chain. The new methodology will be based on performance indicators analysis, which will allow identifying the critical areas of the supply chain in a systematic way. These performance indicators introduce a more quantitative approach to the VSM.

1.3 Methodology

The following methodology will be applied in this master dissertation. The list of steps is presented in the figure 1.

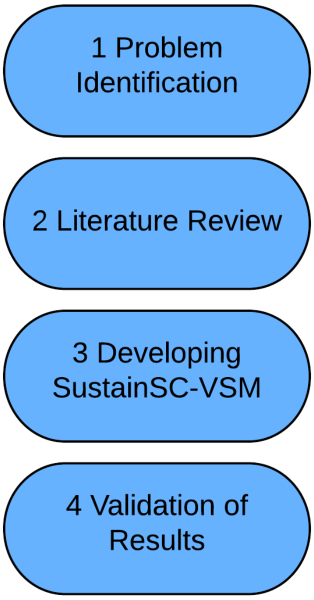


Figure 1: Thesis methodology

The first stage consists of charactering the scope of the thesis and describing the problem that will be studied.

The second step involves a literature review to identify, analyse and evaluate the previous work in this field as well as the main unanswered or unresolved issues. This reviewing is mainly focused on the lean philosophy, the techniques of *Sustain-Pro* and VSM and the measuring the supply chain performance

On the third stage, a methodology is developed to integrate the described tools in the state of art. The developed methodology is fragmented in 5 steps. Each step is presented and justified.

On the fourth step, it is studied a case of a supply chain by applying the developed methodology in order to test and validate it. This case study is based on the work developed by Persson (2011).

1.4 Structure

After the introduction of the thesis in this chapter, the following chapter will describe the main findings in the literature with special emphasis in the *Sustain-Pro* methodology, the technique of extended value stream mapping and the measuring performance in supply chain systems. At the end of the chapter, the aforementioned methodologies are combined in a structure manner, which later would compose the root of this work.

Chapter 3rd describes in detail the proposed methodology. In Chapter 4th, the proposed methodology is applied, and the results obtained from the methodology are discussed and validated. Finally, the conclusions of this work will be derived from the results.

2. State of the art

This chapter is intended to present an overview of the principles and methods, which will be the basis of this work and the previous literature presented in each technique.

In section 2.1, it is introduced the concept of sustainability, sustainable supply chain management and the main developed techniques in this field.

In section 2.2, It is defined the main features of the methodology and the targets of *Sustain-Pro* -tool used as basis in this current work.

In the section 2.3, it is introduced the need of measuring supply chain performance, the concept of multi-dimensional indicators, the main developed models in the industry and the constraints of these techniques.

In the section 2.4, it is introduced the lean philosophy and its goals. In the subsection 2.4.1, it is reviewed the "Toyota way" and the main features of this production system. In the subsection 2.4.2, it is presented a classification of lean tools and the goals that pursue the implementation of these tools.

In the section 2.5, it is presented the concept of the value stream map and the extended value stream map, the basics developed procedures and the targets.

A final subsection presents a representation with the linkage of methods and tools presented in the state of art. This final subsection presents the motivation of this work and the targets that this project pursues to accomplish.

2.1 Sustainability

The concepts of sustainability and sustainable development have emerged since governments, academic institutions, companies and non-governmental organizations have realized the increasing impact of human activity on the earth (Hutchins and Sutherland, 2008). The Brundtland Report (WCED, 1987, p. 15) settled a widely recognized definition of sustainable development as "*a development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". The Brundtland report pointed out the necessity of the society to create new coordinated strategies among all the stakeholders (Simões, 2014). However, this generic definition is difficult to apply for companies because it does not provide a solution to determine the future needs (Gimenez et al., 2012). Sustainability requires corporations' commitment to maintain the integrity of social and environmental systems while undertaking their business operations (Hutchins and Sutherland, 2008). In fact, many companies have adopted sustainable practices as a potential source of adding value, reputation building and revenue increase (Simões, 2014). There is a wide consensus that the concept of sustainability is built over the integration of three pillars: society, economy and environment (Mauerhofer 2007, Lozano 2007, Hutchins and Sutherland, 2008).

However, it is not so clear the relation and boundaries between these dimensions. Mauerhofer (2007) listed the main divergences in the literature:

- Misjudgement of equity between the three pillars
- The constrains of a sustainable system
- A lack of adequate decision support
- Misinterpretations of the integration of the three concepts

Supply chains (SC) are one of the areas that significantly impact the environment and the society. There is a general consensus in the literature to define SC. For instance, Aitken (1998, p.2) defined supply chain as *"a network of connected and interdependent organizations mutually and co-operatively working together to control, manage and improve the flow of materials and information from suppliers to end users*". Later on, Mentzer et al. (2001, p.4) defined supply chain as "*a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer.".* In other words, a supply chain consists in a group of firms both upstream and downstream that work together to bring a product to a customer.

In order to ensure the sustainability of the supply chain, it is necessary to understand how supply chains can be considered sustainable. In this context, Sustainable Supply Chain Management (SSCM) aims to harmonize environmental and social issues into Supply Chain Management (SCM) in order to increase the company's environmental and social performance as well as the suppliers' and customers' performance without compromising its economic performance (Gimenez et al., 2012). To achieve a sustainable supply chain (SSC), cooperation and integration are essential requirements at all the stages: from raw materials purchase to end customers' consumption (Ratão, 2014).Therefore, special emphasis should be given to collaborative approaches between members in the supply chain. In fact, improvement should be pursued using collaborative approaches (Gimenez et al., 2012). The triple bottom line has become a popular practise in the literature and the industry to achieve a SSC (Norman and MacDonald, 2004).

The triple bottom line (TBL) was developed by John Elkington and it was defined as: *"Triple Bottom Line accounting attempts to describe the social and environmental impact of an organization's activities, in a measurable way, to its economic performance in order to show improvement or to make evaluation more in-depth"* (Elkington, 1997). The TBL paradigm is based on the idea that the long-time success of a company or performance should be measure using economic, social and environmental parameters (Tripathi et al., 2013, Norman 2004, Amini 2013). Elkington (1997),quoted by Amini (2013) maintained that the three dimensions of sustainability are interrelated, thus economic sustainability cannot be separated from social and environmental sustainability. Norman and MacDonald (2004) summarized in the following reasons why firms ought to adopt the TBL:

- Convergence : Measuring the performance helps companies to detect the weak points and improve the performance
- Transparency: The firms have obligations towards all the stakeholders to show true and clear picture of all its account.

- Responsibility: The firms have the obligation to optimize their bottom line to obtain the highest net positive impact possible in society and environment.

John Elkington has also rephrased the TBL dimensions as the 3Ps: People, Planet and Profit in an attempt to clarify his work. In the following paragraph, it is defined the scope of each dimension.

Firstly, the profit dimension can be defined as*: "the organization's impacts on the economic conditions of its stakeholders" (*Global Reporting Initiative, 2011, p. 25). These impacts stems from the flow of capital among the different stakeholders and the main economic effects of the organization throughout society (Global Reporting Initiative, 2011). Secondly, the planet dimension can be described as: *"The organization's impacts on living and non-living natural systems, including ecosystems, land, air, and water." (*Global Reporting Initiative, 2011, p. 27). Finally, the people dimension is defined as: "*the impacts an organization has on the social systems within which it operates." (*Global Reporting Initiative, 2011, p. 29). The figure 2 displays the integration of all this dimensions.

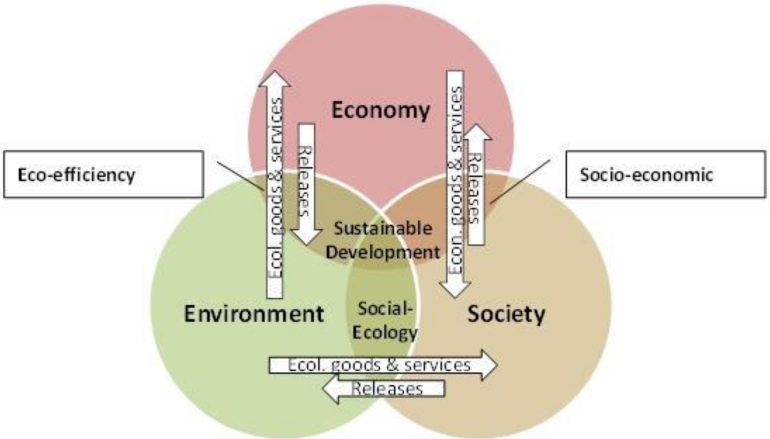


Figure 2: The Triple Bottom Line (Ruiz-Mercado et al., 2012)

Many authors has criticized the TBL approach for being difficult to implement (Amini 2013).For instance, the TBL has been criticized due to the assumption that all measures are reducible to a common unit of currency- which is true to measure the economic dimension (revenue, expenses, assets, etc...)- but not so obvious to make quantitative assessments of the goodness or badness of an action (Norman and MacDonald, 2004). Moreover, it is difficult to balance the trade-off between people, planet and profit because, most of the times, investing in people and planet undermines corporate resources to obtain more profits (Tripathi et al. 2013).

Corporate Social Responsibility (CSR) also plays an important role in the SSCM because CSR constrains the supply chain members to perform in a responsible and transparent way towards the stakeholders (Garriga and Mele, 2004). It is commonly accepted that supply chains cannot be successful in the long term if these supply chains frequently neglect the concerns of stakeholders (Norman and MacDonald, 2004). Therefore, there are strong linkages between the concepts of CSR and sustainability (Hutchins and Sutherland, 2008). Maloni (2006, p.36) explained that CSR focuses on the idea that "a corporation may be held socially and ethically accountable by an expansive array of stakeholders such as customers, employees, governments, communities, NGOs, investors, supply chain members, unions, regulators, and media." In the figure 3, it can be observed the interactions of each company with all their stakeholders.

Figure 3: Stakeholders in the SC (http://www.metricstream.com) 31/03/2015

However, the implementation of CSR presents some deficiencies such as a consumption of corporate resources to address the targets which can be an entry barrier for small companies (Ciliberti *et al.*, 2008) or a complex integration due to the great amount of factors to assess among all the supply chain actors (Simões, 2014).

Having reviewed the main aspects related to sustainable supply chains, it is clear that this work should cover the social and the environmental performance in order to achieve a positive impact over the stakeholders of the supply chain. The thesis should also pursue a systematic procedure to avoid complex integrations among different partners or subjective assessments like in the TBL or CSR. Hence the next section presents a methodology, which approaches sustainability in a systematic way, leading to a good basis for the development of this work.

2.2 Sustain-Pro

SustianPro is a tool that employs an indicator based methodology for designing new sustainable design alternatives in any process (Carvalho, 2013). The main features of this methodology are:

- A step by step procedure, which allows a systematic analysis
- Tracing and locating the bottlenecks in an industrial process
- Designing new sustainable alternatives
- Applicable to any industrial field, although it has been originally developed for chemical processes, it is a generic approach.

The methodology proposed in Carvalho, *et al.* (2008) and Carvalho, *et al.* (2009a) follows a six step procedure: Step 1-Data collection; Step2- Flowsheet decomposition into open- and closed-paths; Step 3: Indicators calculation; Step 4: Indicators Sensitivity Analysis; Step 5: Operational Sensitivity Analysis; Step 6: Generation of New Design Alternatives.

In step 1, data concerning mass and energy balances are required. This data can be obtained from simulation results or from real plant data. This data is imported to *Sustain-Pro* which then performs the flow-sheet decomposition into open- and closed-paths (Step 2). Closed-paths are the process recycles with respect to each compound or in other words flow-paths which start and end in the same unit of the process (see Figure 4). Open-paths consist of an entrance and an exit of a specific compound in the process. The presence of the compound in the system can be due to its entrance through a feed stream or by its production in a reactor unit. The exit of the respective compound can be due to an exit stream or by its reaction in a reactor unit.

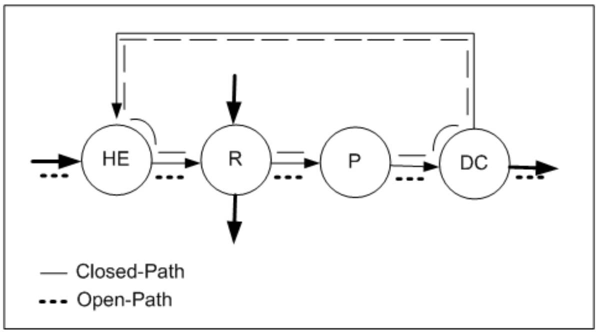


Figure 4: Open- and closed-paths representation (Carvalho, 2009b)

The flow-sheet decomposition is based on the graph theory applied to process design analysis, described by Mah (1983). The units of the flowsheet are called vertices. These vertices are connected through intermediate streams, called edges. Bold arrows pointing the vertices are referred to supply flows and the bold arrows leaving the vertices are the demand flows.

In Step 3, a set of indicators is calculated in order to determine the process bottlenecks. The set of indicators covers areas, such as value added paths, energy consumption, accumulation factors, batch operations time, etc and they were presented in Carvalho, *et al.* (2008) and Carvalho, *et al.* (2009a).The table 1 summarize the main indicators of *Sustain-Pro*

Based on the values of the indicators it is possible to point out the critical points in the process and to infer on what should be done to improve the process. On the 4th step an algorithm called indicator sensitivity analysis is performed in order to determine the target indicators. To further analyse the selected indicators, a second sensitivity analysis is conducted to the operational variables that influence the target indicators. With this 5th step it is possible to identify the variable that should be changed/ improved in order to generate a new design alternative that should be more sustainable. Finally, in the last step based on heuristics a new design alternative is created and evaluated through the use of sustainability metrics developed by Azapagic et al. (2002).

Table 1: Main indicators *Sustain-Pro*

Indicator	Formula	Parameters
Material Value Added (MVA)	$MVA = Mop(PPop - PRop)$	Mop flowrate, *PP* the sale and PR the purchase price
Energy Waste Cost (EWC)	$EWC = \sum PE * Q * \frac{m * A}{\sum m_{uk} * A_{uk}}$	Pe price of the utility, Q the energy consumption and A allocation factor
Reaction Quality (RQ)	$RQ = \sum\sum \frac{\xi_{r,rk} * E_{r,rk}}{\sum MM}$	$\xi_{r,rk}$ extend of reaction, MM molar flow, E is a parameter of the reaction
Total Value Added (TVA)	$TVA = MVA - EWC$	
Energy Accumulation Factor (EAF)	$EAF = \frac{ebl}{\sum(\sum f_{iv,k} + \sum d_{iv,op})}$	ebl energy base level, $f_{iv,k}$ and $d_{iv,op}$ are the compound flows leaving the cycle flow, *Iv* the total number of such vertices
Demand Cost (DC)	$DC = PRD * EOP$	PRD utility/stream cost, EOP flowrate of energy
Total Demand Cost (DCT)	$DCT = \sum DC$	
Total Free Volume Factor (TFVF)	$TFVF = \frac{V - \sum \frac{Map_C}{\rho_C}}{V}$	V equipment volume, ρ_C is the density of the compound c and Map is the mass of accumulation path
Operation Time Factor (OTF)	$OTF = \frac{t_j}{\sum t_j}$	Tj is the time of the operation j and
Operation Energy Factor (OEF)	$OEF = \frac{E_j}{\sum E_j}$	Ej is the energy of the operation j.

Sustain-Pro has mainly been used to locate bottlenecks in industrial processes. This works aims to enlarge the scope of the *Sustain-Pro* to identify the critical points in SC. Thereby, the adaptation of *Sustain-Pro* in the SC represents an opportunity to reduce the waste and improve the business operations. However, as Sustain-Pro has never been implemented to analysis supply chains, it is necessary to implement complementary indicators to cover all the range of the SC. Thus, the next section introduces the concept of measuring supply chain performance.

2.3 Measuring supply chain performance

Supply chains contain several echelons (e.g. supply, manufacturing, distribution, and consumers) and each echelon may comprise numerous facilities. This turns supply chains into complex structures. Given this inherent complexity, selecting appropriate performance measures for supply chain analysis is crucial (Beamon, 1999).Neely et al. (1995), quoted by Chan (2003), defines performance measure as the process of quantifying efficiency and effectiveness of an action. Performance measurement in supply chain provides decision-makers with important data which enable to monitor performance reveal progress, identify problems and improving opportunities (Waggoner et al. 1999)- “If you cannot measure it, you cannot improve it” Lord Kelvin (Sir William Thompson). However, Van Hoek (1998); Holmberg (2000) and Gunasekaran et al. (2001) identify some weak points in performance measurement systems:

- Not alienated with the company’s strategy:
- Lack of balance approach to integrate financial and non-financial measures
- Loss of the big picture, encouraging local optimization

Maskell, (1991), quoted by Beamon (1999), affirms that performance measures of the supply chain must be alienated with the strategy goals of the company. The two reasons cited for applying this principle are:

- People in the organization focus on the performance indicators; thus the performance measures will steer company direction.
- Manager can determine whether the performance is meeting the company goals

Generally, the company's strategy is based on a wide variety of aspects; thus the model to assess the supply chain also must have a multi-dimensional approach. Although the models of a single performance measure, usually cost, are attractive because of its simplicity; there are significant weaknesses. Beamon (1996) presents a number of features that are displayed to be effective in performance measurement systems. Thus, Beamon (1999) suggests extrapolating these characteristics in order to evaluate measurement systems. These features include:

- Inclusiveness: measurement of all pertinent aspects.
- Universality: allow for comparison under various operating condition.
- Measurability: required data is measurable.
- Consistency: measures consistent with organization goals.

In addition, the performance measurements must consider the effects of uncertainty in order to adapt to future changes (Beamon, 1999). That is, the used supply chain model must fit with the real world practices.

A good set of performance measurements is critical for companies to improve supply chains' effectiveness and efficiency. Decision-makers in supply chains usually focus on developing measurement metrics for evaluating performance (Cai et.al., 2009). Several metrics have been proposed in the literature and in order to systematize these metrics some works have classified the metrics according to some categories. The most common classification, divides the metrics into four categories: **quality** (Beamon, 1999; Shepherd, 2006), **time** (Beamon, 1999; Bolstorff, 2003; Shepherd, 2006), **cost** (Beamon, 1999; Gunasekaran, 2004; Shepherd, 2006), **flexibility** (Beamon, 1999; Angerhofer, 2006). The high number of metrics proposed by the scientific community led to the development of several models that try to systematize this information. Estampe et.al. (2013) presented a framework for analysing the different models used to assess supply chains. From the models collected in the framework, the more relevant for this work are presented here.

The BSC: Balanced ScoreCard, proposed by Kaplan and Norton (1996), is a model that seeks to balance measures to support the company's strategy, based on four categories: customers, finance, internal processes and innovation-growth (see, figure 11). The aims of this model are to link a company's long-term strategy with its short-term actions by choosing the indicators depending on the company's objective; and to provide a tool to managers to evaluate whether the implemented strategy works.

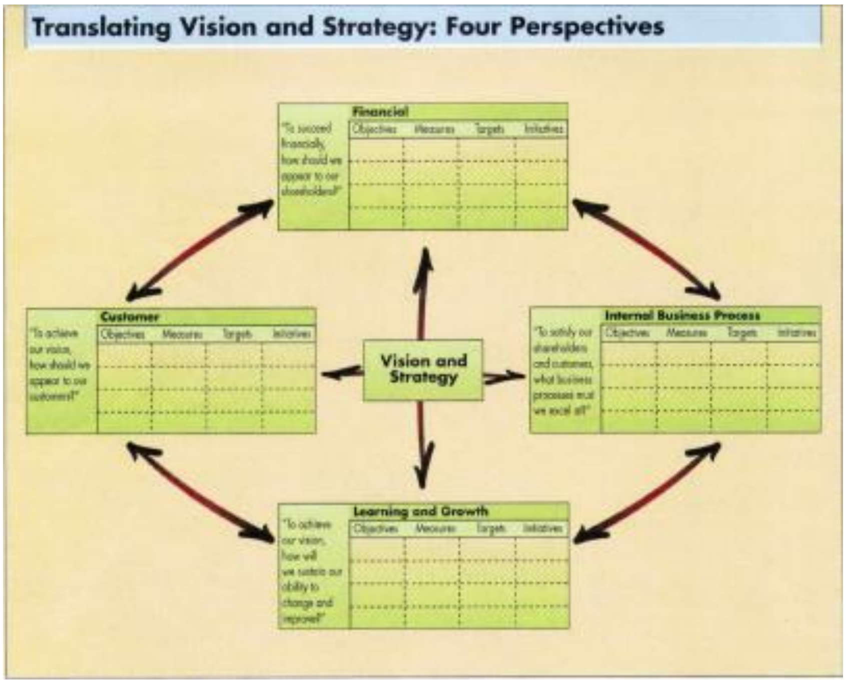


Figure 55: The four covered areas by BSC (Kaplan and Norton, 1996)

The SCOR: Supply Chain Operation Reference Model was proposed by the supply chain council (SCOR, 2013) and analyses five core supply chain performance attributes: reliability, responsiveness, agility, costs and assets. A set of standardized metrics is proposed to assess all those aspects. These metrics are hierarchized in three different levels where the first level presents the overall health of the supply chain and the last level the root causes of a performance gap in superior levels (see figure, 12). SCOR metrics provides standards down to the level where process descriptions are applicable across range of industries. Further detail is determined by the nature of the industry or the company (SCOR, 2013)

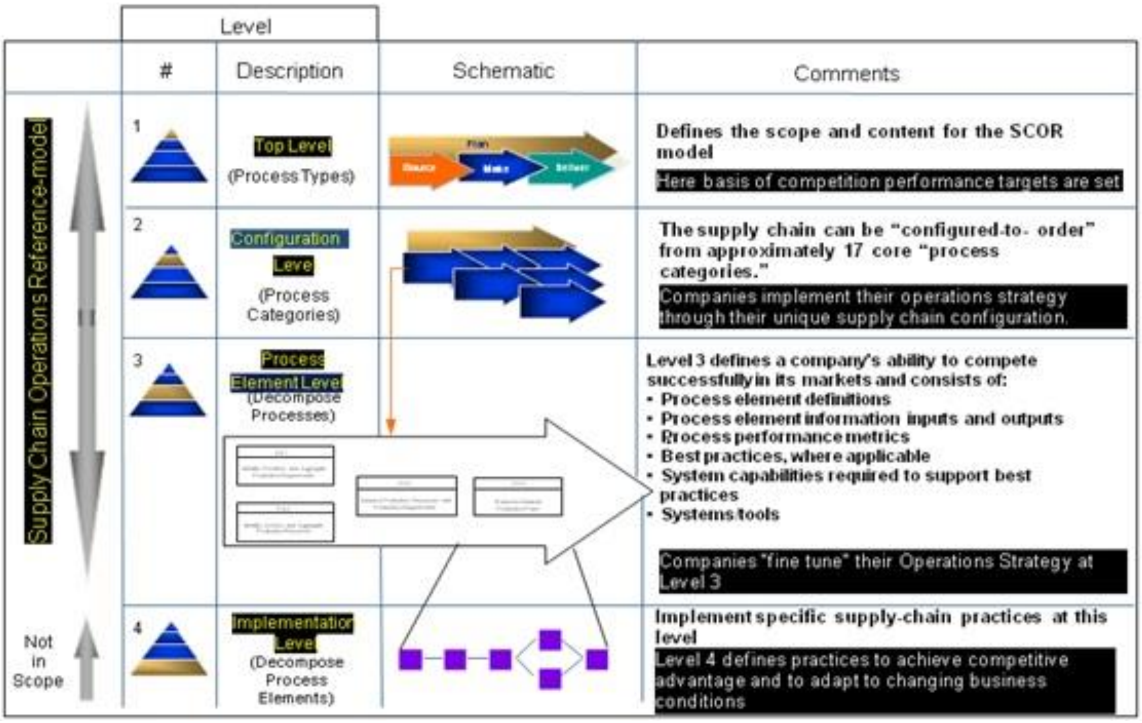


Figure 6: The metric levels of the SCOR (http://logisticsviewpoints.com) 12/03/2015

Based on the existing models and the correspondent metrics, managers have to identify the critical KPIs that need to be monitored. However, it is difficult to give priorities for KPIs, making this aspect a bottleneck for many companies in their effort for improving their supply chain management (Cai et.al., 2009). In addition, once the bottleneck has been identified and selected, it is time-consuming for managers to find the accurate improving action in order to not undermine the performance of other KPI due to the difficulty of identifying correlations and relations among indicators (Cai et al 2009). For instance, Lee and Billington (1992), quoted by Gunasekaran (2004), observed that the discrete sites in a supply chain do not maximize the efficiency if each pursues goals independently. Moreover, these models do not provide definite cause-effect between indicators and future improvements.
Although, implementing new supply chain performance indicators in Sustain-Pro helps to cover all the relevant aspects of a supply chain analysis, it is necessary to integrate additional tools to screen waste and visualize the flows in the supply chain. Thus, the next section presents the lean philosophy and its techniques.

2.4 Lean

The term lean was first introduced in the Machine that Changed the World (Womack et al., 1990). Womack et al. (1990) also highlighted the superior performance achieved applying the techniques and principles of lean philosophy, comparing with the traditional production.

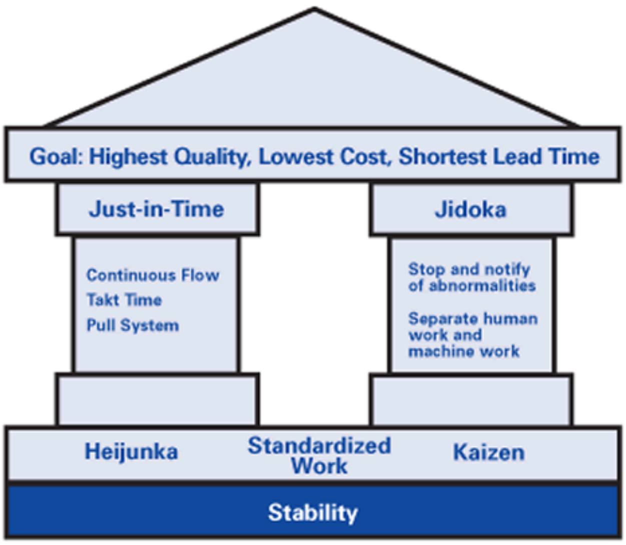
The lean principle holds that only a small portion of the lead time and necessary efforts to process a product add value to the end customer (Melton, 2005). Lean thinking begins with the customer and the concept of value (Melton, 2005). The value is determined by the quality, the price and the delivered time. The value that you add to a product is what the customer is willing to pay (Rother and Shook, 1999).Therefore, the main goal of lean thinking is to reduce waste and non-value actions in order to react better to the needs of customer and increase the performance levels. In the next subsection, the foundations of the Toyota Production System (TPS) are presented as reference model to show that beyond the philosophy there is a structured methodology.

2.4.1 Toyota Production System

Lean philosophy was developed in Toyota by Eiji Toyoda and Taiichi Ohno as a result of the extreme scarcity of resources which motivated the appearance of the Toyota Production System, after the Second World War (Abdulmalek and Rajgopal, 2007).

The foundations of TPS are built over the stability of the value stream process. Stability is defined as "the capability to create consistent results over the time"(Liker and Meier, 2004, the Toyota way p.78); while instability displays variability in the production system. The main goal of stability is to see real opportunities of improvement (Liker and Meier 2004). Stability can be implemented through standardization which ensures that work is carried out in a specific procedure. However, in the TPS, the standards are dynamic entities which are improved through *"kaizen"* sessions (Ramos, 2010)

As it can be observed in the figure 5, the TPS is sustained in two pillars: just in time and *"Jidoka".* The following paragraphs introduce these techniques



Toyota Production System "House."

Figure 7: Toyota Production System "House" from www.lean.org

Just in time is based on the premise that an upstream process only produces when a downstream is asking for a unit of production. The idea stems from the replenishment of the supermarkets where when the product stock is below a certain point, it triggers a new replenishment order (Ramos, 2010). This concept is undertaken by applying techniques such as production levelling (*"Heijunka"*) which enables avoiding peaks and valleys in the production schedule (Hüttmeir et al., 2006); or the Kanban cards which composes the information flow (Baykoq e Erol, 1998).

"Jidoka" (intelligent machines) is the second pillar of the TPS house. *"Jidoka"* refers to the machine's ability to detect problems and stop itself in order to reduce waste. *"Andon"* is one of the principal elements of "*Jidoka"* method. *"Andon"* is a signboard which notifies a quality or process problem to maintenance or other works (Liker and Meier, 2004).

TPS is more than a set of techniques; under these practices underlie a culture which Liker and Meier (2004, The Toyota Way p.48) described as: "It is about how you behave every day... and what you learn". Dennis (2007), quoted by (Ramos, 2010) states that people through their creativity and their engagement, provide the required motivation to boost lean manufacturing

All these procedures and concepts can be classified regarding their scope and their area of focus. The next section presents a classification as well as the steps to implement these techniques.

2.4.2 Lean tools and lean implementation

Lean manufacturing has been adopted by many businesses in order to gain competiveness in the global market (Abdulmalek and Rajgopal, 2007). Lean production integrates a variety of management practises to pursue creating a streamlined, high quality system that produces finished products at the pace of customer demand with little or no waste (Shah and Ward, 2003). Waste is defined as all the activities and process which do not add value to the customer (Melton, 2005). To identify value, it is necessary to adopt the customer approach and ask if you would pay less for a product or be less satisfied with it if a certain process was removed from the supply chain (Womack and Jones, 2002). Taiichi Ohno, (1988), former chief of Engineer at Toyota, identified seven different types of waste in the VSM (Figure 6):

- Over production: Manufacturing items in an upstream process before the downstream process requires these items.
- Inventory: More products that the necessary amount to meet the customers' requirements.
- Over processing: Activities not adding value that can be eliminated without damaging the process
- Transportation: Moving material between several facilities without adding any value to the customer
- Waiting: Materials wait to be processed or people waiting for materials to process them.
- Defects: Errors during the process or the delivery
- Motion: Excess movement of resources, information and decisions

Figure 8: The seven types of wastes identified by Taiichi Ohno (1988) (Melton, 2005)

Pettersen (2008) proposed a classification between a set of lean practices and their specific actions, see table 2.

Table 2: Lean techniques (adapted from Pettersen, 2008)

Collective term	Specific characteristics
Just in time	Production levelling (*heijunka*)
	Pull system (*kanban*)
	Takted Production
	Process Synchronization
Resource reduction	Small lot production
	Waste elimination
	Set up time reduction
	Lead time reduction
	Inventory reduction
Improvement Strategies	Improvement circles
	Continuous improvement (*kaizen*)
	Root cause analysis (5 why)
Defects control	Autonomation (*jidoka*)
	Failure prevention (*poka yoke*)
	100% inspection
	Line stop
Standardization	Housekeeping (5S)
	Standardized work
Supply chain management	Value stream mapping / flowcharting
	Supplier involvement

The goal of these practices is to improve the production system, but not all the systems work on the same standards or are constrained by the same factors. Thus, it is important to understand that these techniques are just a guideline and each system should tackle their problems with a personalized approach. However, the implementation could be systemized; for instance, the lean institute listed five principles for guiding the implementation of lean techniques (Lean Enterprise Institute 2008):

- Identified value from the standpoint of the customer
- Defined the value stream of the product, and eliminate whenever it is possible all the non-value steps
- Create a smooth flow towards the customer to deliver the product
- Establish a closed loop system by fulfilling the customers' needs all only when they require it.
- Seek perfection by beginning this process again until a state of perfection is achieved in which value is created with no waste.

Figure 9: Implementation Circle (Lean enterprise Institute)

Although implementing lean techniques involves a challenge to any organization, the business effectiveness and the forces supporting the application of lean are greater than those resisting it (Melton, 2005). In the figure 8 are summarized the main driving forces to adopt a lean approach and the typical issues that arise when a production process embraces a lean approach

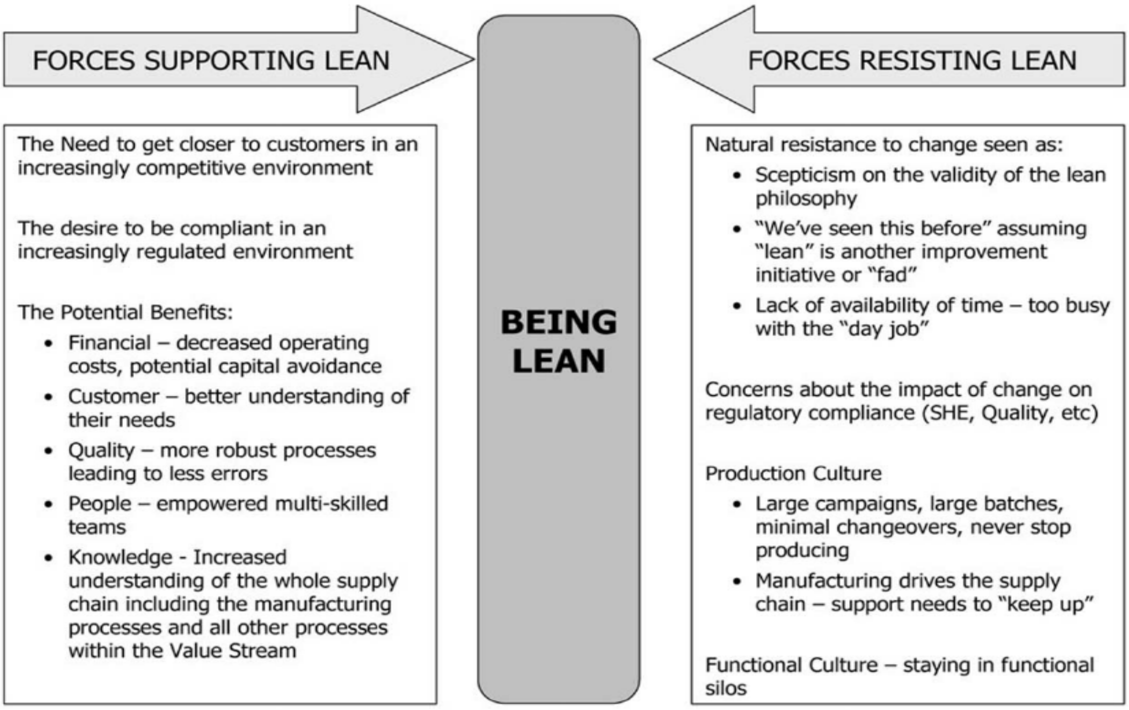


Figure 10: The forces opposing and driving a change to lean from (Melton, 2005)

The lean approach is applicable to all aspects of the supply chain and should be applied to obtain the maximum benefits in a sustainable way (Melton, 2005). As this work intends to analyse the bottlenecks in the supply chain to eliminate the waste; it is necessary to use a tool to screen the waste and all the supply chain's operations. Therefore, the Value Stream Map will help mapping and displaying the waste for managers.

2.5 Value Stream Mapping and Extended Value Stream Mapping

Value Stream is a collection of all actions, value added as well as non-value-added, which is required to bring a product (or a group of products) through the main flows, starting with raw material and ending with the customer (Rother and Shook, 1999). These actions consider both the flow of information which, moves upstream through the VSM from customer to supplier, and the flow of material which, moves downstream from supplier to customer. The two flows have equal importance in the supply chain because the information flow regulates the material flow. The two flows constitute a closed loop of demand and response (Womack and Jones, 2002).

The question that motivates the whole VSM applications is: "How can we flow the information so that one process will make **only** what the next process needs when it needs it?" (Rother and Shook, 1999, p13). The ultimate goal of VSM is to identify all types of waste ("*muda*") in the value stream and to take steps to try and eliminate these (Rother and Shook, 1999).

Several authors have been applying VSM in order to obtain lean processes and more efficient procedures in terms of manufacturing. McDonald et.al (2002) applied this tool to present a new solution for the production of high-performance motion control products manufacturing plant in the southeast US. Data was collected from Industrial Motors plants and the motors manufactured there were used in the machine tool, medical products, and aerospace and defence industries. Abdulmalek and Rajgopal (2007) presented a case where VSM was adapted for the process sector for application at a large integrated steel mill in order to achieve a new process considering the lean principles. Al-Tahat (2010) used VSM for analysing and controlling the flow of material and information through the pattern making process. The VSM allowed documenting production methods, recording relevant information and analysing the flows of information involved in the system. Later, Dotoli, et.al. (2011) applied this tool for the improvement of operations performance in a world leading manufacturer of forklifts.

While VSM is a tool whose range of scope is mainly facility-level, the Extended Value Stream Map (EVSM) is a tool which focuses on the overall supply chain. However, both techniques are based on the same principles and are complementary to each other. In fact, Womack and Jones (2002) state that the first step towards a lean EVSM is to apply the VSM procedures, in each facility belonging to the supply chain. Moreover, both techniques pursue a lean production and distribution system.

EVSM and VSM are graphical tools, in a format of a flow chart that uses a predefined set of standardized symbols, to depict and improve the flow of inventory and information. In the EVSM, it appears data boxes which typically include inventories, working hours and days, EPEI, percentage of defects, distances and sizes of batches, as it can be observed in figure 9. Moreover, there is a line chart at the bottom of the EVSM that shows cumulative data such as value and non-value steps and lead times. Therefore, this tool creates a common language about a production process, enabling more purposeful decisions to improve the value stream (McDonald et.al, 2002). Ramesh (2008) said that this visual representation helps the process of lean implementation by helping to identify the value-added steps in a value stream, and eliminating the non-value added steps. VSM also shows the linkage between the information and the material flow (Rother and Shook, 1999).

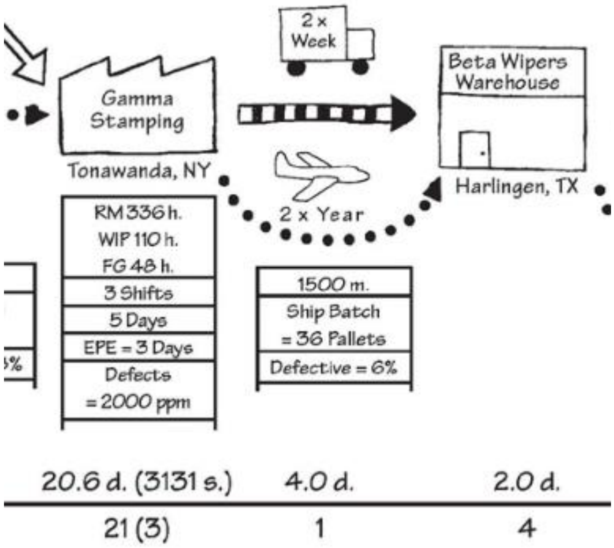


Figure 11: Part of an EVSM, (Womack and Jones, 2002)

The main purpose of EVSM and VSM is to find a new value added map that reduces waste. Rother and Shook (1999) and Womack and Jones (2002) defined a structured approach for improving an EVSM and a VSM based on 3 main steps presented in Figure 10.

- Step 1: Identify the relevant product families and select the ones that will be studied
- Step 2 :Construct a current state map for the product value stream, using information gathered from the actual production process;
- Step 3: Map the future state, which should reduce the waste of the process.

Figure 12: Steps to follow in a VSM analysis

Womack and Jones (2002) identified six features that must be accomplished to build a lean extended value stream.

- Produce at a closed rate of customer consumption.
- Very little inventory.
- Minimize transport links between steps in the production process.
- Minimize information processing, with pure signal and no noise in the information flows that remain.
- Minimize the lead time

- Changes introduced to smooth flow, eliminate inventories, and eliminate excess transport and lead time, should involve the least possible or even zero cost.

Rother and Shook (1999) identified eight questions that must be answered to construct the future state map, table 3. Five questions are concerned with "basic" issues related to the construction of the future state map, the next two address technical implementation details such as the control system ("*heijunka*"), while the last question addresses the improvement actions ("*kaizen*") needed for transition from the current to the future state. The table 3: displays the eight identified questions

Table 3: Identified Questions for future VSM

Future State Questions	
Basic	What is your takt time?
	Will you build to a finished goods supermarket from which the customer pulls, or directly to shipping?
	Where can you use continuous flow processing?
	Where will you need to use supermarket pull systems?
	At what single point in the production chain (the "pacemaker process") will you schedule production?
Heijunka	How will you level the production mix?
	What increment of work will you consistently release?
Kaizen	What process improvements will be necessary?

Although this procedure supports the design of new future state map, it is not always a straightforward procedure and companies sometime are not able to make a step forward because the questions to define the future map are subjective and wastes are difficult to identify. Hence it would be advisable to have another tool to assess the direction of the next step. First, Mcdonald et al. (2002) and later Abdulmalek and Rajgopal (2007) address this issue by implementing a simulation tool to optimize the process of mapping the future VSM. Al-Tahat (2010) approaches this issue by mapping the future VSM with an automated pattern making system. Finally, Dotoli, et.al., (2011) uses an analytic hierarchy process (AHP) tool to identify future breakthroughs in the VSM. All they coincide that combining different techniques with VSM allowed them to identify the most appropriate response. Therefore, this thesis wants to improve the EVSM implementing indicators to have a basis to work towards the future state of the EVSM.

2.6 Conclusion

This chapter has mainly presented the integration of the concepts of sustainability and lean in the supply chain.

Consolidating sustainability in the business operations is a must for companies to achieve the stakeholder's requirements. Thus, SSCM should be fully implemented among all the supply chain actors in order to reach these requirements. The TBL arose to cover the performance gap of social and environmental dimensions in the supply chains. However, the TBL and CSR do not provide a systematic approach to standardize the sustainability in the supply chain. Thereby, *Sustain-Pro* should provide a solid basis to address this issue in a systematic manner. The steps which conform *Sustain-Pro* will serve as the main scheme of the new methodology. Nevertheless, it is necessary to complement this technique with other to fully cover all the supply chain relevant aspects. In this context, adopting a lean approach allows to reach all the scope of the supply chain. The combination of Sustain-Pro and lean will reduce the waste and improve the supply chain's operations. The reviewing of lean has displayed the available techniques to improve the supply chain performance and the philosophy behind them. EVSM is highlighted among the lean introduced techniques because it provides information of the operations and links between the processes allowing managers to screen the waste. In addition, EVSM is useful to analyse complex systems without losing the big picture and avoid local optimization. Moreover, its simplicity and its standardized language convert EVSM in a universal tool as well as a workable tool for managers. However, one of the major limitations in the EVSM analysis is the quantitative procedure actually available, which sometimes leads to a difficult process and not a straightforward procedure. This weak point offers an opportunity to improve this technique implementing indicators to measure the supply chain performance. These indicators should quantify the performance and point out the critical areas. The identified bottlenecks should be addressed in the future state map.

The new methodology should be based on some of the previous developed concepts, improving and further developing them. Figure 13 schematically represents the combination of the two tools.

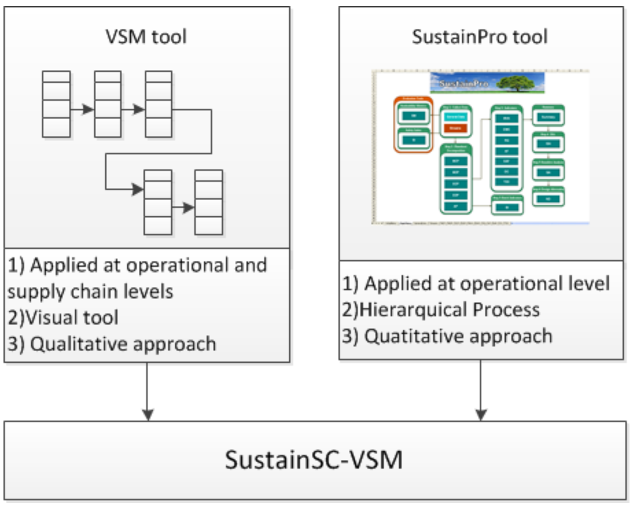


Figure 13: Combination of two tools

3. SustainSC-VSM

The SustainSC-VSM intends to provide a new alternative to detect bottlenecks in the supply chains combining qualitative and quantitative sustainable-procedures. The developed methodology is based on two pillars:

- Develop a methodology which does not compromise the future sustainability of the supply chain.
- Lean practices in order to consolidate the company share in the market and perform high efficacy and efficiency standards.

The goal of integrate a quantitative approach (introduced by *Sustain-Pro*) to the EVSM is related to the Theory of Constraints (TOC) where to improve the system is necessary to focus the efforts on the boundaries of the system. The implementation of the KPIs pursues a systematic approach to point out the bottlenecks in the supply chain;- and therefore improving the capabilities of the supply chain (Cai et.al., 2009). The theory of constraints coincides with lean thinking in the way that it considers an organization as a system of structured resources connected by a process whose ultimate goal is selling a product (Melton, 2005).

In the previous literature, It has been reviewed the measuring supply chain performance because this work aims to integrate new indicators in the *Sustain-Pro* in order to broaden the scope of the methodology and consider all the aspects of the impact of supply chain. These new indicators would facilitate the creation of a more complex model, closer to the real world.

The main goal that pursues the SustainSC-VSM is to create a methodology, which enables managers to identify bottlenecks and eliminate/ improve them, without missing the holistic perspective of the supply chain. This framework consists of an EVSM analysis that is combined with the methodology developed in the *Sustain-Pro* considering a different metric with multi-dimension and generic characteristics that will support the identification of bottlenecks points.

The flow-diagram of the proposed methodology is presented on Figure 14. Each step is explained in detail on the following section.

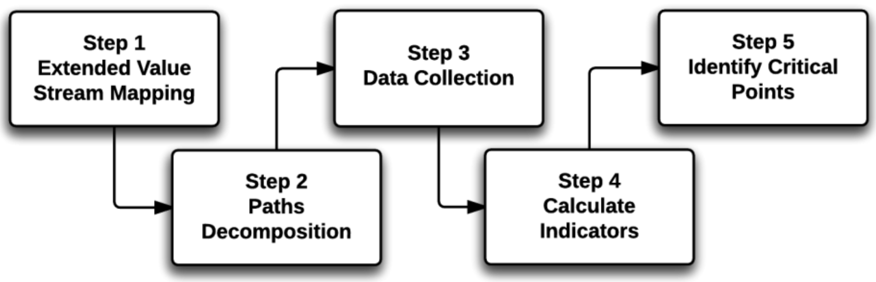


Figure 14: Flow-diagram of the new methodology

3.1 Step 1: Extended Value Stream Mapping

In this step, the sequence of entities and operations within the supply chain are represented through the EVSM. To represent the EVSM, it is recommended to follow the following procedure (Womack and Jones, 2002).

The figure 15 presents a brief scheme of the procedure to represent the EVSM.

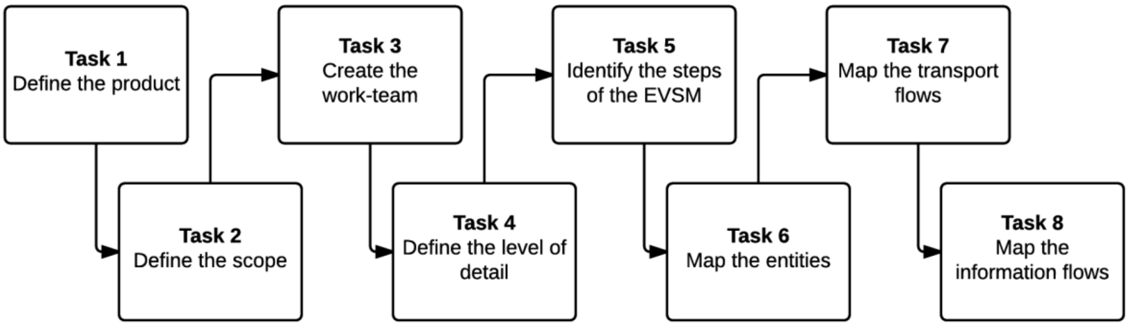


Figure 15: Flow-diagram of the EVSM tasks – Step 1 of methodology

Task 1: Identify the product family which will be studied. A product family is composed by a group of products, which follows almost the same production procedures; an example could be two products that have the same functionality or similar features, but different detailed finishes.

Task 2: It is essential to determine a manageable field of view. Womack and Jones (2002) advise to divide the whole supply chain in different parts, since the whole supply chain structure is usually too complex to be represented together. SustainSC-VSM extends the scope of EVSM by dividing the complex structure of the supply chain into smaller areas called open-path (see Step 2 of methodology).

Task 3: Although this task is not mandatory for the analysis procedure, it is recommended to create a work-team involving all the entities and companies of the supply chain, to work together. As reviewed in the literature, improvement must involve all the actors in the supply chain.

Task 4: it is essential to determine the level of detailed of the EVSM. It is important to notice that the scale of EVSM is much larger than the VSM which focuses on facility-level. Therefore, it is critical to include the essential information of the flows, and define a suitable boundary; otherwise all the amount of information is overwhelming and the EVSM is no longer useful.

Task 5: The information about the flow-rate, which undergoes the value stream should be quantify. Also, the lead times that the flow undergoes and the value added times should be quantify too.

Task 6: Start mapping from the retailer or last entity in the supply chain, which is the one that triggers the entire production, to the more upstream process. Since supply chains are very large network, it is recommended mapping each entity like a single process. Three kinds of entities are differentiated: factories, warehouses or cross-docks and retailers (the last entity in the path). Each entity is drawn following the standards symbols (some of them in figure 16).Each entity has a data box where all the required data appears. The data box varies depending on the entity:

- If the entity is a factory, the data box includes the average times that the flow spends in the raw material warehouse, being processed and in the final good warehouse; the ratio of defects and the EPEI.
- If the entity represents a retailer, the data box includes the daily or weekly demand of each product of the family.
- If it is a warehouse, the data box needs to specify the ratio of defects and the average time that the flow spends in the warehouse

Task 7: After defining the entities, the transportation flows are mapped using the predefined symbols. It is important to differentiate between the usual shipment flow which must include the frequency of the shipments and the expedited shipment flow (a dotted line). Although it only will be analysed the usual shipment flow in the 3rd step of the methodology (SustainSC-VSM), it is necessary to include both on the EVSM in order to reflect the frequency of the rush or special orders between facilities. Under each transport flow, it is necessary to add a data box displaying:

- Distance between facilities
- Time between facilities
- Shipment average order batch size
- Average ratio of defects of the shipment process

Task 8: After defining the transport flows, the information flows are mapped using the predefined icons. Each flow must detail the frequency of the communications and each production control department ought to specify the processing time of the information data.

The symbols proposed by Rother and Shook (1999) are used to represent all actions from suppliers to customers. Figure 16 presents the main symbols used in this tool.

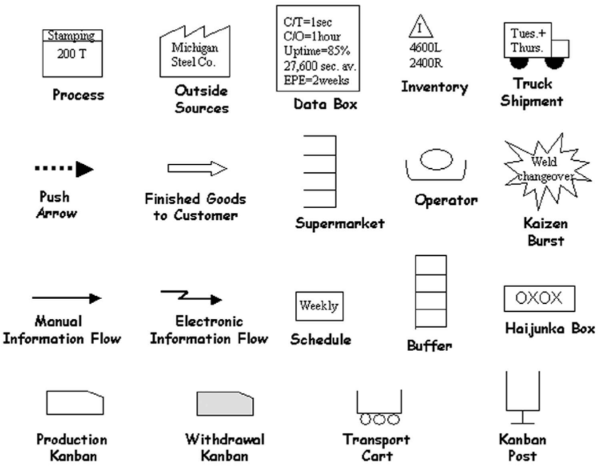


Figure 16: Most common symbols used in VSM (McDonald, 2010)

After this step, the work-team can already visualize the sequence of all activities in the supply chain. All activities with value added and non-value added will be identified accordingly to their sequence and connection.

3.2 Step 2: Path Decomposition

The supply chain network, represented by EVSM, will be analysed using the graph theory. The entities will be considered as the vertices. These vertices are connected through intermediate streams, called edges. Following the aforementioned procedures the decomposition of the EVSM into open- and closed-paths should be performed in this step. For each path it will be calculated the correspondent flow of components. The flows for open- and closed-paths will be determined following the methodology presented in Carvalho, et.al (2008) and Carvalho et al. (2013).

The decomposition into paths allows to break down the supply chain network into smaller areas facilitating the process of bottleneck identification. Since the paths are correlated to a specific compound, it easier to identify the compound and the respective path that is presenting a problem. To identify and prioritize the major bottlenecks a set of indicators should be analysed, so that they can evaluate the different closed- and open-paths. The indicators are calculated in the 4th step.

3.3 Step 3: Data Collection

In this step, all important data on the supply chain operations needs to be collected. This means the already specified data for EVSM analysis and additional data. Each supply chain must establish the scope of the data. The considered time might vary depending on the type of supply chain. For instance, if there are seasons with a demand peak or a slowdown such periods must be treated separately. It is recommended to the users to assess the demand pattern of the supply chain and to try to delineate the best time interval that frames the most common operations or the critical periods were this methodology should be applied. The table 4 displays all the data that should be collected

Table 4: Data to collect

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 Law Sues	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 Law Sues		
Demand downstream entity		
Lower Salary		
Higher Salary		
Working hours per year		

3.4 Step 4: Calculate Indicators

Designing the future EVSM is not always an evident procedure despite the six features that were identified by Womack and Jones (2002). Thus, in this step, a set of indicators is proposed in order to assess the supply chain paths. The indicators are applied to all paths allowing carrying out a comparative analysis among the paths and prioritizing the retrofits actions that should be taken to improve the initial EVSM. The suggested KPI’s pursue pointing out the bottlenecks of EVSM.

In the literature, there is a gap when it comes to integrate coordination among members of the supply chain in order to improve the three dimensions of sustainability. The proposed indicators will cover all the sustainable areas plus a new information area which will ensure the optimal coordination between entities in order to increase the sustainability performance. In fact, the proposed indicators should lead companies to embrace sustainability. In the figure 17 can be observed the integration of this new proposed dimension with the classical sustainable dimensions.

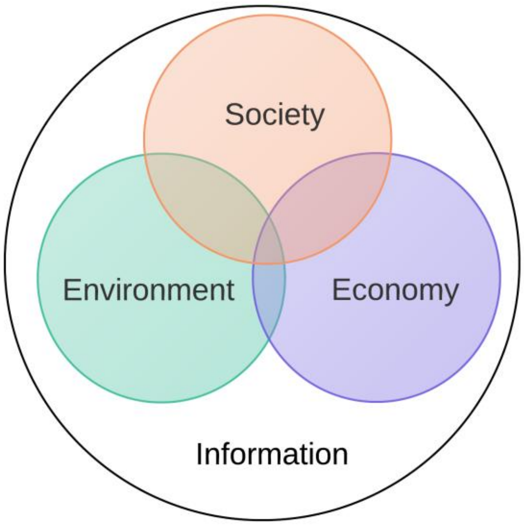


Figure 17: Integration of sustainability dimensions for supply chain assessment

It is important to be aware that some indicators are contrary to other; thus a trade-off needs to be accomplished between conflicting objectives. Moreover, companies must not improve all the indicators; otherwise too many resources are consumed. Therefore, managers must select carefully the indicators regarding their business vision; understanding vision as the state of the company once the companies have reached their mid-term or long-term goals.

The indicators will be presented grouped in the aforementioned categories. Each category comprises a group or subgroups of indicators where it can be found the explanation of the indicator, the formula and the desired value of the indicator. Some indicators have been adopted from previous works (those that have a reference citing the original author) and the others that don't have reference are the new proposed indicators

3.4.1 Economic Indicators

The economic indicators do not only comprise financial reporting measures, but the creation of value measures. These economic indicators aim to assess if the limited resources of the company are applied effectively to create wealth for the company and value for the customer. As presented in section 2.5, several authors state that the accomplishment of the strategic goals in any supply chain implies a good control system, which should include performance measurements regarding cost, quality, time and flexibility of the supply chain (Beamon, 1999; and Sheperd 2006). These attributes are enough to display the competitiveness of the supply chain

3.4.1.1Cost

The cost of the supply chain is the most important aspect of supply chain's models. However, it is required a deep understanding of the total distribution cost to accomplish a competitive supply chain. Gunasekaran et al. (2004, p.6) states that "The efficiency of a supply chain can be assessed using the total logistics cost—a financial measure. It is necessary to assess the financial impact of broad level strategies and practices that contribute to the flow of products in a supply chain". To this end, this subsection proposes a set of indicators to assess the most relevant costs in the supply chain.

Material Value Added –SC (*MVA-SC*)

MVA-SC gives the value added between the entrance and the exit of a given material, meaning the value generated between the start and the end point of the path. MVA-SC is calculated through equation 1.

$$MVA\ SC = Fop * (P_{Ex} - P_{En}) \tag{1}$$

Where *Fop* is the flow of the open-path, P_{Ex} is the price of the product when leaving the supply chain and P_{En} is the price of the raw material or the product before the value added chain. This indicator is expressed in € and consequently negative values of *MVA-SC* point out the need for improvements. *MVA-SC* was adapted to the supply chains context from a previous work developed by Carvalho et.al (2008).

Energy Cost-SC (*EC*)

EC-SC provides the value of the energy consumption through the path. *EC-SC* is calculated applying equation 2.

$$EC\ SC = \sum_{e=0}^{E} P_{Ut} \times En_e \times AF_e \tag{2}$$

Where P_{Ut} is the price of the utility (fuel, electricity, etc), *En* is the energy consumed in each entity of the path and *AF* is the allocation factor, which gives the allocation of the energy consumed per path. *AF* can be calculated depending on the companies' policies to be given in mass or in volume allocation (see equation 3 and 4).

$$AF = {}^{MF}/_{\sum_{p}^{P} MF} \tag{3}$$

$$AF = {}^{VF}/_{\sum_{p}^{P} VF} \tag{4}$$

Where *MF* is the mass flow, *VF* is the volume flow, *p* is the path and *P* is the total number of paths passing in that entity. This indicator is expressed in €. High values of *EC* point out the need of improvements, since high energy costs are being observed in a given path. This indicator was adapted to the supply chains context from a previous work developed by Carvalho, et.al (2008).

Total Inventory Level Cost (*TILC*)

Although inventory is necessary to buffer market and operational uncertainties; it is also true that inventory sometimes hides inefficient management of supply chain processes that causes extra costs in the supply chain and damages the supply chain competiveness (Jammernegg and Reiner, 2007). According to the US Department of Transportation (2002) the inventory cost represents a 33% of the logistic cost. Aiming of keeping track of this issue, the Total Inventory Level Factor (*TILC*) indicator gives information about the most critical paths in terms of inventory costs. This indicator presents high values when the inventory for a given stock keeping units (*SKU*) is in excess of inventory. Equation 5 is applied to calculate the TILC indicator.

$$ILC = \sum_{e=0}^{E} Inv_e * HC_e * Afe \quad (5)$$

Where *Inv* is the inventory of entity *e*, *HC* is the holding cost of a given *SKU* in an entity *e.* This indicator is given in €, therefore the higher the indicator value, the higher is the inventory cost in a specific path. This means that high *TILC* values point out supply chains improvements.

<u>Entity Inventory Level Cost (*EILC*)</u>

EILC gives the information about the most critical entity in terms of inventory cost, within the identified critical path in terms of *TILC*. Equation 6 gives the expression to calculate this indicator.

$$EILC = \frac{Inv_e \times HC_e * Afe}{\sum_{e=0}^{E} Inv_e * HC_e * Afe} \quad (6)$$

This indicator is given in a ratio; therefore the closest value of *EILC* to 1 represents the bottleneck of the path in terms of inventory cost.

<u>Backorder Cost (*BC*)</u>

When a company runs out of stock, the company is exposed to lose the order as a result of the customer's need to purchase a product. Even worse, the poor service level might lead the customers to change to a competing brand (Ye, 2014). Thus, it is necessary to monitor these losses through the Backorder Cost indicator which displays the total value of lost sales in a given path. *BC* is calculated by equation 7.

$$BC = (Dem_c - F_{OP}) \times ((1 + i) \times P_{Ex}) \quad (7)$$

Where Dem_c is the demand of component *c*, F_{OP} is the flowrate of the open-path, P_{Ex} is the price of the product when leaving the supply chain and *I* (penalty rate) is the increment in percentage over P_{Ex}. The price of not selling a given *SKU* is usually higher than the selling price. This happens because when the orders are not accomplished customers might be lost and the customers' company might have to be compensated by the failure in the delivery. Therefore, the price considered in the *BC* expression is the price of the product when leaving the supply chain with an increment which each company must adjust it regarding their specific position. High values of *BC* point out to the need of improvements, since many backorders are being observed.

3.4.1.2 Time

The flow usually spends a lot of time and goes through a lot of operations in the supply chain, without adding any value to the customer. On the contrary, as mentioned on the literature review, customer would be more satisfied if the product could be delivered faster. According to Womack and Jones (2002), most value streams can be compressed in order to eliminate unnecessary processing time. For this, this subsection proposes three indicators related to the time in the supply chain.

Lead Time Factor (*LTF*)

Lead time is a key factor to measure the performance in a supply chain due to the fact that it directly influences the inventory performance and the production forecast (Warren and Chang, 2010). Short lead times gives an enormous competitive advantage to companies; for example, if a company manages to shorter enough their lead time, it may enable the value stream to respond to real orders rather than inaccurate forecast and therefore reducing the quantity of waste (Womack and Jones, 2002). Lead time also plays a very important role in the bullwhip effect,- a long lead time in replenishment orders aggravates the distortion of information (Lee et al., 2004). Distortion of information will be discussed later in the subsection 3.4.4. In this context, *LTF* gives the total lead time in each path (see equation 8). This indicator allows the determination of the most critical paths in terms of lead time to the final customers, or in other words the paths that more easily can contribute to a problem in the service level accomplishment due to the waiting time associated.

$$LTF = \sum_{e}^{E} LT \qquad (8)$$

LT respresents lead time of the entity *e*. This indicator is calculate in time units; usually days. High values of *LTF* point out the need of improvements. This indicator was adapted to the supply chains context from a previous work developed by Carvalho, et.al (2009).

Operational Lead Time Factor (*OLTF*)

OLTF gives the information about the most critical entity in terms of lead time, within the identified critical path in terms of *LTF*. Equation 9 gives the expression to calculate this indicator.

$$OLTF = \frac{LT_e}{\sum_{e}^{E} LT} \qquad (9)$$

OLTF is a ratio, the highest value of *OLTF* points out the bottleneck in terms of entity lead time. This indicator was adapted to the supply chains context from a previous work developed by Carvalho, et.al (2009).

Inventory Turnover (*IT*)

Order batching is a common phenomenon in supply chain,- Supply chain members tend to reduce costs by implementing economies of scale. For example, buyers have several discounts when purchasing large quantities and transport cost tend also to be reduced. However, these policies that can be considered as local-optimizations can provoke the bullwhip effect (Lee et al., 2004). Inventory turnover is a common metric used to display the number of times that the inventory is consumed in a time period. In this paper, the *IT* indicator is used to point out the inventory which takes longer to empty in a given path. This indicator is only applied to entities with inventory; *IT* is calculated applying the following equation 10

$$IT = max\left(\frac{Inv_e}{Dem_e}\right) \qquad (10)$$

Where *Inv* is the largest inventory of the entity *e*, *Dem* is the demand of the downstream process in the considered period of time. *IT* is expressed in time units, usually days. The higher is the value of *IT*, the higher is the lead time, the less agile is the path and the more likely is to appear the bullwhip effect in the path. The *IT* indicator was adapted to the supply chains context from a previous work developed by Womack and Jones (2002).

3.4.1.3 Quality

Measures of quality reflect the ability of a supply chain to deliver a high customer service (Sheperd and Günter, 2006). While a positive perception of a company's service quality can lead to its long-term survival, a negative perception can result in an erosion of trust of all stakeholders, thereby damaging seriously the viability of the firm (Soltani et al. 2010). Therefore, quality performance can be used as competitive advantage to gain market share. Having a competitive value stream means a high level of quality which implies serving zero defects products to the customer in the required quantity and on the proper time (Rother and Shook, 1999) Thus, this subsection proposes a set of indicators to measure all the relevant aspects of quality in the supply chain

Service Level Quantity Factor (*SLQF*)

A lack of attention in the service level in terms of quantity or time leads to a loss of customers which promotes the competing brands and compromises the economic sustainability of the company. To address this problem, the *SLQF* indicator gives information about the accomplishment of the delivered quantity when compared to the placed orders. This indicator is calculated through the application of equation 11.

$$SLQF = \frac{Dem_c - Fop}{Dem_c} \tag{11}$$

The *SLQF* is expressed as a ratio. Values different from 0 of SLQF highlight that the service level in terms of quantities delivered are not being accomplished and consequently that path is not satisfying the customer.

Service Level Time Factor (*SLTF*)

Deng and Wortzel (1995) carried out an empirical study of supplier selection criteria and the service level time was considered one of the most important features among the companies of the study. Thereby, *SLTF* indicator gives information about the accomplishment of the delivered time when compared to the schedule. Equation 12 presents the expression used to calculate this indicator.

$$SLTF = \frac{F_{OP-OnTime}}{F_{OP}} \tag{12}$$

Where *OnTime* is the flowrate of the open-path delivered according to the schedule time. Values different from 0 of *SLTF* stress the need of improvement in the service level in terms of time delivery; thus the path is not performing according the customer requirements.

Ok-Parts (OP)

Many supply chain models assume perfect manufacturing processes,- but, in any production system, there are defects in the manufacture processes as result of human error, machine settings or other factors (Giri and Sharma, 2014). As previously mentioned in the literature defects represents a waste in the value stream (Taiichi Ohno, 1988), in order to keep track of it and try to raise awareness of this issue the Ok-Parts indicator displays the percentage of flow which goes from the raw material to the customer arms and reaches the suitable quality. The indicator is calculated applying the following equation 13.

$$OP = \prod_{e=0}^{E}(1 - \frac{Def_e * Afe}{Fop}) * 100 \quad (13)$$

The *Def* is the defective flow rate of the entity *e*. The *OP* indicator is expressed as a percentage. The farther the percentage is to 100, the lower is the quality performance of the path. A low quality performance shows a need of improvement due to the fact that the path is not accomplishing the supply chain quality standards.

Overall throughput effectiveness (*OTE-SC*)

The production performance of each member has a great impact in the supply chain. Buchmeister et al., (2012) verified that the Overall Equipment Efficiency (*OEE)* level on downstream stages has a significant influence on inventory fluctuation and order variability in the supply chain. Therefore, it is important to take into account the stability and the performance of production to assess the supply chain. Muthian and Huang (2007) introduced the Overall Throughput Effectiveness (*OTE*) metric for factory-level performance monitoring; *OTE* is based on the *OEE* which was developed by Nakajima (1988). The *OTE-SC* metric proposed in this work is developed based on the idea of comparing actual productivity to maximum attainable productivity for a given path. The indicator is calculated applying the following equation 14.

$$SC - OTE = \frac{\mathrm{Fop}}{TFop} * 100 \quad (14)$$

TFop stands for the theoretical flow of an open-path working at full yield. The *OTE-SC* indicator is expressed as a percentage. Low values of *OTE-SC* display a poor production performance and point out the need of improvement the production yield. *OTE-SC* was adapted to the supply chains context from a previous work developed by Muthian and Huang (2007)

3.4.1.4 Flexibility

Flexibility provides the ability to manage rapid changes in demand or supply (Sheperd and Günter, 2006). There are several aspects that should be considered regarding supply chains' flexibility. Beamon (1999) proposes that supply chains' flexibility should be assessed considering four aspects Volume Flexibility, Delivery Flexibility, Mix Flexibility and New Product Flexibility. However these dimensions are not always a problem to all supply chains. Some of them just appear in some specific supply chains and they depend on the product that is being commercialized. Slack (1983), quoted by Beamon (1999), identified that flexibility should be applied to enhance the production objectives such as delivery or volume. Moreover, Das and Abdel-Malek (2003) identified time and volume flexibility as a frequent source of disagreement between buyers and suppliers. Thus, this work will cover volume flexibility and time flexibility. Volume flexibility is required to overcome customer order fluctuations and time flexibility is essential to fulfil rush orders or special orders (Beamon, 1999). However, it is recommended that companies verify their needs in terms of indicators covering other flexibility aspects, when required.

Flexibility Volume Factor (*FVF*)

Beamon (1999, p.286) states that "given the universality of the uncertain environment in which supply chain systems exist, volume flexibility is commonly desirable". To this end, *FVF* indicates if a company has capacity to adapt its production to demand changes in terms of quantity. This indicator can be calculated through equation 15.

$$FVF = \min(\frac{Cap_e - Dem_e}{Cap_e}) \qquad (15)$$

Where Cap_e is the process capacity of the entity *e* of a given path. The *FVF* is expressed as a ratio value. The lower the value of the *FVF*, the lower is the capacity of the company to adapt its production to demand fluctuations.

Flexibility Time Factor (*FTF*)

Ideally, a supplier should provide the buyer with the needed flexibility to adjust their supply process as demand conditions change (Das and Abdel-Malek, 2003). Therefore, FTF displays the company ability to adapt its production to meet the demand changes in terms of time. This Indicator can be calculated applying equation 16.

$$FTF = \frac{(DDD - EDD)}{(DDD)} \qquad (16)$$

Where *DDD* is the due date for delivery, *EDD* is the earliest due date which the delivery can be submitted. *FTF* is expressed as a ratio value. This indicator was adapted to the supply chains context from a previous work developed by Beamon, (1999). The lower the value of *FTF*, the lower is the capacity of the company to deliver their products in front of a change of deadlines.

The table 5 presents a summary of the introduced indicators in the dimension of economic sustainability of the SustainSC-VSM methodology:

Table 5: The economic indicators of SustainSC-VSM

Indicator	Indicator Description	Units
Material Value Added	Value added in the supply chain per each path	Euro
Energy Cost	The cost of energy consumption per each path	Euro
Total Inventory Level Cost	The cost of the inventory per each path	Euro
Entity Inventory Cost	The percentage of cost that represents each entity	Ratio
Backorder	The total value of lost sales per each path	Euro
Lead Time Factor	The total lead time per each 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 each path	Time
Service Level Quantity Factor	The accomplishment of the delivered quantity per each path	Ratio
Service Level Time Factor	The accomplishment of the delivered time per each path	Ratio
OK-Parts	The quality of the delivered product per each path	Percentage
Overall throughout 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

3.4.2 Environmental Indicators

As a result of an intensive economic growth in the last century, the production of goods has increased the pressure on the environment (Mintcheva, 2004).To reverse this situation, some companies influenced by stakeholder's pressure have adopted environmental indicators as a support tool to enhance friendly environmental policies. Many quantitative performance metrics has been developed to determine the impact of the supply chain in the environment such as GHG emissions, waste generation, material recycle or energy use (Chaabane et al., 2010). Investing in more environmentally respectful materials and procedures can lead to resource reduction and manufacturing efficiency, resulting in reduced manufacturing costs (Gimenez et al., 2012). In addition, environmental indicators display a green image which influences the demand of customers (Pishvaee and Shakouri, 2009). The proposed indicators are diverse and cover different environmental aspects of the supply chain

Carbon emission (*CE*)

According to a survey carried out by Accenture (2009), more than one-third of companies have no awareness of the level of emissions in their supply chain network and only 10 per cent of companies have implemented an active policy to reduce their supply chain carbon footprints. However, Chaabane et al. (2010) proved with their model that efficient carbon management strategies are compatible with achieving sustainable targets in a cost effective way. To keep track of this issue, it is necessary to implement the *CE* indicator that quantifies the CO_2 emissions of each open path of the supply chain into the atmosphere. Equation 17 represents this indicator.

$$CE = \sum_{e=0}^{E} AF_e \times CDE_e \quad (17)$$

Where *AF* is the mass allocation factor and *CDE* is the carbon footprint emitted by each entity. The *CE* indicator can be expressed tons of CO_2. High values of *CE* point out to the need of adopting more energy efficient equipment, vehicles and facilities; or optimizing the supply chain operations.

<u>Waste Factor (*WF*)</u>

A green strategy pursues the recovery of waste by promoting recycling, instead of getting rid of disposals (Lam et al., 2012). Thereby, measuring the waste of material represents an opportunity to reduce the waste and improve the green image of the company. The *WF* provides information about the disposal of material that is produced in the supply chain per each path. This indicator can be calculated through the Equation 18.

$$WF = \frac{\sum_{e=0}^{E} W_e * AF_e}{Fop} \quad (18)$$

Where *We* is the waste of material in the entity *e*. This indicator is expressed as ratio. High values of *WF* point out a need for improvements due to the fact that the excess of material waste represents an overexploitation of environmental resources and one opportunity to reduce purchasing costs.

<u>Sustainable Energy (*SE*)</u>

In 2012, fossil energies were dominating the energy market with a share of 87% (Lam et al., 2012). However, as this energy is not sustainable in a long-term, it is necessary to boost a cleaner and affordable energy to meet the increasing customer demand (Lam et al., 2012). In order to address this issue, *SE* indicator aims to improve energy efficiency. The sustainable energy indicator displays the company commitment to use friendly-environmental resources to manufacture and transport the product in a given path. Equation 19 presents the expression used to calculate this indicator.

$$SE = \frac{\sum_{e=0}^{E} Gen_e * Af_e}{\sum_{e=0}^{E} En_e * Af_e} * 100 \quad (19)$$

Where *En* is the consumption of energy of entity *e* and *Gen* is the consumption of green energy of the entity *e*. The *SE* is expressed as percentage value. Low values of *SE* reveal a low degree of environmental sustainability in the supply chain and the need of policy changes in terms of energy consumption. *SE* was adapted to the supply chains context from a previous work developed by Mintcheva, (2014).

The table 6 presents a summary of the introduced indicators in the environmental sustainable dimension of the SustainSC-VSM methodology:

Table 6: The environmental indicators of SustainSC-VSM

Indicator	Indicator Description	Units
Carbon Emission	The CO_2 emissions into the environment per each path	Tons CO2
Waste Factor	The disposal of waste material per each path	Ratio
Sustainable Energy	The ratio of renewable energy used per each path	Percentage

3.4.3 Social Indicators

Indicators of social performance display the company's policies towards their stakeholders (suppliers, employees, customers…). These metrics provides information about the employee situation in the company and the relationship of the company with other private and public institutions or community groups (Carvalho, 2009). However, there is still a lack of consensus in the literature to determine the best approach to evaluate social sustainability (Simões, 2014). However, Simões (2014) identifies 4 elements that stakeholders believe worthy of protection:

1. Labour practices
2. Human Rights
3. Product Responsibility
4. Society

The proposed indicators cover all the aforementioned topics.

Labour Equity (*LE*)

The main driving force of the labour market is the salary,- Companies provide their employees with salary, healthcare insurances and other advantages in return of the employee's labour, skills and expertise (Hutchins et al., 2008). To assess this trading, the labour equity indicator describes the distribution of employee compensation including all benefits such as bonus within an organization. This Indicator can be calculated applying equation 20.

$$LE = \min(\frac{Ls_e}{Hs_e}) \tag{20}$$

Where *Ls* represents the lowest salary of a given entity *e* and *Hs* is the highest salary including all the benefits (usually, the Chief Executive Officer (CEO)). The closer the LE ratio is to one, the greater is the equity distribution. This indicator was presented by Hutchins et al., (2008) and adapted to supply chains.

Fatal Accident Rate (*FAR*)

The *FAR* is a statistical method that reports the number of incidents (usually applied to deaths) of an activity based on the total amount of employees working their entire lifetime. "Fatal accidents included all the incidents that occurred at the workplace, excluding non-work-related traffic accidents and self-inflicted poisoning by alcohol or drugs." (Roberts, 2008, p.45). This Indicator can be calculated applying equation 21

$$FAR = \frac{\sum_{e=0}^{E} Ninc_e * 10^8}{\sum_{e=0}^{E} NE_e * Wh_e} \qquad (21)$$

Where *Ninc* is the number of incidents in the entity *e*, for example deaths or major injuries, it depends on the field of the industry is being analysed and the object of the analysis; *NE* the number of employees that works in the entity *e* and *Wh* the working hours per year. The *FAR* is expressed as event/(workers*time). High values reveal need of improvement in the company's procedures or a change in the operations. The *FAR* was introduced by the British chemical industry and adapted to supply chain analysis.

<u>Corruption (*C*)</u>

Corruption represents a risk for companies because it destroys free market competition and undermines their image. It also enables enormous flows of illicit money outside the real economy; in the form of unpaid taxes, bribes and laundered funds (Kowalczyk-Hoyer, 2012). A clear example of how corruption damages social sustainability is that some of the countries with large amount of natural resource are also home of the world's poorest communities. If there were less corruption in payments made to governments to exploit their natural resources, there would be more money available for development. The *C* indicator is calculated applying the following equation 22.

$$C = \sum_{e=0}^{E} Nls_e \qquad (22)$$

Where *Nls* means number of law sues of each entity. The corruption indicator is expressed in law sues. Values not equal to 0 reveal need for improvements to avoid corruption practices.

The table 7 presents a summary of the introduced indicators in the dimension of social sustanability of the SustainSC-VSM methodology:

Table 7: The social indicators of SustainSC-VSM

Indicator	Indicator Description	Units
Labour Equity	The distribution of employee compensation per each path	Ratio
Fatal Accident Rate	Statistical method that reports the number of incidents per each path	Inc/(Em*Time)
Corruption	The total number of law sues per each path	Law sues

3.4.4 Information Indicators

This new proposed field of sustainability in the supply chains aims to assess the effectiveness of coordination among the members of the supply chain and the potential breakthroughs that can be implemented in the information sharing policies. The performance of the supply chain depends on the quality of the information used. Thus, information flows are a vital part of coordination among the members of the supply chain. The information flows have a direct impact on the inventory levels, the production schedules and the shipments (Lee et al. 2004). The information distortion can lead the supply chain to the appearance of the bullwhip effect. Lee et al. (2004, p.1875) refers to the bullwhip effect as "the phenomenon where orders to the supplier tend to have larger variance than sales to the buyer (i.e, demand distortion), and the distortion propagates upstream in an amplified form (i.e., variance amplification)". Lee et al. (2004) quotes a report of Kurt Salmon Associates that quantifies the economic impact of the bullwhip effect in excess cost around 12.5% to 25%. The proposed indicators display will prevent the bullwhip effect and ensure the coordination of the supply chain.

Variability of Lead Time (*VLT*)

Assuming lead time as constant is not feasible in a supply chain, - A lot of non-controllable factors influence the lead time. Sabato and Bruccoleri (2005), cited by Canella et al. (2013), concluded that considering lead time as a constant would lead to underestimate the bullwhip effect on about 30%, they also showed that in some cases, reducing lead time variability is more effective than reducing lead time average to remove the bullwhip effect. The *VLT* aims to provide a tool to monitor this issue. *VLT* can be calculated applying equation 23.

$$VLT = \frac{\sigma_{LTF}}{LTF} \qquad (23)$$

Where *LTF* is the Lead Time Factor of the given path and σ is the Standard Deviation operation. This indicator is expressed in the same units that *LTF*. High values of *VLT* reveal a need for improvement in the stability of the information flow across in a given path of the supply chain.

Bullwhip Effect (*BE*)

The information distortion in the supply chain leads to the bullwhip effect which propagates upstream in an amplified form. The demand amplification can affect the performance of the supply chain promoting extra costs and periods of overproduction and underproduction (Lee et al., 2004). The implementation of techniques such as information sharing to prevent the bullwhip effect is highly recommended. However, high variations in the demand cannot be anticipated with these techniques (R. Dominguez et al., 2013). Fuller et al., (1993) estimated that 75 billion $ from the 100 million $ which is worth the grocery market inventory were due to inefficiencies in the supply chain. Hence, these figures reflect the need for an indicator to monitor this issue. In this context, *BE* indicator provides information about the demand variation in the more upstream process of a given path. *BE* indicator can be calculated applying equation 24.

$$BE = \frac{\sigma_{Fop}}{\sigma_{Dem}} \qquad (24)$$

Where σ_{Fop} and σ_{Dem} represent the variance of the orders of the first entity of a path and the demand of the flow in a given path. The order rate variance ratio, also known as bullwhip magnitude, was proposed by Chen et al. (2000) to be used as a quantifier of the bullwhip effect. The original formula has been adapted to fit with the context of the open-path. Since the larger variations of order quantity are located in the most upstream process (Lee et al. 2004), each path only focuses on the demand amplification of the first entity considered in the analysis. High values of BE highlight the need of enhancement.

The table 8 presents a summary of the introduced indicators in the dimension of information sustainability of the SustainSC-VSM methodology:

Table 8: The social information of SustainSC-VSM

Indicator	Indicator Description	Units
Variability of lead time	The variability of the Lead Time Factor per each path	Time
Bullwhip Effect	The demand variation of the first entity per each path	Ratio

3.5 Step 5: Identify Critical Points

The indicators above described are applied to each path and based on their values it is possible to identify the most critical supply chain areas. The indicators are ordered from the most critical value to the less critical value. Indicators in the top are the bottlenecks of the supply chain process and consequently they are the ones that should be firstly analysed and efforts to improve them should be done.

In the following table 9, there are a few guidelines that suggest a way to improve each indicator. These guidelines must be used as a point of reference. As stated in the literature, each supply chain has different factors and bottlenecks so it should deal with their bottlenecks from a particular approach.

Table 9: Guidelines to address the critical points

Indicator	Best Practises
MVA-SC	Redesign the production process
EC-SC	Invest in more efficient equipment, vehicles or facilities or reduce the number of operations
TILC *EILC*	Reduce the level of production and demand uncertainty. The production uncertainty can be reduce implementing robust production processes and the demand uncertainty can be reduce locating a large buffer near the end customer to protect the supply chain from market uncertainties or applying a production levelling technique *("heijuka")*
BC	Enhance supply chain coordination and inventory management policies.
LTF *OLTF*	Ideally, all activities should be located at the same place near the end customer. However, this situation it is not possible, so the advisable way to proceed is to locate facilities that share material flows as near as possible, taking into account the costs that suppose this enterprise. Promoting just in time tools such as pull systems or process synchronization also short the lead time
IT	Reduce the inventory gradually making sure that it does not compromise the service level or reducing the size of the batches and increasing the pick-up frequency.
VF *TF*	Redirect the flow of material to another path with less workload or increment the work capacity purchasing newer and more effective machinery and tools.
OK-P	Implement failure prevention techniques ("poka yoke") in every facility to reduce scrap and rework in the production processes.
SLQF *SLTF*	Enhance the information sharing between members of the supply chain to know the capacity constraints and the inventory management of each supplier. In accordance with the collected information, find out a way to deliver the required orders in the proper quantity and time.
OTE-SC	Implement kaizen workshops to reduce the production uncertainty (technical losses, organizational losses, quality losses and changeover times)
VLT	Standardize all the process of the value stream to gain stability and create consistent results over the time
BE	Implement a centralized multi-echelon inventory control system; they have a superior performance that independently operating site-based inventory.
CE	More energy efficient equipment, vehicles and facilities; or optimizing the supply chain operations
WF	Redesign the production process to be more efficient and promote recycle policies
SE	Improving the energy efficient and investing in renewable energies
LE	Improving the lowest salary or reducing the highest salary
FAR	Improving labour conditions by implementing more security standards and training the employees about the risks of their jobs
C	Workshops to raise awareness among managers and more information transparency towards external agents of society

3.6 Conclusions

A generic methodology for assessing sustainable supply chains has been presented. The proposed methodology has a generic approach and can be applied to assess any supply chain. First, the methodology presents an EVSM that allows to picture the flows and operations that takes place in the supply chain. Later on, the supply chain is divided in different open-paths. To these paths, a set of indicators is applied. The proposed indicators cover the economic, environmental, social and information performance of the supply chain. Comparing the values of the indicators within a given supply chain, it is possible to determine the bottlenecks of the supply chain. At this point, a set of best practices is suggested to address the identified critical points. Through this procedure, every supply chain can be analysed in a systematic way. Applying this methodology should point out towards the direction to design the new improve EVSM.

In the following chapter, the methodology is tested to validate the proposed methodology.

4. Case Study

Firstly, it is presented the description of the case study where it is explained the case study and the scope of the case study in the section 4.1. Secondly, SustainSC-VSM is applied to the case study; each section from 4.2 to the 4.6 represents a different step of the methodology. Thirdly, a sensitivity analysis is conducted to validate the results in the section 4.7. Finally, the conclusions from the case study are presented in the section 4.8

4.1 Case Study Description

The case study used to apply the proposed methodology is based on a supply chain of a heat exchangers' manufacturer (see Figure 19). The case study was adapted from Persson (2011). The original case study was based on the Swedish company Alfa Laval. "Alfa Laval is a global provider of specialised equipment, systems and services, dedicated to heat, cool, separate and transport products such as oil, water, chemicals, beverages, foodstuffs, starch and pharmaceuticals" (Persson 2011, p.292)

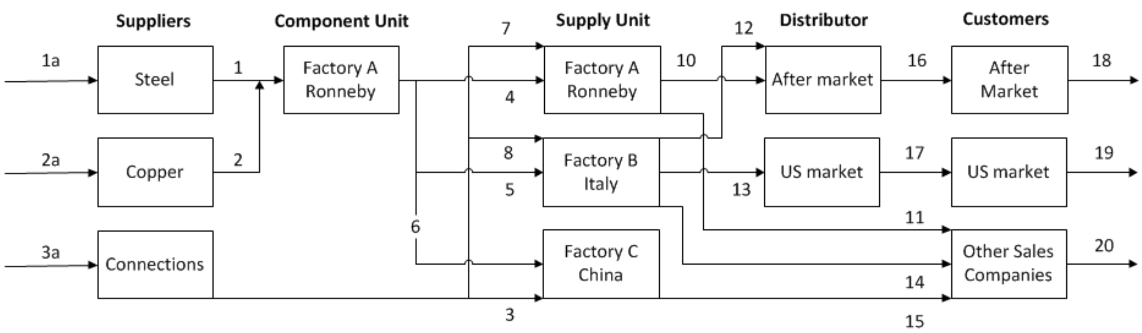


Figure 18: Supply Chain (Adapted from Persson, 2011)

The supply chain of the heat exchangers starts with the suppliers of the main components used in the manufacturing. Steel and copper are sourced from different suppliers to the main manufacturing component unit, located in Ronneby. The critical components are then distributed to the three supply units located in Ronneby, Italy and China. Connections are sourced locally for each supply unit. The US and the aftermarket are supplied by distribution centers. The other sales companies and end customers are supplied by all supply units and not through the distribution centers.

The component unit in Ronneby manufactures a critical component used in manufacturing of the end product. The manufacturing of the critical component is divided into one part that supplies the Ronneby supply unit in a make-to-order (MTO) environment and the other part manufactures the component in a make-to-stock (MTS) environment, based on forecasts. The manufacturing of the supply units (Ronneby S.U. and Italy S.U) is made in a MTO environment.

In this thesis, it will only be studied in depth the parts of the supply chain that serve to the after-market and to the U.S. customer market due to time constraints. Therefore, the other companies market is not analysed. This fact has forced to make the simplification of considering only the flow relevant to the after-market and U.S. customer market; instead of taking into account the entire flow-path for the decomposition and the application of indicators. Although, this simplification slightly modifies the final results, it is reasonable to accept the validity of the obtained results from this case study, since the structure in study is already complex enough.

4.2 Case Study - Step 1: Extended Value Stream Map

The supply chain structure presented in the figure 18 should be discomposed into three EVSM representations. However, this thesis only presents in deep the after-market EVSM, which is introduced in the figure 19. The following paragraphs and tables explain the structure of the after-market EVSM and the source of the data. At the end of the subsection, figure 20 displays the EVSM of the U.S. customer market too.

The after-market supply chain comprises various echelons: the supplier stage is represented in blue colour, the manufacture stages are represented in green colour, the distributor stage is represented in orange colour and finally the retailer stage is yellow. In the thesis, it has been assumed that the Italian factory is located in Monza where Alfa Laval has a real manufacturing unit (http://www.alfalaval.com/contact-us/?countryid=860), viewed on 9/06/2015 and the distribution center is located in Denmark where Alfa Laval has a real distribution center (http://www.alfalaval.com/contact-us/?countryid=860) viewed on 9/06/2015. All the distance and time data of the EVSM have been estimated using google maps. All the other data that appear in the data boxes (EPEI, defects, inventory days, batch and demand) of the EVSM have been estimated by collecting information from different EVSMs (Womack and Jones, 2002), the Alfa Laval sustainable report (Alfa Laval, 2014) and some assumptions. In the following bullet points, all the data is justified and all the assumptions are explained in detail.

- The frequency of the shipments, the time, the defects, the EPEI and the number of steps were estimated by resemblance with other EVSMs (Womack and Jones, 2002). In the column of steps, the first and the second figures represent the total number of steps that the flow undergoes in an entity and the value added steps respectively.
- The distance and the shipment time were obtained from google maps.
- The demand was estimated from the Alfa Laval report (Alfa Laval, 2014) and from some assumptions such as the heat exchangers represents the 40% of the sales in the equipment divisions and the after-market represents a 35 % of the total market share.

The tables 10 and 11 summarize all the entity and transport information of the EVSM respectively.

Table 10: Summary of the data boxes of the entities

Data Boxes	TIME				Total	Epei	Defects	Steps
	Rm(days)	WIP(days)	FG(days)	Value added(s)				
Ronneby C.O.	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 11: Summary of the data boxes of the 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	0,2 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%	2x Week	1
Ronneby C.O-IT	2,4 days	2122	10 pallets (50 u/p)	2,01%	Weekly	1
Ro C.O. -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%	4x 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 represent the offices where the information flows are managed in the supply chain. All the data is transmitted electronically from one entity to another. As it has been explained previously, the part of the component unit that serves to Italy S.U. works in a MTS environment. The supply unit and the part of the component unit that serves to Ronneby S.U. work in a MTO environment. This implies that the supply units only schedule batches in response to a confirmed order. The following table 12 explains briefly the nature and the frequency of the information flows. The entire data that appears in table 12 has been estimated by resemblance with others EVSM (Womack and Jones, 2002) and the supply chain description from Persson (2011). The numbers that appear in the information flows of the EVSM (figure 19) are associated with the column number of the table.

Table 12: Description of the information flow of the EVSM

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	2x Week	Source Stocked Product
8	Ronneby S.U.-PCRonneby	4x Week	Shipping Release
9	PCRonneby-Ronneby S.U.	4x 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.O.-PCRonneby	Daily	Shipping Release
14	PCRonneby- Ronneby C.O.	Monthly	Forecast

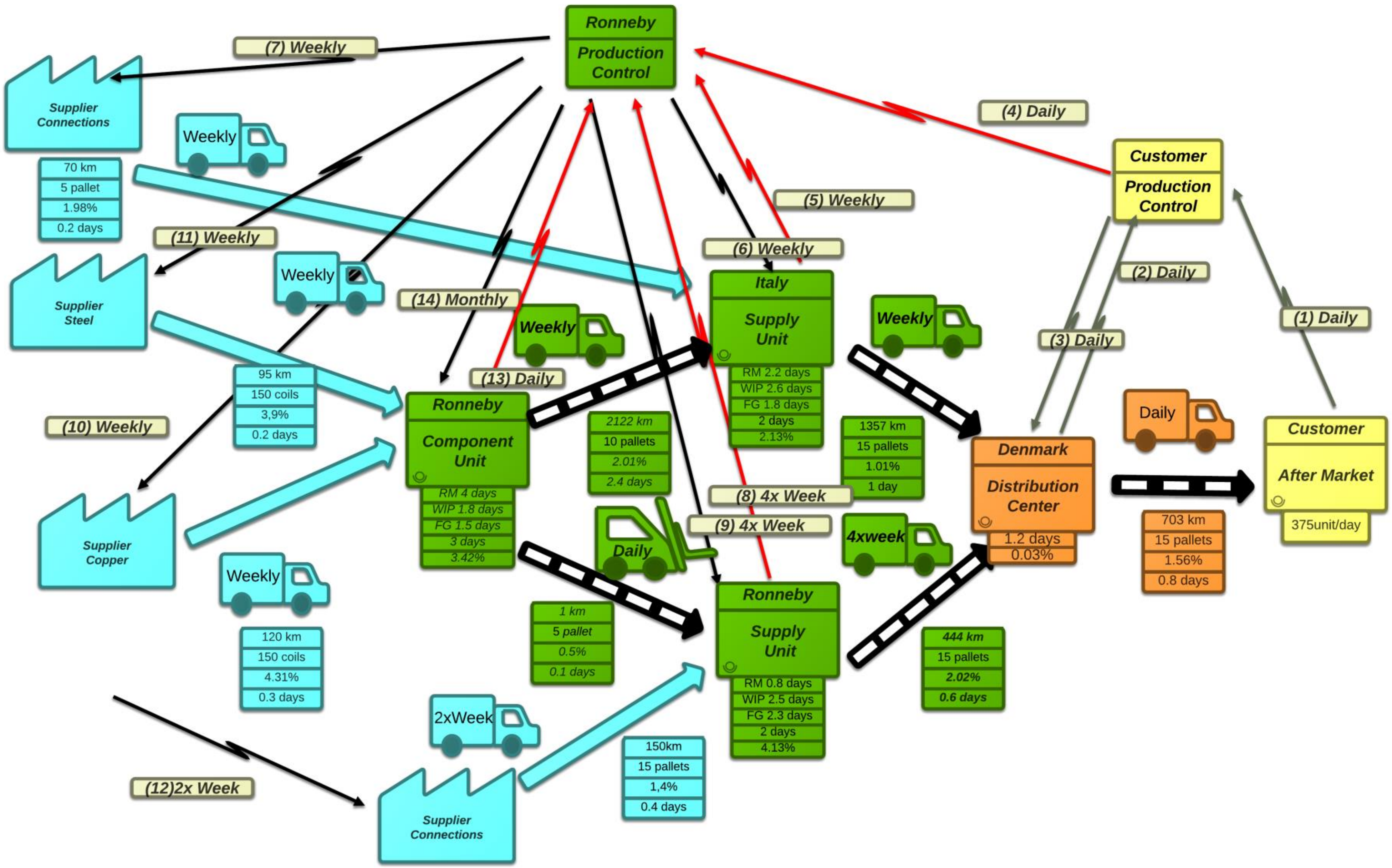


Figure 19: EVSM representation of the after-market.

Firstly, it will be described the material flow of the EVSM (figure 19) in the following paragraph and later on it will be described the information flow.

The material flow of the EVSM can be described as follow:

1. Weekly, the steel and copper suppliers send a shipment of 150 coils to the Ronneby C.O.
2. In Ronneby C.O., it is manufactured the component unit.
3. A part of the finished goods are sent to Italy S.U. by truck and the others are sent to the Ronneby S.U. by milk run
4. In each supply unit, the heat exchangers are manufactured. The heat exchangers are made of the component unit, which was previously sent from Ronneby C.O. and a connection component, which was obtained from a local supplier
5. Once the heat exchangers are manufactured, the supply units factories send the finished good to the distribution center in Denmark
6. In the distribution center, the finished goods are distributed to all the retailers.

The information flow of the EVSM can be described as follow:

1. Daily, all the retailers send information about the sales to the office of customer production control.
2. In the production control office, all the data is processed and the shipment orders are sent to the distribution center.
3. The distribution center sends back to the office of customer production control the confirmation of the shipments.
4. The office of customer production control also sends the consumption information and the orders to the production control office of Ronneby.
5. There, the information is processed and orders are sent to the supply units located in Ronneby and in Italy.
6. The Ronneby and the Italian supply units answer back with the confirmation of the shipments daily and weekly respectively.
7. The production control office of Ronneby also sends the material requirements to the suppliers, weekly.
8. Monthly, the production control office of Ronneby sends the forecast of the production to the Ronneby C.O.

As previously mentioned in the begging of the section, the EVSM of U.S. customer market is pictured in the figure 20. The distribution center has been located in Indianapolis where Alfa Laval has a real distribution center for supplying the U.S. market (http://local.alfalaval.com/en-us/contact-us/us-locations/pages/alfa-laval-locations-us.aspx) viewed on 9/06/2015.

The data presented in this step aims to show the supply chain operations in a standardized and simple manner. The EVSM representation has identified all the activities accordingly to their sequence and connection.

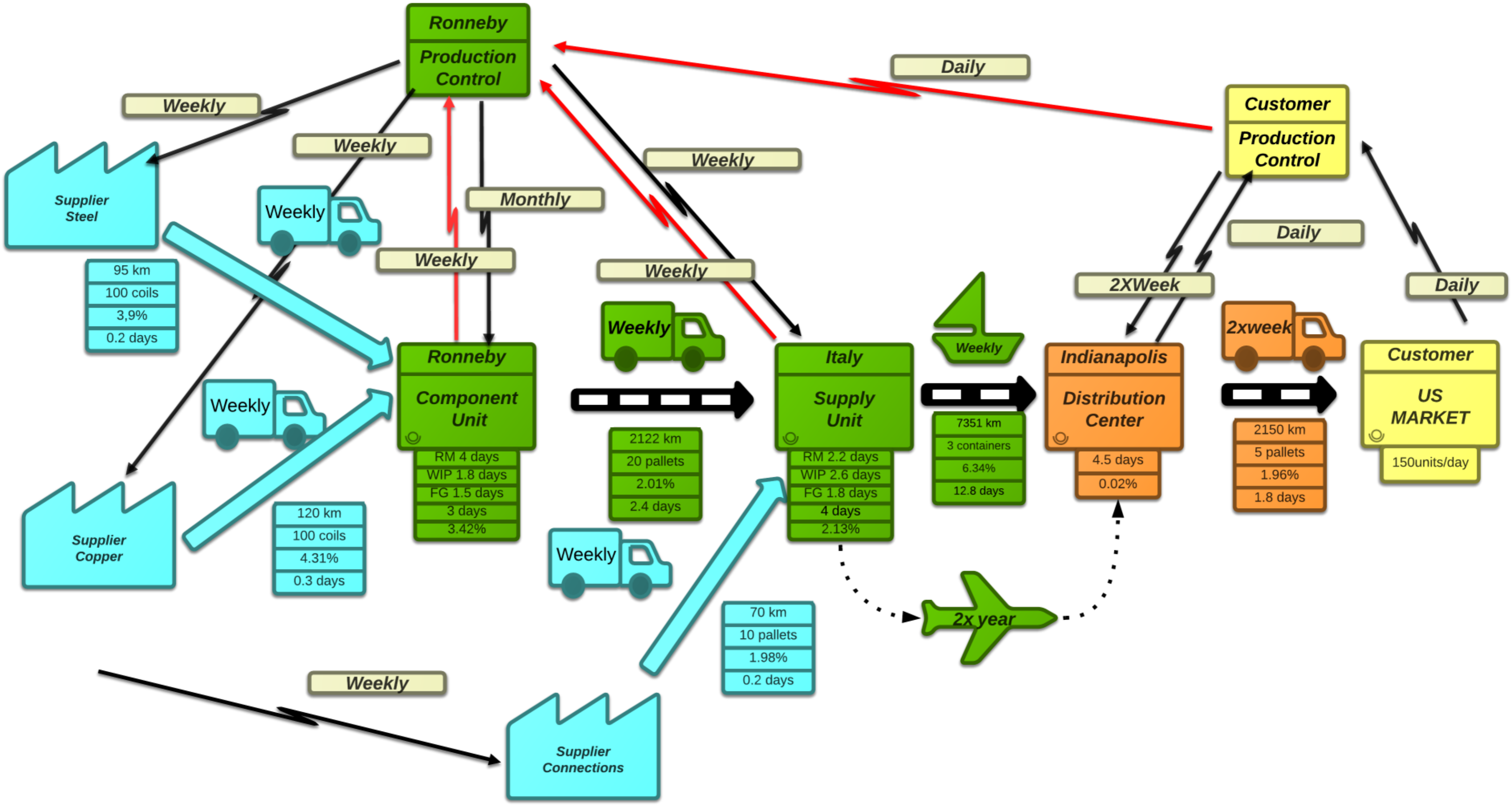


Figure 20: The EVSM of the U.S. customer market

4.3 Case Study - Step 2: Path Decomposition

The network decomposition was applied and a total of 15 open-paths were obtained in the whole supply chain. This study only focuses on the paths related to the after-market and U.S. customer market as stated before. Therefore, nine open-paths will be analysed. *Sustain-Pro* was used to generate the open-path for the 2 EVSM (Carvalho, et.al, 2008; and Carvalho et al., 2013). Each path is associated with a component and a flow which form the flow-path. The paths that compose the U.S. customer market and the after-market are presented and enumerated in the following figures.

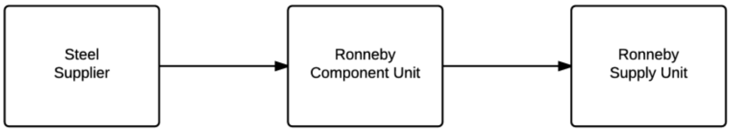


Figure 21: Open-path 1, component steel, flow=180.000 kg/year, after-market and U.S. market

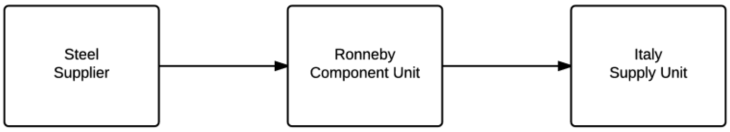


Figure 22: Open-path 2, component steel, flow=45.000 kg/year, after-market and U.S. market

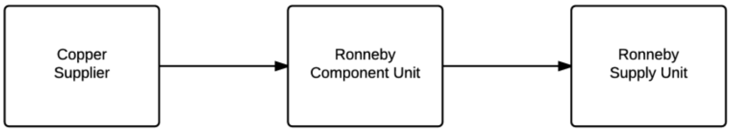


Figure 23: Open-path 3, component copper, flow=53.333,13 kg/year, after-market and U.S. market

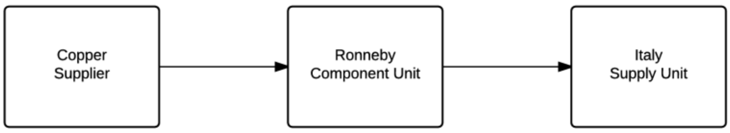


Figure 24: Open-path 4, component copper flow=13.333,33 kg/year, after-market and U.S. market

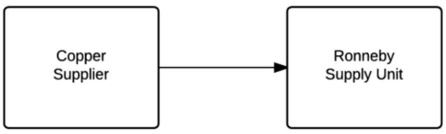


Figure 25: Open-path 5, component connections, flow=140.000 kg/year, after-market and U.S. market

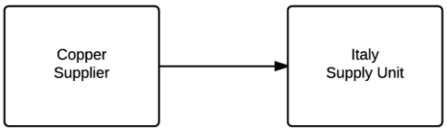


Figure 26: Open-path 6, component connections, flow=35.000 kg/year, after-market and U.S. market

Figure 27: Open-path 7, component heat exchanger, flow=248.888,88 kg/year, after-market

Figure 28: Open-path 8, component heat exchanger, flow=62.222,22 kg/year, after-market

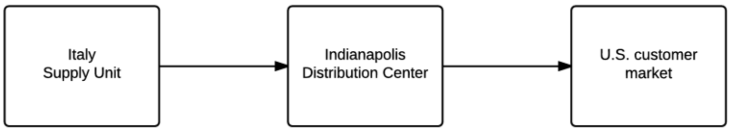


Figure 29: Open-path 9, component heat exchanger, flow=150.000 kg/year, U.S. market

4.4 Case Study - Step 3: Data Collection

The structure of the supply chain and the production approach of each entity were obtained from Persson (2011). Some data also was acquired from the sustainability report of Alfa Laval (Alfa Laval, 2014). However, in the sustainability report, the given figures and values include all company operations, which most of them are not relevant for this work. Thus, some assumptions were made to generate the data. In the following paragraphs, all the data is justified and all the assumptions are explained in detail.

The total inventory, the lead time, the demand, the defective flow and the inventory were required for the EVSM and therefore the data was presented in the section 4.2 (tables 10 and 11). The table 13 and 14 present all the data considered for each facility and transport flow (price of utility, energy consumption, inventory, holding cost, lead time, demands, defective flows, capacity, carbon footprint waste, green energy, number of incidents, employees, law sues, salaries and working hours) and the description of data collections is presented in the following points:

- **Price of Utilities:**

For entities, the data was obtained from (http://ec.europa.eu/ eurostat/statisticsexplained/index.php /File:Half-yearly_electricity_and_gas_prices,_firsthalf_of_year,_2011%E2%80%9313_(EUR_per_kWh) _YB14.png) for European electricity prices and from (http://www.eia.govelectricity/monthly/epm_table_ grapher.cfm?t=epmt_5_6_a) for USA electricity price. Convert Dollars to Euros (https://www.google. com/finance/converter); 20/05/2015.

For transport flows, the fuel (gasoline) prices come from (http://www.globalpetrolprices.com/ gasoline_prices/) viewed on 19/05/2015.

- **Energy Consumption:**

The consumption was estimated from the annual report (92.381 MWh) and the Alfa Laval ratio (1 Million Euros of Value Added/ 300 MWh) (Alfa Laval, 2014)

For transport flows, the energy consumption was determined assuming that the average fuel consumption of a truck (17.4l /100km) (http://cta.ornl.gov/data/chapter5.shtml) viewed on 21/05/2015

- **Holding Cost:**

The holding cost was estimated considering the premise: the more complex is the component, the higher is the cost and from the annual figures of the inventory cost (258 Milion SEK =27,85 Milion Euros(10/06/2015)) (Alfa Laval,2014)

- **The Green Energy:**

For entities, the consumption of green energy was estimated from the annual report of the company (827 MWh) (Alfa Laval, 2014). The annual report figures consider all the divisions of Alfa Laval; therefore the data is 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 (Alfa Laval, 2014). The annual report figures consider all the divisions of Alfa Laval (16.468 employees); therefore the data is just a fraction of the total number. In the allocation of employees in each factory, it was considered the amount of flow and the nature of the entity. 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 is the demand for an entity, the higher is 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 CO_2 manufacturing) (Alfa Laval, 2014)
- The ratio between transport and production emissions (49.777 tons CO_2 transport/ 34.440 tons CO_2 manufacturing) (Alfa Laval, 2014).

For transport flow, the data of the carbon footprint was estimated using the ratio (105.5 g/(tonne*km)) (Alfa Laval, 2014).

- **Waste:**

For entities, the waste was determined adding the defective flow and a complementary mass flow of material disposal which was assumed, since there was not 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

- **Law sues, Salaries and Incidents:**

The number of law sues, the salaries and the numbers of incidents were assumed, since there was 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://stats.oecd.org/ Index.aspx?DataSetCode=ANHRS); viewed on 22/05/2015.

The table 13 and 14 presents the data of the entities and transport flows respectively.

Table 13: Data of entities

Factories/Warehouse	Ronneby C.O.	Italy	Ronneby S.U.	Danish Distributor	EEUU Distributor
Price Utility (€/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(€/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	25697,78	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)	23000	13500	28750	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 Law Sues	1	0	1	0	0
Largest Inventory(units)	1500	585	750	450	675
Lowest Salary(€/year)	21.000	19000	23.000	23.000	24.000
Highest Salary(€/year)	68.000	66000	70.000	85.000	76.000
Working hours (year)	1607	1752	1607	1411	1770

The table 15 introduces the relevant data of each open-path (Price of product, price of raw material, customer demand, on time, theoretical flow due date for delivery, earliest due date, variance of lead time, variance of demand, variance of flow-path and penalty rate) and the description of data collections is presented in the following points:

- **Price of product and raw materials:**
  The price of the steel and copper is from (http://www.metalprices.com/metal/stainless-steel/stainless-steel-flat-rolled-coil-304) and (http://www.metalprices.com/p/CopperFreeChart?weight=KG&size=M&theme=1011) viewed on 16/05/2015, respectively. The final price of the heat exchanger was estimated from an Alfa Laval catalogue (http://www.etl.cz/attachments/Cenik%20Alfa% 20Laval %202014.pdf) viewed on 16/05/2015
- **Customer demand, ontime flow and theoretical flow:**
  The customer demand, the ontime 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 date were estimated from the Lead Time Factor
- **Variance of lead time, demand and flow-path:**
  The variance of lead time, demand and flow path were assumed since there was no data available. It was used mean value as a reference on the assumptions.

Table 14: Data of transport flows

Transport	Sup Steel	Sup Copper	Sup Con IT	Sup Con RO	Ro C.O-IT	Ro C.O. -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(€/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 (tones/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 Law Sues	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(€/year)	17.000	20.000	18.000	16.000	17.000	18.000	19.000	22.000	26.000	26.000	19.000
Highest Salary(€/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 15: Data of open-paths

Path	OP1	OP 2	OP3	OP4	OP5	OP6	OP7	OP8	OP9
Price of Product (€/kg)	140	140	140	140	140	140	140	140	140
Price of Raw Material (€/kg)	2,1	2,1	5,68	5,68	3.50	2,6	140	140	140
Customer Demand (kg/year)	180000	45000	55000	13500	142500	35000	250000	62222,22	150500
On time (kg/year)	180000	45000	50000	10000	125000	34000	230000	61000	146000
Theoretical Flow (kg/year)	210000	52000	61500	15500	160000	37500	275000	67500	170000
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
Variance of Lead Time (days)	2,2	2,6	1,2	1,5	2,2	0,8	2	2,2	4
Variance of Demand (kg/y)	10000	5000	4000	1000	6000	5000	50000	10000	7500
Variance of flow-path (kg/y)	10500	5550	4800	1050	7000	5100	65000	11500	8800
Penalty rate	0,1	0,15	0,1	0,15	0,1	0,15	0,7	0,7	0,6

4.5 Case Study - Step 4: Calculate Indicators

In this step, the values of the indicators for the U.S. market paths and the after-market paths are presented. Only the most relevant indicators values are presented for each indicator. Indicators are grouped in the sustainability dimensions.

Economic Indicators

The following tables, introduces the values of the most critical economic-cost indicators. Most of these indicators are expressed in € units. The higher is the listed value; the worst is the performance of the path.

Table 16: Most critical EC values

Paths	EC-SC (€/year)
OP9	493.554,15
OP1	434.374,41
OP7	296.006,60
OP2	205.537,44
OP8	191.387,78

The most critical value in terms of energy cost is OP 9. This means that OP 9 is the path that holds the higher energy cost. This fact might be motivated for the high transportation cost.

Table 17: Most critical TILC Values

Paths	TILC(€)
OP1	24.751,29
OP7	16.800,00
OP9	13.503,57
OP3	7.333,71

The most critical path in terms of inventory is the path 1 (Ronnerby C.O. inventory and Ronnerby S.U. inventory), thereby the EILC indicator is applied only to this path. The values of the EILC indicator are listed in the table 18.

Table 18: EILC indicator of the path 1

Open-Path 1	EILC
Ronneby C.O.	0,741
Ronneby S.U.	0,259

The Ronneby C.O. holds the higher inventory costs. This fact reveals an excessive amount of inventory in Ronneby C.O.

Table 19: Most critical BC values

Paths	BC(€/year)
OP7	264.444,44
OP3	256.666,66
OP5	154.000
OP9	112.000

The most critical path in terms of backordering is OP 7. Being the most critical path means that OP 7 supports the higher cost regarding delivery failures.

The next indicators are related to the economic-time field. The higher is the value the lowest is the performance of the open-path or entity.

Table 20: Most critical LTF values

Paths	LTF (d)
OP9	25,70
OP4	16,60
OP2	16,50
OP3	13,30
OP1	13,20

The most critical path is the path OP9 (Italian S.U.→ Indianapolis Distribution Center → U.S. market), in terms of lead time, consequently the OLTF presented below will be only related to this path. The values for the OLTF are listed on Table 21.

Table 21: OLTF for a critical path 4

Open-Path 4	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

The transport from Italy factory to Indianapolis distribution center is the most time-consuming process of the OP 9

Table 22: Most critical IT values

Paths	IT (d)
OP 9	4,50
OP1 /OP 2/OP 3/ OP 4	4,00
OP6/ OP8	2,60
OP5 /OP 7	2,50

OP 9 is the bottleneck regarding inventory turns; this means that OP 9 has the less agile warehouse of all the supply chain which damages the performance of lead time factor of OP 9.

The following indicators are related to the flexibility of the supply chain, the lower is the value the lower is the flexibility of the open-path.

Table 23: Most critical FVF values

Paths	FVF
OP1/OP 3/OP 5/ OP 7	0,016
OP2 /OP 4	0,063
OP6 /OP 8 /OP 9	0,1

OP 1, 3, 5 and 7 have the lower volume flexibility, this means that these paths are producing at a rate close to the capacity limit. Therefore, they are not able to meet the demand fluctuations from the downstream process.

Table 24: Most critical FTF values

Paths	FTF
OP 5	0,067
OP 7	0,110
OP 1/ OP 3	0,133
OP 9	0,143
OP 2	0,222

The most critical path in time flexibility is OP 5 that it is translated into little slack time which does not allow OP 5 to meet the rush orders from the downstream process

The coming indicators give information about the quality of the supply chain. The higher the value is sorted the worst is their performance.

Table 25: Most critical SLQF values

Paths	SLQF
OP3	0,0303
OP4	0,0123
OP5	0,0079
OP7	0,0044
OP9	0,0033

OP 3 is the bottleneck regarding service level of quantity; this means that the path is not serving the required quantity of flow to the downstream process.

Table 26: Most critical SLTF values

Paths	SLTF
OP4	0,250
OP5	0,107
OP7	0,076
OP3	0,062
OP6	0,029
OP9	0,026

OP 4 is the critical point in terms of service level of time; this means that the path it is not delivering the flow at the scheduled time.

Table 27: Most critical OP values

Paths	OP
OP3	88,16%
OP1	88,54%
OP4	88,63%
OP2	89,01%
OP9	90,85%

The most critical path regarding the production quality is OP3 which translates into losses in form of scrap flow and rework.

Table 28: Most critical OTE values

Paths	OTE-SC
OP1	85,71%
OP4	86,02%
OP2	86,54%
OP3	86,72%
OP5	87,50%
OP9	88,24%
OP7	90,51%
OP8	92,18%

OP 1 is the worst productive performance path. This means a low efficiency in the performance due to technical, quality and organizational losses.

Information Indicators

The next indicators are related to the information sharing performance among supply chain members. The higher the value, the worst is the coordination.

Table 29: Most critical VLF values

Paths	VLT (d)
OP5	0,3667
OP7	0,2439
OP8	0,2292
OP1	0,1667

OP 5 is the critical point in terms of lead time variability; this fact means that OP 5 production processes are unstable and unreliable.

Table 30: Most critical BE values

Paths	BE
OP7	1,300
OP3	1,200
OP9	1.173
OP5	1,167
OP8	1,150

OP 7 is the bottleneck regarding the bullwhip effect. This is translated into high fluctuations in the production orders which damage the sustainable performance of the path

Environmental Indicators

The following indicators are associated with the environmental performance of the supply chain. The higher is ranked a value, the worst is their behaviour

Table 31: Most critical CE values

Paths	CE(t)
OP9	8780,47
OP7	6668,55
OP1	4241,45
OP8	2035,46
OP2	1748,29

The most critical path in terms of carbon emission is OP 9. This fact might be explained for the high carbon footprint of the transportation flow.

Table 32: Most critical WF values

Paths	WF
OP9	0,2173
OP4	0,1862
OP2	0,1821

OP 9 holds the worst performance regarding waste in the supply chain; this fact means that OP 9 is the path that generates more material disposal

Table 33: Most critical SE values

Paths	SE(%)
OP6/ OP8/ OP9	0,00%
OP7	3,02%
OP4	3,36%
OP2	3,37%
OP5	5,06%

OP 6, 8 and 9 represent the bottleneck in sustainable energy, since none of these paths consume renewable energies.

Social Indicators

The coming indicators are correlated to the social performance of the supply chain. The values listed on the top of the list need to be address first.

Table 34: Most critical LE values

Paths	LE
OP8/ OP7	0,2705
OP2/OP4/OP6/OP9	0,2878
OP1/ OP3	0,3088
OP5	0,3285

OP 7 and 8 are the critical points in terms of salary distribution. This fact displays a large difference between the best and the worst wage.

Table 35: Most critical C values

Paths	C(NIs)
OP3	3
OP1 /OP 4	2
OP2/ OP5/ OP6/ OP7/ OP8	1
OP9	0

The most critical path regarding corruption is OP 3. Being the bottleneck in corruption displays a poor social performance of the OP 3.

Table 36: Most critical FAR values

Paths	FAR (Inc/(wks*t))
OP7	537
OP8	308
OP3	246
OP5	237
OP1	197
OP4	171

OP 7 is the bottleneck in terms of fatal accident rate. Therefore, OP 7 is the most dangerous path for workers in the supply chain.

The table 37 presents the values of all the indicators per each path.

Table 37: Values of the indicators

			OP1	OP2	OP3	OP4	OP5	OP6	OP7	OP8	OP 9
Economic	Cost	EC	434.374 €	205.537 €	129.682 €	61.145 €	89.493 €	80.837 €	296.007 €	191.388 €	**493.554 €**
		TILC	**24.751 €**	6.931 €	7.334 €	2.054 €	4.995 €	1.827 €	16.800 €	5.228 €	13.505 €
		B	- €	- €	256.667 €	26.833 €	154.000 €	- €	**264.444 €**	- €	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	**0,016**	0,063	**0,016**	0,063	**0,016**	0,100	**0,016**	0,100	0,100
		TF	0,133	0,222	0,133	0,263	**0,067**	0,444	0,111	0,364	0,143
	Quality	SLQF	0,000	0,000	**0,030**	0,012	0,007	0,000	0,004	0,000	0,003
		SLTF	0,000	0,000	0,062	**0,250**	0,107	0,029	0,076	0,020	0,027
		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	0,167	0,158	0,090	0,090	**0,367**	0,118	0,244	0,229	0,156
		BE	1,050	1,110	1,200	1,050	1,167	1,020	**1,300**	1,150	1,173
Environment		CE	4241,45	1748,29	1261,65	519,24	885,21	452,91	6668,55	2035,46	**8780,47**
		WF	0,169	0,182	0,173	0,186	0,060	0,052	0,085	0,073	**0,217**
		SE	0,059	0,034	0,058	0,034	0,051	**0,000**	0,030	**0,000**	**0,000**
Society		LE	0,309	0,288	0,309	0,288	0,329	0,288	**0,271**	0,271	0,288
		C	2	1	**3**	2	1	1	1	1	0
		FAR	197	114	246	171	237	0	**537**	308	0

4.6 Case Study - Step 5: Identify Critical Points

In this section, the bottlenecks of the supply chain are identified and analysed. Moreover, it is suggested a solution to improve the yield of each indicator. Indicators are grouped in the same order than they have been presented in the previous section.

Economic Indicators

The economic indicators are analysed to identify potential breakthrough to improve the creation of wealth for the customer and assess the effectiveness of the organization resources in the supply chain. A high performance in the economic area reflects a satisfactory level of competitiveness of the supply chain.

Material Value Added (MVA-SC): There is little space for improvements. The supply chain is working in the right conditions, since there are not any MVA-SC negative values.

Energy Cost (EC-SC): Open path 9 (Italian S.U.→ Indianapolis Distribution Center → U.S. market), which is related to the distribution of the heat exchangers from Italy to the USA market, appears as the most critical path in terms of energy consumption. This indicator points out the possibility of opening or use an existing factory in U.S. to produce the components that are at the moment produced in Italy. This option would also require a change in the suppliers of the raw materials. This solution would reduce the transportation costs and consequently will reduce the energy consumption.

Total Inventory Level Cost (TILC) and Entity Inventory Level Cost (EILC): Open Path 1 (Steel Supplier → Ronneby C.O. → Ronneby S.U.) is the most expensive path in terms of inventory. As it can be observed in the EILC indicator, the Ronneby C.O. factory has the largest allocation of inventory cost in the path. This result comes as a consequence of centralizing all the production of component units which provokes the largest circulation of flow through the Ronneby C.O. entity. Due to this justification, it would be advisable to consider a change from the current MTS policy to MTO in order to reduce unnecessary inventory.

Backorder Cost (BC): Open path 7 (Ronneby S.U.→ Distribution Center→ After-market) is the most expensive path in terms of losses for not meeting the demand requests. This specific indicator must be addressed immediately due to the fact that the most competitive market with less customer-loyalty is the after-market (see the penalty rate, table 15) and backordering can compromise the future economic feasibility of the supply chain. The OP 3 and OP 5 are ranked as the second and third worst open-paths respectively regarding backordering. This fact points out the need for a detail analysis to Ronneby S.U. facility because the three paths share the Ronneby S.U. facility. (Look later flexibility indicators)

Lead Time Factor (LTF) and Operational Lead Time Factor (OLTF): The most critical path in terms of LTF is open-path 9 (Italian S.U.→ Indianapolis Distribution Center → U.S. market) which is related the distribution of the heat exchangers from Italy to the U.S. customer market. Analysing the OLTF of the OP 9 is possible to see that the transportation time from the Italian factory to the Indianapolis distribution center is the main supply chain bottleneck in terms of lead time (see table 21). As mentioned in the EC indicator, it would be advisable to study the possibility to use the facilities that Alfa Laval has in U.S. to produce the components that are at the moment produced in Italy. This solution would reduce the transportation time.

Inventory Turn (IT): Open-paths 9 is the most critical regarding inventory turns. Analysing in detail this path in the EVSM (see EVSM, figure 20), the distribution center appears to be the bottleneck. The reason is that there is only one shipment per week from Italy to Indianapolis distribution due to the great distance between these entities. Therefore, each order batch is very large and takes long time to be consumed. Adopting the proposed solutions in the EC and LTF indicators, it would allow more regular shipments from the supplier with a lower order batch which would reduce the non-value added time and improve the financial performance. In case that it would not be possible to change the production factory, the implementation of techniques such as a pull system to link the demand of downstream process with the production of upstream process should also help to reduce the inventory time.

Flexibility Volume Factor (FVF): Open-paths 1, 3, 5 and 7 have the lowest volume flexibility ratio of the supply chain. These paths share the Ronneby S.U. factory which appears to be the bottleneck in terms of volume flexibility. Being the bottleneck of volume flexibility means have a very tight production schedule. In this supply chain, it translates into losses due to backordering (see table 19 and BC analysis). To address this issue, it is necessary to balance the workload of the supply unit factories (A share of the production volume can be transferred to Italian supply unit factory) or invest in new machinery to increase the production capabilities of the Ronneby S.U.

Flexibility Time Factor (FTF): The most critical paths in terms of time flexibility is open-path 5 (Connections Supplier→ Ronneby S.U.) followed by OP7 OP1 OP3. The result of this indicator is tightly related to the little volume flexibility of Ronneby S.U. Therefore, as it has been stated in BC and FVF, the aforementioned measures must be implemented as soon as possible to solve this potential threat to the supply chain.

Service Level Quantity Factor (SLQF) and Service Level Time Factor (SLTF): Open-path 3 (Copper supplier→Ronneby C.O. → Ronneby S.U.) holds the worst delivery performance in terms of quantity of the supply chain. The open-path 4 (Copper supplier→Ronneby C.O. →Italian S.U.) is the most critical path in terms of time service level and the second worst in quantity service level. Both paths share the same copper supplier (see EVSM, figure 19) which seems to be the source of the low service level. This fact points out for the possibility of looking for new suppliers in order to ensure a steady flow of raw material.

Ok-Parts (OP): Open path 3 is the most critical path in terms of manufacturing quality. The following ones are open-paths 1, 2 and 4 (see table 27). All the paths flow through the Ronneby C.O. factory and represent the most upstream paths in the supply chain (see EVSM, figure 19). In order to reduce the scrap and the rework, the most upstream entities should launch a "*kaizen*" project to implement *"jidoka"* and *"poka yoke"* (mistake-proofing processes) approach.

Overall throughput effectiveness (OTE-SC): Open-path 1 has the lowest overall throughput effectiveness in the supply chain. As it has been mentioned in the previous point, the major cause presumably comes from quality losses. However, a deeper study should be conducted to assess the technical losses (machinery breakdowns) and organizational losses (lack of resources to manufacture). Each facility ought to undertake workshops to improve their productivity and efficiency (Total Productive Maintenance (TPM)).

Information Indicators

The information indicators are analysed to identify potential breakthrough to point out the information deficiencies and improve the coordination of information and material flows among the supply actors.

Variability Lead Time (VLT): Open-path 5 (Connection Supplier→Ronneby S.U.) has the largest relative variance in the supply chain. This uncertainty undermines the production performance of the Ronneby S.U. factory causing organizational losses such as re-scheduling and forces the Ronneby S.U. factory to keep a large inventory to protect against the material disruptions. It would be advisable to establish well-defined standards to prevent the SC from this time fluctuations. If it is impossible to reach an agreement, Ronneby S.U. factory should look for a new supplier to assure a steady flow of raw materials

Bullwhip Effect (BE): Open-path 7 (Ronneby S.U.→ Danish distribution center → after-market) is the most critical path in terms of material distortion. After-market is an unsteady market so a lot of unforeseen variations triggers rush orders causing malfunction in the supply chain. Two policies are suggested to enhance information performance: first, implementing a vendor-managed inventory (currently the costumer production control sends orders to the Ronneby production control, (see EVSM, figure 19) and; second, increasing the inventory units in the distribution center to protect it against the uncertainties of the market demand. Thereby, the downstream process can picture a steady demand.

Environmental Indicators

Thirdly, the environmental indicators are studied to identify the bottlenecks in the environmental performance of the supply chain. The improvement in the consumption of raw material and energy; and the minimization of waste frequently turn out into a more competitive supply chain.

Carbon Emission (CE): Open path 9 (Italian S.U.→ Indianapolis Distribution Center → U.S. market) has the largest carbon footprint in the supply chain. The transportation flow from Italy S.U. has a significantly impact in the environment, thereby it is strongly recommended to adopt the aforementioned solution. Apart from moving the production of the supply unit, it is advisable to increase the equipment efficiency especially the vehicles that account the largest share of carbon emissions in the supply chain (see table 13).

Waste Factor (WF): Open-path 9 is again identified as the bottleneck in terms of material waste. This fact reinforces the conclusions taken in the EC, TLF, IT and WF indicators. The solution presented would also probably reduce the waste; (notice a high level of waste during the transport from Italian S.U. to Indianapolis distribution center, table 13). Another important factor that greatly influence the waste is the production performance in terms of quality because the higher the scrap, the higher is the waste. Thus, a quality improvement should also reduce the environmental impact of the supply chain.

Sustainable Energy (SE): Open-path 6 (Supplier Connection →Italian S.U.) and OP 8 (Italian S.U. → Danish D.C. →After Market) and OP 9 (Italian S.U. → Indianapolis D.C. → U.S. market) do not consume any green energy, just non-renewable energy. Analysing the value of the indicators and the data, two issues come up: first the Italian factory is the only one that does not consume any kind of renewable energy and second that all transport energy comes from fossil energy. Since, transport holds a great share of the energy, it is necessary to reduce the transport in the supply chain (do not add any value to the customer) and invest in cleaner ways of transport such as hybrid vehicles or trains.

Social Indicators

The social indicators are analysed to correct misbehaviours in the supply chain and identify new policies to improve the relations with the all the involved stakeholders in the supply chain.

Labour Equity (LE): Open-path 8 (Italian S.U. → Danish distribution center → After Market) and OP 7 (Ronneby S.U.→ Danish distribution center → after-market) are the most critical paths in terms of labour equity. This means that in these open-paths it is located the greatest difference between the lowest and the highest salary (26.000€ and 84.000€) of the overall supply chain. Raising the lowest salary should be on the agenda of the supply chain management to reduce the breach of wealth distribution and increase the motivation of the workers.

Corruption (C): Open-path 3 (Copper Supplier→ Ronneby C.O. → Ronneby S.U.) holds the worst performance regarding corruption. All the entities of this path account a law sue for breaking the law and the business ethic code of the supply chain. This represents, without any doubt, a non-sustainable social performance which would probably damage the whole supply chain. Therefore, measures must be immediately implemented to raise awareness among workers about the importance of fair competition. In addition, an internal audit program would help to revise the current standards in order to significantly decrease these figures.

Fatal Accident Rate (FAR): Open-path 7 (Ronneby S.U. → Danish distribution center → After-market) sustain the highest fatal accident rate in the supply chain. It means that open-path 7 is the most unsecure path and workers are overexposed to suffer an accident while carrying out their job. This fact must be unacceptable for all the companies of this path. Given that, companies have the moral obligation to protect by all means the integrity of their workers. Enhancing policies of workforce protection and raising awareness among workers should be the highest priority to reduce the number of accidents. These implemented actions to improve the health and the safety rules should be standardized across the supply chain.

The presented indicators have identified all the relevant critical points of the supply chain. The indicators have provided enough information to steer the future state of EVSM. The figure 30 displays the number of critical points that each path holds.

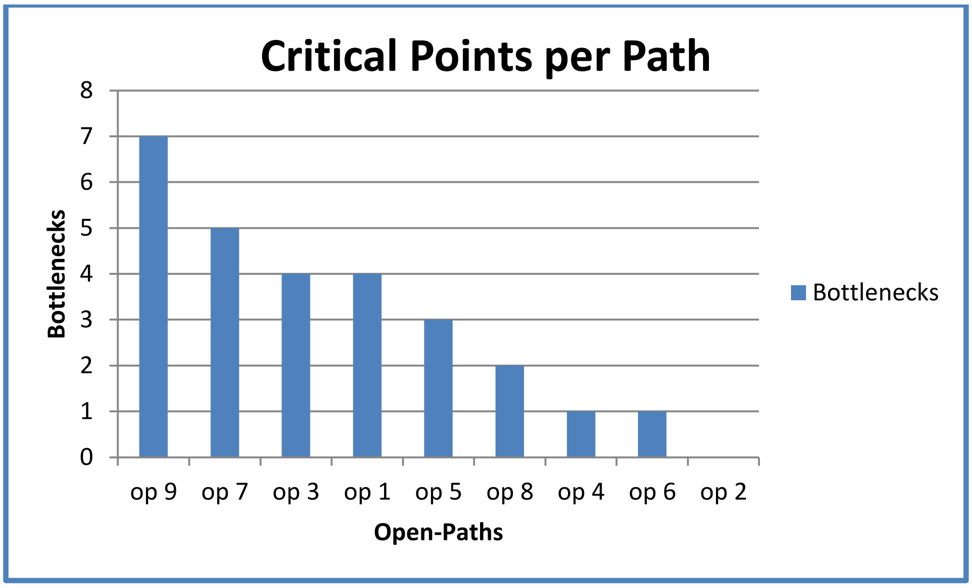


Figure 30: Critical points per Path

As it can be observed in the figure 30, the OP9 (Italian S.U. → Indianapolis distribution center→ after-market) is the first path that should be address because it is the path that accounts more critical points (energy cost, lead time, inventory turn, carbon footprint, waste and sustainable energy). The OP7 (Ronneby S.U. → Danish distribution center→ after-market) is the second path that accounts more bottlenecks (backordering, volume flexibility, bullwhip effect, labour equity and fatal accident rate).Therefore; OP 7 also requires further improvements.

4.7 Sensitivity Analysis

Since some assumptions were made to determine the data: energy, lead time, demand employees, waste, capacity, law sues, salary, incidents, theoretical flow, delivery due date, earliest due date, variance of the demand, variance lead time, variance of the flow path

It is necessary to undertake a sensitivity analysis to check if a slight change of data values represent an abrupt variation of the indicator values which would lead to obtain fragile conclusions. Therefore, it is advisable to carry out a sensitivity analysis of the indicators to guarantee well-founded conclusions. The analysis is made by changing the data values ±5% and ±10% in order to validate the indicators.

Three sensitivities analysis were conducted one for the FTF indicator, other for the SE indicator and other for the FAR indicator. Although, many indicators are influenced by the assumptions, most of the indicators have linear simple formulas and a slight change in the data does not change the ranking order. The three indicators were selected among the other indicators following these criteria:

1. The selected indicators cover the three sustainable dimensions
2. The selected indicators have a complex formula and a variation on data values might represent a potential change on the indicator value.

In the sensitivity analysis of the FTF indicator, the modified variable was the EDD of the path 5. As it can be appreciated in the figure 31, the modification of the data value does significantly change the indicator value (there is almost an increment of 100% of the indicators value, if the Earliest Delivery Day variable is modified -5%). Although the indicator value suffers an abrupt variation, it does not change the bottleneck ranking of FTF (see table 24).

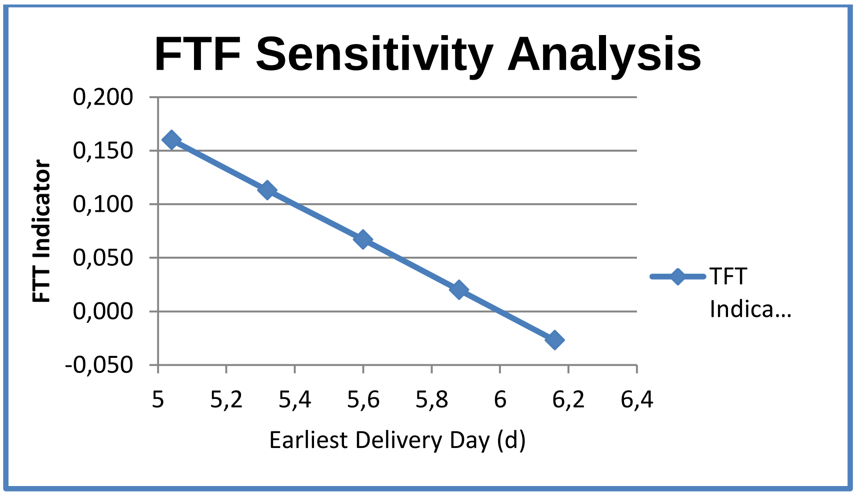


Figure 31: FTF sensitivity chart

In the analysis sensitivity of SE, the modified variable was the energy consumption of the Ronneby C.O. factory (path 4), again the figure 32 shows that there is not any abrupt modification in the shape of the curve. Although it is seems to be a linear relation between the SE and the modified value (see figure 30), it is non-linear relation.

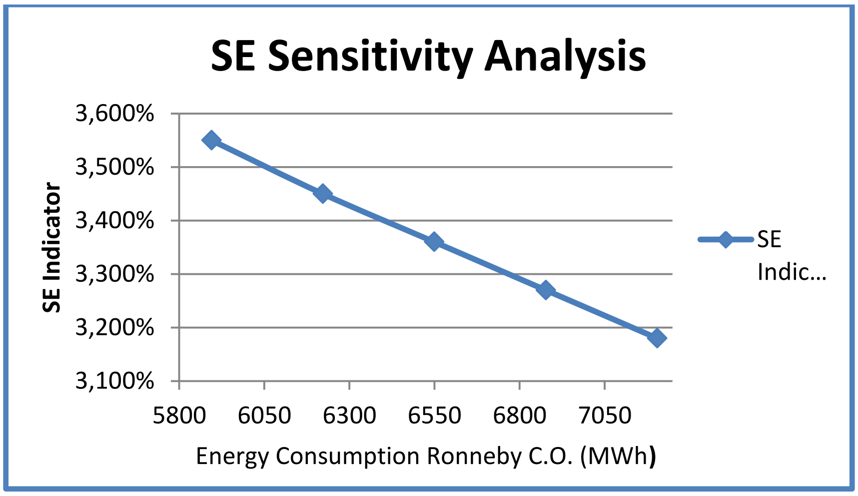


Figure 32: SE sensitivity chart

The FAR sensitivity analysis displays a harmonious chart without sudden changes. This time the changed variable was the number of employees of the path 7. The relation between the FAR indicator and the number of employees is also non-linear.

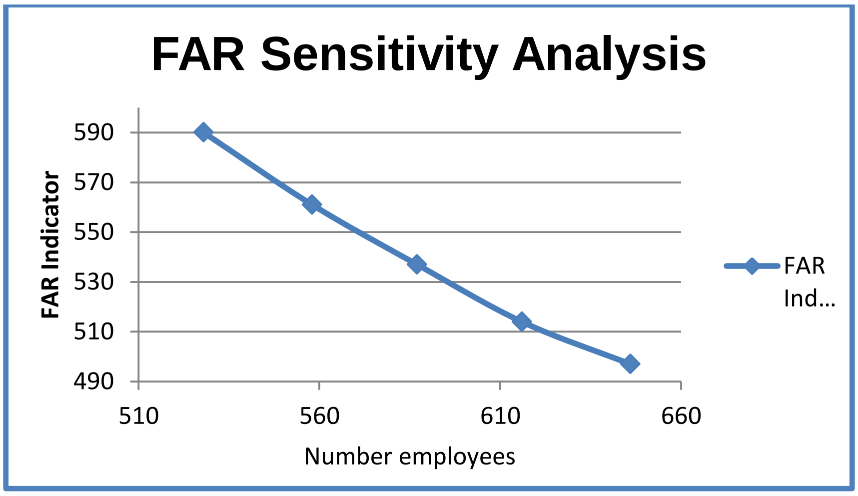


Figure 33: FAR sensitivity chart

It is concluded from the sensitivity analysis that although a slight change on the data changes the value of the indicator, it does not influence the ranking order of the most critical paths. Thereby, the sensitivity analysis reinforces the validity of the obtained results.

4.8 Conclusions of the Case Study

Following step by step the methodology, it is possible to display the main bottlenecks of the supply chain allowing the design of the future state of the EVSM. Thereby, the obtained results have validated the applicability of the methodology. Moreover, it can be inferred from the case study that SustainSC-VSM can cover a wide range of supply chain due to his generic indicators. Therefore, SustainSC-VSM can be considered a useful tool to analyse and improve any supply chain.

The table 38 presents a brief summary of each path with the main findings of the SustainSC-VSM analysis (notice that in some cases paths share bottlenecks because they have common facilities or transportations flows):

Table 38: Summary of the bottlenecks

Open-path	Description Path	Bottlenecks
1	(Steel Supplier --> Ronneby C.O. --> Ronneby S.U.)	TILC/ EILC/ OTE-SC/ FVF
2	(Steel Supplier --> Ronneby C.O. --> Italian S.U.)	
3	(Copper Supplier --> Ronneby C.O. --> Ronneby S.U.)	FVF/ OP/ SLQF/ C
4	(Copper Supplier --> Ronneby C.O. --> Italian S.U.)	SLTF
5	(Connections Supplier --> Ronneby S.U.)	FTF/ FVF/ VLT
6	(Connections Supplier --> Italian S.U.)	SE
7	(Ronneby S.U. --> Danish distribution center --> after-market)	BC/ FVF/ BE/ LE/ FAR
8	(Italian S.U. --> Danish distribution center --> after-market)	LE/ SE
9	(Italian S.U. --> Indianapolis distribution center --> after-market)	EC-SC/ LTF/ OLTF/ IT/ WF/ CE/ SE

5. Conclusions and Future Work

At the begging of the thesis, one question was formulated and it emerged as the motivation of this thesis; - Which is the best procedure to extend the scope of the VSM in order to embrace a sustainable supply chain in a systematic way? -.

To answer this question, a new methodology was created to provide a tool to identify the supply chain bottlenecks, screen waste and analyse the supply chain's sustainability performance in a systematic procedure. To achieve this goal, SustainSC-VSM was built over two pillars: 1) the lean philosophy of zero wastes, smooth flow and adding value for the customer; and 2) the sustainability concept of meeting the current needs without compromising the future resources. Three different operational techniques or methodologies related to the aforementioned principals were adopted and further developed: Value Stream Map, *Sustain-Pro*, performance indicators. The solid structure of *Sustain-Pro* contributes providing the methodology with a rigorous basis to undertake a systematic analysis. The VSM screens and identifies the supply chain flows and the production activities that undergo the flow. This identification is then combined with a set of indicators that address economic, environmental and social concerns of the supply chain. This thesis also explores the coordination and the information sharing performance among the supply chain actors with the purpose of improving the sustainability performance. The incorporation of the information flows analysis is an important improvement when considering a supply chain instead of a single process through VSM. Therefore, this new dimension aims a perfect integration of the sustainability concerns in the supply chain. This approach was adopted in response to the consensus in the literature where it is stated that coordination is a must in SSCM.

The methodology was tested and validated by a case-study. The obtained results allowed pointing out the supply chain bottlenecks and giving directions towards the improvement of the current EVSM. Moreover, SustainSC-VSM proved to be a systematic analysis applicable to any supply chain. Therefore, it is reasonable to affirm that SustainSC-VSM has succeeded in answering the research gap presented at the begging of this work. Information area, which was presented as a breakthrough has helped to cast light between the coordination of facilities; however, since the data is not completely accurate, it would be premature to withdraw more categorical conclusions.

As future work SustainSC-VSM needs to be tested again with real data to validate the thesis results. This test is also important because only a partial part of the supply chain has been analysed (the U.S. market and the After-market) due to the time constrains of the thesis. Thus, some simplifications have been made that may have slightly changed the analysis results such as considering only the flow of material that flows through the after-market customer in the studied supply chain entities; instead of studying the entire paths decomposition together.

Companies that may adopt SustainSC-VSM must understand that this is a generic tool for all supply chain and much customization is needed to meet the requirements of a specific field such as developing more operational indicators regarding the company's strategic goals or designing the future state map with a heuristic procedure based on the indicators values- for example, weighting the indicators through a multi-criteria approach.

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