Application of Multi-Layer Stream Mapping to a manufacturing production system

An extension to the “inter-processes” operations

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Resumo

À luz das atuais preocupações relacionadas com eficiência de recursos impactos ambientais e competitividade de custos em ambiente industrial, torna-se essencial criar novas metodologias de forma a reduzir desperdícios e aumentar a produtividade, na busca constante pela excelência.

É neste contexto que surge o projecto MAESTRI que visa promover a sustentabilidade de industrias europeias através da implementação de uma abordagem inovadora – The Total Efficiency Framework.

Dada a importância da eficiência de recursos e geração de resíduos no enquadramento geral da Total Efficiency Framework, apresenta-se uma nova metodologia, o Multi-Layer Stream Mapping (MSM), que tem como objectivo avaliar o desempenho de sistemas produtivos.

O objectivo deste trabalho é, então, a aplicação e validação do MSM num caso de estudo real, a produção de aquecimentos portáteis. O sistema produtivo é assim analisado, descrevendo-se a empresa onde foi realizado o estudo e todas as atividades necessárias à criação do produto, desde a matéria prima até à expedição para o cliente.

Elabora-se de seguida o diagnóstico do estado atual do sistema produtivo, recorrendo ao MSM, com a criação de quadros de eficiência simples e intuitivos que permitem identificar desperdícios e limitações durante a produção dos equipamentos em estudo. Propõe-se, ainda, uma análise complementar à quantificação de desperdícios, limitação encontrada na metodologia original, que permite ser incorporada na mesma.

Por fim, apresentam-se propostas de melhoria com base no diagnóstico efectuado e é dimensionado o estado futuro do sistema produtivo de forma a prever e antecipar novos problemas e ineficiências.

Palavras-chave: MAESTRI, Total Efficiency Framework, Multi-Layer Stream Mapping, Eficiência de Recursos, Desperdício, Acções de Melhoria;

Abstract

Under the current concerns of resources efficiency, environmental impact and costs competitiveness within an industrial environment, it is essential to create methodologies to reduce wastes and increase productivity, in the constant pursuit for excellence.

It is in this context that the MAESTRI project, which aims to advance the sustainability of European manufacturing industries by implementing an innovative approach – the Total Efficiency Framework, arose.

Due to the relevance of resources efficiency and waste generation within the scope of the Total Efficiency Framework, a new methodology, the Multi-Layer Stream Mapping (MSM), is presented to assess the performance of production systems.

The aim of this work is the application and validation of the MSM in a real case study specialized in the manufacture of heating devices. The production system is thus analysed, being made a description of the company, and all the required activities to manufacture the case study's product, from raw material until expedition.

Then, the current state of the production system is diagnosed, resorting the MSM, with the creation of simple and intuitive efficiency tables that allow to identify wastes and misuses along the production system. It is also proposed a complementary analysis to the quantification of wastes, a limitation identified in the original methodology, which can be integrated in the MSM.

Finally, improvement actions are presented based on the diagnosis made, and the future state of the production system is estimated to anticipate new inefficiencies and misuses that can occur.

Keywords: MAESTRI, Total Efficiency Framework, Multi-Layer Stream Mapping, Resources Efficiency, Waste, Improvement Actions;

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Nomenclature

MAESTRI	- Energy and resource management for Improved efficiency in the process industries
MSM	- Multi-Layer Stream Mapping
ecoPROSYS	- Eco-Efficiency Integrated Methodology for Production Systems
ISQ	- Instituto Soldadura e Qualidade
INEGI	- Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial
IST	- Instituto Superior Técnico
IoT	- Internet of Things
WSCSD	- World Business Council for Sustainable Development
OECD	- Organization for Economic Co-operation and Development
EPA	- Environmental Protection Agency
VSM	- VSM
KPI	- Key Performance Indicators
MCG	- Manuel Conceição Graça
WIP	- Work-in-process
ECW	- Effective Contribution to Waste

1. Introduction

In parallel with the increase of globalization, environmental concerns and the deceleration of the economy in the developed countries, grows the market competitiveness and the need of organizations to reduce their resources consumption, operating costs and environmental impact in the most effective way while improving the quality of their products/services

The present work was developed under the scope of the MAESTRI project, which aims to promote an innovative approach within European industries to oppose these vicissitudes of the modern world, based on principles such as Lean manufacturing, eco-efficiency and new methodologies to evaluate the efficiency of process industries: The Total Efficiency Framework.

The Total Efficiency Framework combines several methods with the overall purpose of promote a culture of continuous development and assist the decision-making process by defining priorities to improve the operational, environmental and economic performance.

The Multi-Layer Stream Mapping (MSM) is one of the MAESTRI methodologies to assess the efficiency of production systems, created to overcome some of the limitations of the current Lean tools to evaluate the environmental dimension of industrial companies. Recently, this methodology was target of a great improvement that allowed to characterize and evaluate a production system in an ampler way, evolving to MSM 2.0.

This new methodology consists of adding multiple layers, which represent variables or parameters, like time, energy or consumables, that are fundamental in controlling all the activities within the production system (processes and logistics operations such as setups, transports or waitings). For each variable is clearly distinguished all the “value-added” and “non-value added” actions, where a reference target for these portions is defined according to the objectives of the company. The efficiency of each variable is obtained by the ratio between the target value and the total current value in each operation.

With the MSM 2.0 application to Manuel Conceição Graça Lda company, producer of heating devices, in which a three months internship was carried out, it was possible to test and validate this methodology in a real industrial environment.

At the beginning of this work, in chapter 2, a brief characterization of the MAESTRI project, with the description of the Total Efficiency Framework, based on Lean principles and incorporating the eco-efficiency concept, is presented. It is also in this chapter that the MSM methodology is introduced with all its developments and capabilities that have made it a powerful tool for assessing resources efficiency.

In Chapter 3 is presented the case study and methodology used to accomplish this work.

Chapter 4 describes the production system with all the activities to bring the product to the customer, and the results obtained by the diagnosis of the production chain of heating devices.

The diagnosis was first made using the Value Stream Mapping (VSM) lean tool, but quickly became perceptible the inability of this tool to evaluate the resources consumption in the most complete way. The MSM methodology was used to overcome the identified limitations of the VSM and fully diagnose the production system, through which was possible to identify several critical misuses/inefficiencies.

With the application of the MSM in a real industry environment, it was also possible to identify some limitations in this methodology, mostly related with results presentation and consequent interpretation, leading to a misguided decision making-process. It was then purposed a complementary analysis, in chapter 5, to overcome this limitation.

For the most critical inefficiencies identified in the diagnosis stage, concrete solutions were developed and presented to the company. Some of them are already implemented, and so it was possible to quantify the impact of these solutions in the production system, as it can be seen in chapter 6.

Finally, in chapter 7 the final conclusions of this master thesis are presented.

2. State of the art

“Over the time, the human kind has always managed to transform the environment. Since the ancient explorers and settlers more and more species have become extinct and in the process the ecosystems have been destroyed. The difference from that time, is that now we are knowingly doing this, and in a much larger scale. The fossil fuels, oil, used in the transportation sector, coal and natural gas used to power most of the electricity, are the major foundations of the present economy. All our modes of transportation, boats, trains, planes, cars, the way we produce our food, the way we build our cities, and all the industries release carbon dioxide, CO2 and that leads to climate changes.” [1]

Due to an immense competitive pressure in a more demanding market, with well-defined customer requirements on the level of quality, costs, deadlines and environmental impact, several studies emerged related to resources efficiency and ecological concerns that apply production models to make a production system more efficient. On this context, the MAESTRI project came to light to meet the needs of the current industries in reducing waste and simultaneous increase the productivity and value of its products. It’s an European project that aims to increase the resources efficiency inside a company by applying Lean methods, introduce concepts like eco-efficiency and implementing a new approach, the Total Efficiency Framework.

The Total Efficiency Framework is an approach developed by the MAESTRI project to assess and increase a company’s performance [2], that integrates the Lean philosophy, based on a set of principles and tools that eliminate wastes, capable of improving the productive efficiency of any company [3] [4], and the concept of eco-efficiency, that is grounded on creating more value with fewer resources, creating less waste [5]. The Total Efficiency Framework also incorporates two methodologies that try to implement the Lean and eco-efficiency logics in an industry environment, the Multi-Layer Stream Mapping (MSM) and the software Eco-Efficiency Integrated Methodology for Production Systems (ecoPROSYS). Respecting the lines of the MAESTRI project, this integration enables to evaluate resources and manufacturing processes, concluding in the assessment of the system’s efficiency and eco-efficiency performance.

This chapter consists on a brief explanation of the theoretical foundations throughout this work, which is based on the MAESTRI vision of applying continuous improvement principles within an organisation and the promoting innovative methodologies used the characterize the efficiency of industrial processes.

2.1. The MAESTRI vision

Europe, in particular, has always contributed to vast innovations in the industrial processes. It has more than 500 thousand companies with more than 7 million workers and generating a 2 billion euros profit [2].

This circumstance represents the responsibility of doing “more and better with less”, contributing to the resources efficiency, decreasing the emissions and increasing the competitivity and production knowing that industries less environmental efficient will not endure in a more open market and widely globalized [6].

With this always in mind, the MAESTRI project, created in 2015 with fifteen partners from five European countries, intends to inspire any production system of any corporation to a culture of improvement, sustainability and monitorization of the company’s environmental and economic performance. It will also be developed new methods to use resources, energy, recycled materials, water and residues more efficiently [2].

The progress and validation of the project will be done during four years, in four different companies in Europe, of different areas of work, adopting concepts such as eco-efficiency (make more with less), decreasing the industries’ costs. It will analyse the observed data, present results and give solutions, in a partnership with several associates such as Instituto Soldadura e Qualidade (ISQ), Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial (INEGI) and Instituto Superior Técnico (IST).

Nowadays, the industries’ current vision is to use and apply resources (raw materials, energy, consumables) without any structured management systems or tools in the company’s strategy. They transform the raw material into products and waste (without recognize that waste can be reused as a resource) and repeat this process continuously.

The MAESTRI vision aims to implement an interactive value chain between companies, creating a cross sectorial collaboration among different industries environments [7]. The production system intends to share and assess resources and energy more efficiently, sustained in the definition of eco-efficiency, “make more with less”. The better use of resources will provide a bigger quantity of final products and less waste that can be reused either internally or externally (synergies between production sites) [2] [6]. All of this will be monitored and optimized by tools that will support the decision process regarding resources, energy and waste efficiency, such as the Multi-Layer Stream Mapping, helping defining priorities to the environmental, economic and social aspects of the company.

The MAESTRI vision is illustrated in figure 1-1, adapted from [2]

Considering this, there are some gaps on the implementation of this original idea of energy and resources management: Those gaps are expressed in table 1-1.

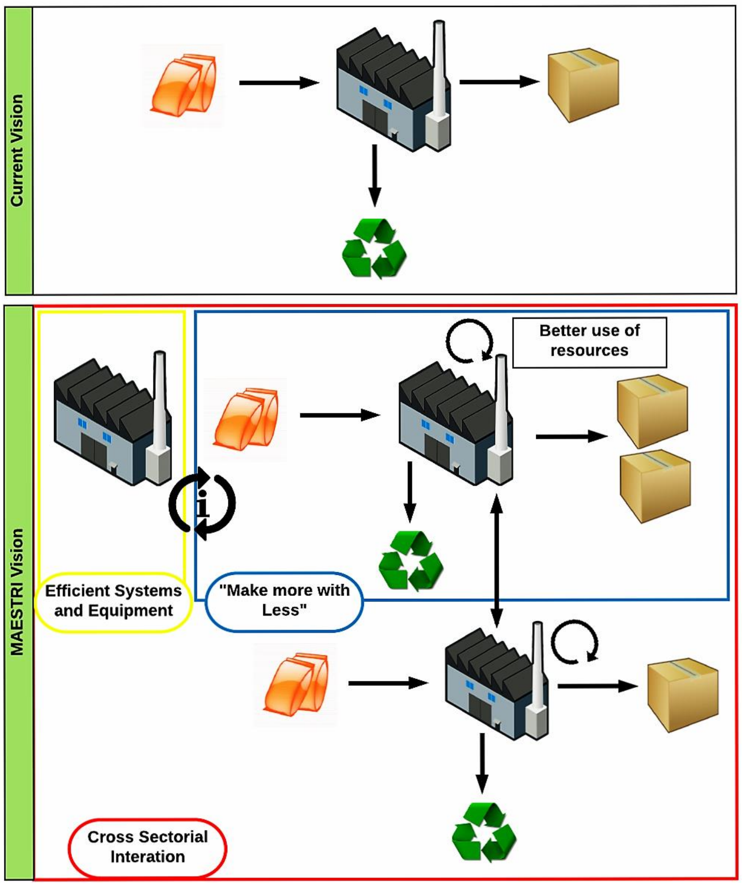


Figure 1-1: The MAESTRI project vision, adapted from [2]

Table 1-1: Main gaps for energy and resources management (technical/technological, management and organizational gaps)

Technical/technological gaps
- Lack of flexible and scalable tools to support decision making regarding resources and energy efficiency - Deficient knowledge to identify the potential use of wastes as resources - Lack of simple tools to assess and optimize resources and energy efficiency, crossing the different environmental and economic aspects - Deficient data quality to support improvement measures
Management gaps
- Non-incorporation of sustainability aspects in company' objectives - Dispersion of relevant data and information across different departments of the company - Difficulty on the definition of Key Performance Indicators (KPI's) and their follow-up - Non-implementation of structured management systems targeting resource consumption and energy efficiency
Organizational gaps
- Difficulty to collect and share information about all processes flow (resource and energy inputs as well as waste and pollutant outputs) - Poor means for sharing resources through the integration of multiple production units of a single company or multiple companies

On this context, the Total Efficiency Framework was proposed to fill these gaps and difficulties of implementing the MAESTRI vision in industrial companies

2.1.1 The Total Efficiency Framework

The MESTRI project intends to develop and implement one new and innovative approach based on the idea of continuously improve all the industrial processes, strategies promoting the operations efficiency and helping on the definition of priorities to increase the company's environmental and economic performance: "The Total Efficiency Framework".

The Total Efficiency Framework is based in four main pillars [2] [8]:

- Management System
- Efficiency Assessment
- Industrial Symbiosis
- Internet of Things (IoT) Platform

The management system tends to develop LEAN strategies related to continuous improvement. It is supported in a motivational strategy, people engagement and cultural education to simplify the approaches and results analysis, and stimulate competitiveness by reducing costs and environmental impact [9].

The efficiency assessment proposes and validates two new procedures: The Multi-Layer Stream Mapping (MSM) and the software Eco-Efficiency Integrated Methodology for Production Systems (ecoPROSYS). The MSM enables an overall view of the efficiency performance, in a simple and alarmistic way, including process time, energy, materials and costs, being a bridge for optimization of the process flow and its eco-efficiency. The ecoPROSYS simulates different scenarios with different inputs patterns letting the user to know the best model of energy and resources efficiency. The identification of major inefficiencies as well as the improvement of the use of energy, resources and process variables and cost analysis are the core targets of this pillar [8].

Industrial Symbiosis instructs the concept of how to see, quantify and exploit waste. It will allow the identification of unused materials and resources and point to new opportunities that can result in exploitable synergies with other production systems, both internally or externally to the company [10].

Finally, the IoT Platform, a dynamic network infrastructure, will be developed to monitor the production system as well as all its inputs and outputs of the different teams in the company at the same time [2].

The Total Efficiency Framework is illustrated in figure 1-2.

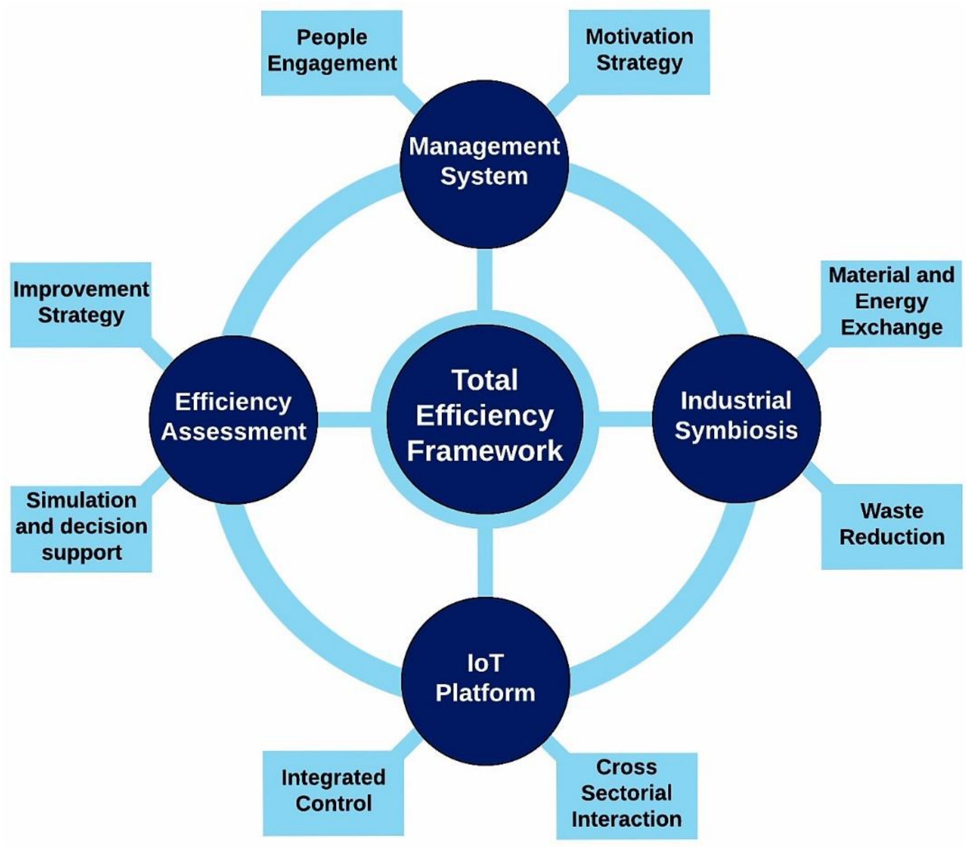


Figure 1-2: The Total Efficiency Framework, available in [2]

As the Total Efficiency Framework is associated with several new methodologies and concepts, it is explained succinctly in the next chapters what is eco-efficiency, Lean, and the MSM methodology, for a better comprehension.

2.2. Eco-Efficiency

Over the last decades the environmental problems have gained a lot of importance in our society. The human specie has been consuming natural resources and polluting the environment faster than it can regenerate, originating a footprint of 1.5 times the Earth biocapacity, placing the future of our society at risk [11]. Industries all over the world have a major role in this shocking concern since they are responsible for more than a third of energy consumption and CO_2 emissions [12].

By this reason, and being part of the MAESTRI vision, it is mandatory to transform this unsustainable development to a sustainable environmental progress without neglecting/reducing the companies profit and increasing the quality of the products [2].

The eco-efficiency definition started with an idea, in the 1970´s, by Paul Ehrlich and John Holdren on trying to measure the impact of human activity in the environment [13]. Furthermore, the term eco-efficiency was first described by Schaltegger and Sturm as a "business link to sustainable development" and was adopted, in 1991, by the World Business Council for Sustainable Development, WBCSD [14]. Nowadays the WBCSD describes that "eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity to a level at least in line with the Earth's estimated carrying capacity" [15].

The WBCSD definition is the most adopted worldwide, but there are more eco-efficiency descriptions: The Organization for Economic Co-operation and Development (OECD) defines eco-efficiency as "the efficiency on how resources are used to serve the human needs" [5]; The Environmental Protection Agency (EPA) presents eco-efficiency as "the ability to simultaneous reach the goals of production and costs with high quality and performance, reducing the environmental impacts and preserving the natural resources" [16].

From an overall perspective, knowing that "eco" from the Greek "oikos" means house and "Efficiency" is the ability to reduce losses when manufacturing something, eco-efficiency is the approach to take care of our house, the world we live in, reducing the environmental impact, energy consumption, waste and CO2 emissions [16].

This concept of eco-efficiency identifies two significant areas that must be related, environmental impact and economic growth [17]. In this sense, it is interesting to evaluate the eco-efficiency of a company and try to benefit both parcels, through measures such as reduction of raw material used, reduction of energy consumption and increasing the organization profit [6] [18].

Eco-efficiency, can be represented by the equation (1) and it's from this ratio that results are obtained and can be used to improvements and comparisons. It intends to improve competitiveness, environmental performance and stimulate productivity and innovation by increasing the product value and decreasing the environmental influence [6].

$$Eco-efficiency = \frac{Product\ or\ Service\ Value}{Environmental\ Influence} \tag{1}$$

Through this definition, eco-efficiency of a production system can be influenced by many factors: the production processes that give value to the product, the infrastructure services that create the necessary atmosphere for the production (lights, heating, ventilation, air condition) and the supporting processes that provide all the necessary inputs for the procedures to work correctly (gases, coolant, compressive air). All resources consumed (materials, energy) or generated (emissions, products, waste) by the production processes and supporting processes need to be determined and perceived to decide (or not) decrease the consumptions, the environmental influence and increase the product value and productivity (see figure 1-3) [12].

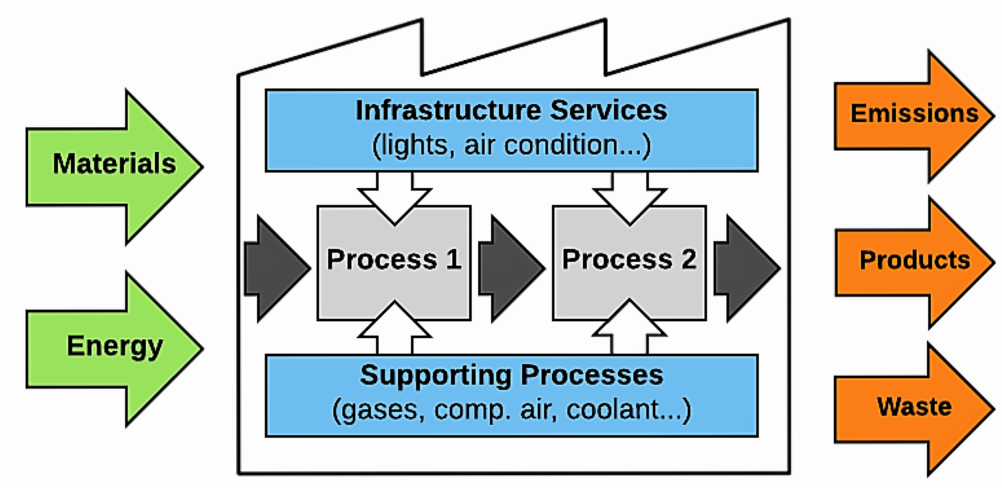


Figure 1-3: Eco-efficiency concept illustrated for an industrial environment, adapted from [12]

Summing, the ultimate goal of eco-efficiency concept is to improve the environmental performance of a company relative to the value of the product and services it provides to society [19].

According to the MAESTRI vision, the concept of eco-efficiency, assessed by the ecoPROSYS software, can be integrated in the Total Efficiency Framework to classify significant environmental issues and support the decision-making, providing a significant indicator for a systematic improvement of resources efficiency and costs of manufacturing companies.

2.3. Lean Manufacturing

Nowadays the competition is growing at a very high rate between industries all over the world [20]. Playing a central role in the world economy, industry serves as a key driver to innovation, research, productivity, job creation and exports. Yet, European industry has lost many manufacturing jobs over the last decade, and is facing tougher competition from other markets with lower-cost source [21].

Cultures like China, with low costs of manufacturing, and the more rigorous costumer requirements, have created a challenging world market where companies' operational efficiency and effectiveness must be at excellent levels to compete in a business world that is in constant change and development [20].

Nowadays, to remain competitive, strategies must be created according to changes in society's demands, working conditions, clean production and environmental concerns. Moreover, at the current economic situation, it becomes even more urgent to reduce the waste sources, increase processes efficiency and the company productivity [22]. One of the most common choice is Lean manufacturing which consists on a set of tools and measures that continuously improve the organization by identifying and eliminate wastes, non-value added activities, and completely satisfy all the dynamic customer needs [23].

According to Melton (2005) the Lean practice is an already validated methodology that came to revolutionize and completely change the manufacture business and all its activities: how the supply chain operates, how directors supervise, how managers administrate and how the employees do on their daily routine [24].

To understand the Lean phenomenon is necessary to learn and comprehend the Lean tools that leads to the Lean principles: a thinking strategy of increasing the value chain of the product and eliminate all the activities that not add value (overproduction, inventory, waiting, motion, transportation, rework and over processing), increase competitiveness and reduce costs, based on a continuous flow and pull production, as it can be seen in table 1-2.

Table 1-2: Lean principles

Lean Principles	Description
Value	Specify value from the standpoint of the costumer
Value Stream	Identify all the steps in the value stream eliminating those that not create value
Continuous Flow	Make the value steps occur in tight sequence so, the product will flow continuously toward the customer
Pull Production	Downstream activities signal their needs to upstream activities to eliminate overproduction and stocks
Perfection	Begin the process again and continue it until perfection is reached in which perfect value is created with no waste

After understanding the Lean principles, there are some tools that should be applied that will lead to the Lean principles. These tools must be applied in a continuous way with the aim of eliminate waste, increase productivity and improve quality. They should be applied with the intent of seeking for improvements without great investment and with the mind set of “do now” (an imperfect improvement is better than the delayed perfection) [25].

Those tools can be to diagnose the system, what are the processes, identify the different phases of the system and characterize the multiple inefficiencies and waste activities [4]. They can also be used to a solutions support that will lead to the development of improvement actions. They are described in table 1-3.

Table 1-3: Lean tools examples

Application	Lean tools	Description
Diagnosis	**Visual Management**	Provide immediate visual information about the system and enables waste exposure in a clear way
	Cause Effect Diagram	Helps to visually display the many potential causes of a specific problem or effect
	KAIZEN Events	Gathers operators, managers and owners of a system in one place, maps the existing process and discusses improvement actions
	5 Whys	Asking "Why?" five times helps uncover the process dynamics and the areas that can be addressed easily
	Value Stream Mapping	Visualise macro level processes and their performance in a simple visual way
Solutions Support	**5S**	Organised approach that ensures tools, parts and other objects that are needed in a process are at optimum locations
	SMED	Single-minute exchange of dies reduces setups by work simplification and standardization
	JIT	Sets out to cut costs by reducing the amount of goods in stock by delivering the materials "just in time" for the next process
	TPM	Total productive maintenance that combines predictive and preventive maintenance. Improves process capability and consistency
	Kanban	Visual devices like cards for one process produces a product when it is needed, minimizing the stocks
	One piece flow	A product is produced by moving at a consistent pace from one value-added process to the next with no delays in between

Although Lean is a powerful tool, and the Total Efficiency Framework follows its main principles and tools, it doesn't focus on ecological concerns, being its principles and tools only directed to productivity and value of the final product [26]. The absence of Key Performance Indicators (KPI's) and metrics related to resources efficiency is a big barrier to fully characterized a production system with the current environmental interests.

Associated with the MAESTRI project, a new methodology, the MSM, based on the Value Stream Mapping (VSM), has been developed to assess the efficiency performance of a production system integrating different KPI's, not only to describe the system, but also to contemplate the resources effectiveness and their impact in the environment, as it is described in the next chapter [27].

2.4. Multi-Layer Stream Mapping

2.4.1 The Origin

The Multi-Layer Stream Mapping (MSM) is a Lean tool developed in INEGI by Lourenço et al. (2013) capable of measure, evaluate and increase the efficiency of a production system in a simple way and helping the decision making and operational management of the company. It was first presented in the 20th CIRP International Conference of Life Cycle Engineering, on April 2013 in Singapore.

According to the authors, the MSM methodology emerged from several problems and needs of the Portuguese companies compared to others in Europe. The low competitiveness and productivity, lack of know-how, high costs on resources and energy, and the demands of a changing worldwide market express enormous challenges to production management [28]. For this reason and difficulty of application of the current Lean tools to evaluate the performance of production systems in terms of eco-efficiency and costs, the MSM arose. The MSM focus on the maximization of the value added of the product and costs reduction such has the easy interpretation and direct understanding of the results and the quick identification of critical aspects and inefficiencies of the system, due to its simple visual layout [29] [30].

The MSM has its origin in VSM, which identifies and distinguish the activities that have value from the ones causing waste required to do a product, from the raw material to the client. The original idea consisted in unify and integrate all the isolated tools to evaluate the efficiency of the different steps associated to the value chain, such as costs, emissions, energy consumption, other resources consumption or waste generated of all unit processes [27]. So, the VSM root is transformed into the MSM concept to diagnose and analyse the overall efficiency of any production system also regarding the environmental and economic performance, and at the same time simplify the identification and quantification of specific inefficient situations [31]. MSM, besides VSM, can also be used to monitor on-line the production flow and by that control in real time all the operations inside the factory from several perspectives regarding the company aims [32].

The analysis must be done according to the current conditions of the company such as operators and technology used.

2.4.2 MSM description

The MSM consists in replicating the VSM approach, associated to a specific product and includes different variables (streams) that can be used to assess the system performance, like time, energy and consumables [29]. The methodology output consists in a matrix (the multi-layer aspect), where the lines are the different variables (streams) used to evaluate the system (time, energy consumption, cost), and the columns are the processes by which the product flows (process units) [27], as it can be seen in figure 1-4.

According to Lourenço et al. (2013) the MSM application must follow these steps [27]:

i. Identification of the system boundaries, processes and relevant KPI's
ii. Definition of the associated KPI for each process
iii. Analysis of the results and identification of the inefficient processes
iv. Prioritization of the improvement actions
v. Implementation of the improvement actions and collect results of the efficiency improvement and costs reduction

As it intends to be a Lean tool, to diagnose and monitor a system, concepts like "value" and "waste" must be always present in the analyses. It can be seen in figure 1-4 each variable has a line flowing throw the different processes of the value stream. The values located below on this line are those which do not add value to the product, such as waste of time, money or resources. The values that are presented above are those that add value to the product, representing useful consumption [33].

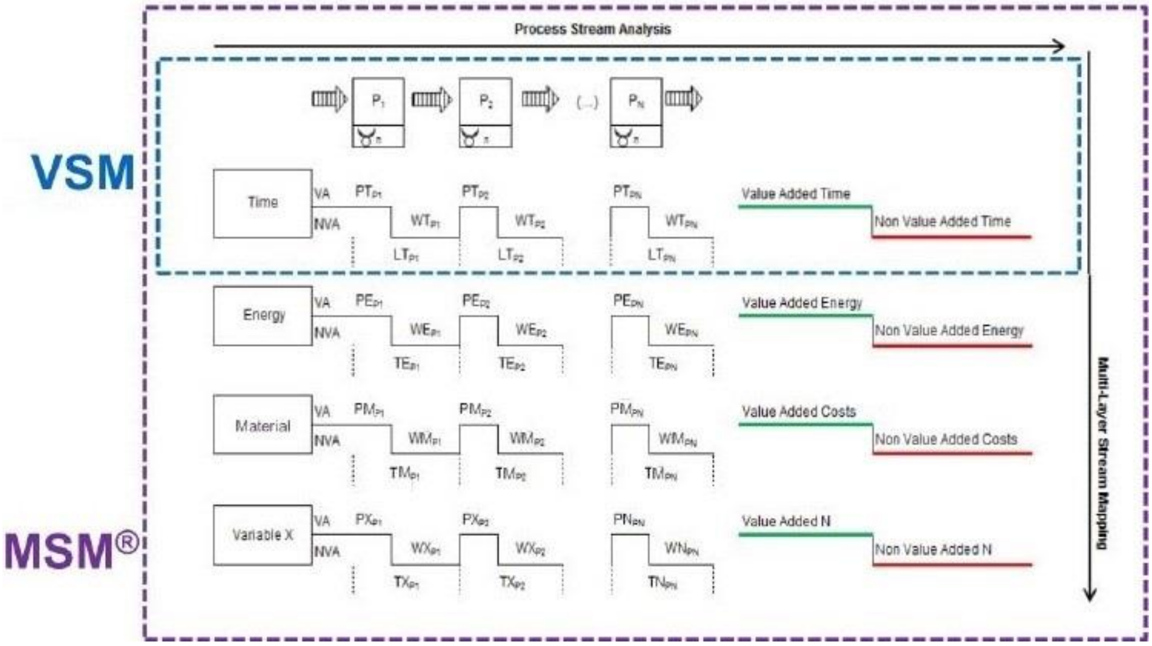


Figure 1-4: VSM and MSM concepts, available in [30]

Where:

PT – process time WT – waste time LT – lead time

PE – process energy consumption WE – waste energy TE – total energy

PC – process material consumption WC – waste material TC – total material

VA – value added NVA – Non-value added

The results presented by the MSM are efficiency ratios resultant from the previous values and are calculated by the equation (2):

$$\Phi = \frac{Add\ Value\ fraction}{Add\ Value\ fraction + Non - Add\ Value\ fraction} \tag{2}$$

Where:

Φ – Efficiency of the system process step, in percentage

Add Value fraction – Portion that add value to the product

Non-Add Value fraction – Portion representing the wastes, such as waitings, waste of resources, waste of energy, transportation or storages.

These results are always concerned to the studying process. The KPI's are created to be maximized and between 0% and 100%. The higher the ratio result, higher the good value of the process step of the system [28].

Because of its visual and alarmistic outlook, a set of colours is used to ease the interpretation of results and spot critical situations. By relating a key of 4 colours, red (process efficiency < 40%), orange (process efficiency between 40% and 69%), yellow (process efficiency between 70% and 89%) and green (process efficiency between 90% and 100%), its faster to assess the efficiency quantity, contributing to prioritization of improvement actions, enhancing continuous improvement. These percentages can be changed according to the company objectives or strategy for the production system [29] (see figure 1-5).

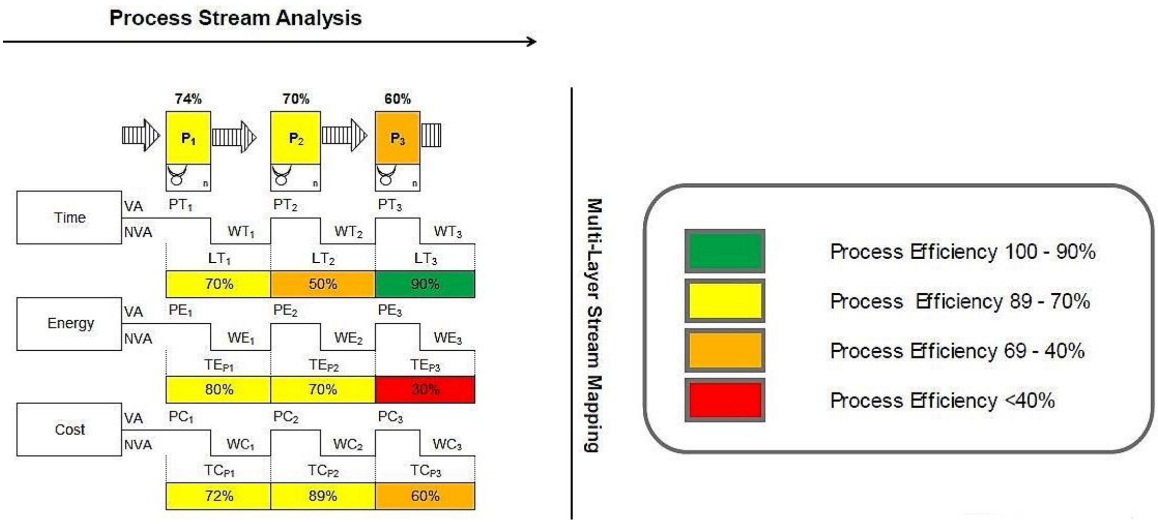


Figure 1-5: Multi-Layer Stream Mapping approach, available in [30]

The MSM methodology promotes an extensive comprehension about the current system performance. By aggregating each unitary efficiency of the different processes, for each KPI, it will be obtained the Process Parameter Efficiency (see in figure 1-6) which is calculated by the ratio between the total added value and the overall total of that stream (equation (3)) [28].

$$Process\ Parameter\ Efficiency = \frac{\sum(Add\ Value)_{KPI}}{(Total\ Value)_{KPI}} \tag{3}$$

Where:

∑ (Add Value)KPI: Total added value of a KPI over the different processes

(Total Value)KPI: Overall total of that KPI, being the value add fraction plus the non-value add fraction of the KPI

By aggregating individual performance levels of the different KPI's in a process unit (equation (4)), it is possible to achieve the Unit Process Efficiency (see figure 1-6) [28],.

$$Unit\ Process\ Efficiency = \frac{1}{n} \sum \Phi\ KPI's \tag{4}$$

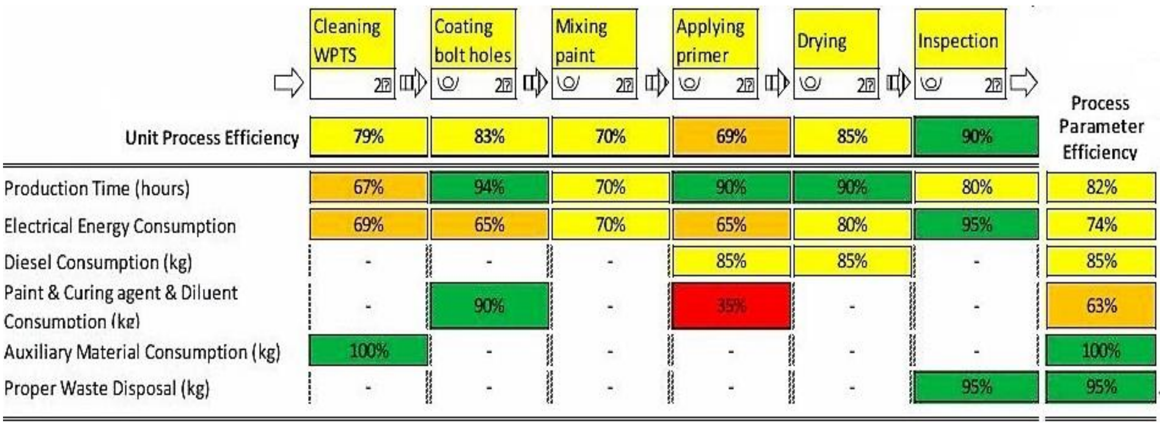
Where:

n: number of KPI's

Φ KPI's: efficiency of the different KPI's in a process unit

The MSM, as the VSM, also includes information about the number of operators in each process that characterizes the analysed flow.

All final results can be displayed in dashboards where the information is presented in a simple and intuitive way. From top to bottom teams, all of them must understand the scorecard without losing too much time and identify the critical processes of the system for a rapid improvement [29]. A scorecard example is illustrated in figure 1-6.



	Cleaning WPTS	Coating bolt holes	Mixing paint	Applying primer	Drying	Inspection	Process Parameter Efficiency
Unit Process Efficiency	79%	83%	70%	69%	85%	90%	
Production Time (hours)	67%	94%	70%	90%	90%	80%	82%
Electrical Energy Consumption	69%	65%	70%	65%	80%	95%	74%
Diesel Consumption (kg)	-	-	-	85%	85%	-	85%
Paint & Curing agent & Diluent Consumption (kg)	-	90%	-	35%	-	-	63%
Auxiliary Material Consumption (kg)	100%	-	-	-	-	-	100%
Proper Waste Disposal (kg)	-	-	-	-	-	95%	95%

Figure 1-6: Example of a MSM scorecard, adapted from [34]

The MSM would bring a successful visual tool to managers, and operators, to understand and interact in an easy way, see their inefficiencies and where they can systematically check their performance to improve and achieve the company demands.

Since the MSM is a new methodology an implementation strategy should be developed. The MSM can be used for diagnosis or for a continuous monitorization of the production system. If it is used for the diagnosis, it can be done manually (just like the VSM) and a substantial set of KPI's can be analysed to fully characterize the system and perceive the main inefficiencies. When it is used for monitoring the system in real time, all the machines used in the manufacture should be capable of collect production data (value-added times, non-value-added times) and show it in the MSM tool.

2.4.3 Key Performance Indicators (KPI's)

A production system of a company is like a network where all the internal and external services must be connected to each other. Production plays an important role in a company's competitiveness and profitability. Productivity, energy and raw material costs or other variables like quality are some aspects that must be controlled and improved [35].

Key Performance Indicators (KPI's) are variables used as an auxiliary tool to top management, control and guidance of an organization business. KPI's provide a set of measures that identify the most critical aspects, the performance of a company and its improvement potential [36].

The KPI's are not the same in every company, depending on its strategy and final goals, and determine if it is necessary to take different actions to improve the results of the business. Mostly of times KPI's are chosen by defining accurate set-points according to the company business strategy and try not to create demotivation in its operators by setting unrealistic targets. Strategies must also be created to operators don't feel they are being evaluated but to understand these KPI's focus on the needs of the company promoting improvement actions and where to implement them [37].

2.4.4 Potentialities

The MSM tool was already tested and validated in three industrial sectors. Its versatility makes it a multi sectorial approach that can be applied in the health, transports, hospitality industry etc. It can be applied as an evaluation or diagnosis of a system or it can be used to monitor the production flow in a continuum way.

The MSM outcome is an intuitive representation of the product flow performance and can be very practical and useful for [28]:

- “Top management decision support”
- “Defining priorities”
- “Identifying inefficiencies in an easy manner”
- “Identifying Key Environmental Performance Indicators (KEPI)”
- “Assessing eco-efficiency performance”
- “Identifying improvement action’s needs”
- “Informing all level of collaborators the efficiency of the production cell or unit”
- How well is the company allocating its resources
- Besides VSM, MSM has a dual capacity of diagnose and monitor multiple streams at the same time.

In addition, this approach can be used to evaluate process reengineering, since in some cases the unit processes, or even the whole production system, have good operational results, but the efficiency is not as high as it could be. Therefore, using this approach to scrutinize “how”, “where”, and “how much” can a unit process and/or a production system improve its financial, environmental and performance aspects, is of great importance for decision-making [38].

Due to its visual acuity and the result data presented in a dashboard or scoreboard format, the target users for the MSM diagram analysis can be everyone in the company, from the top managers to the production line workers since its concepts are straight visual information, from a set of colours creating an alarmistic reaction, without mathematical or complex technical concepts [31].

The scorecards used can be different from team to team inside the same company. The scorecards destined to management teams must include more variables and be more detailed in the costs KPI’s to perform a more wide and complete study of the processes that illustrate the system. These teams can also find on this tool, the possibility of simulating different situations and evaluate the consequent changes on the production system [29].

It is important to state that the MSM methodology must be divulgated and implemented in order to evolve the production system of the companies and perceive its growth capacity and not as a way of evaluating the people within it.

It is a tool that all employees can understand and work together for the good of the business.

2.4.5 **MSM 2.0**

As it was seen before, the MSM is a powerful tool to evaluate and assess the efficiency level of all the add value activities in the production system. However, the production system is much more than the productive activities. All the logistics between processes, the not value added activities, have influence in the lead time and resources used to take the product to the client, and are not included in the MSM methodology.

As Gomes (2016) purposed, the in-between processes activities (figure 1-7) must also be included in the assessment of the system's performance to fully characterize the production system in the company. That means the non-add value phases, like setup operations, transports, storages and waitings, are essential activities to study since they consume resources like time, energy and materials, have costs to the company and have influence in the performance of the add value activities since both, add value and non-add value, are correlated [29].

So, a new approach of the MSM was proposed by Gomes (2016), the MSM 2.0, that integrates the waste activities in the original methodology, making possible to analyze the entire product flow.

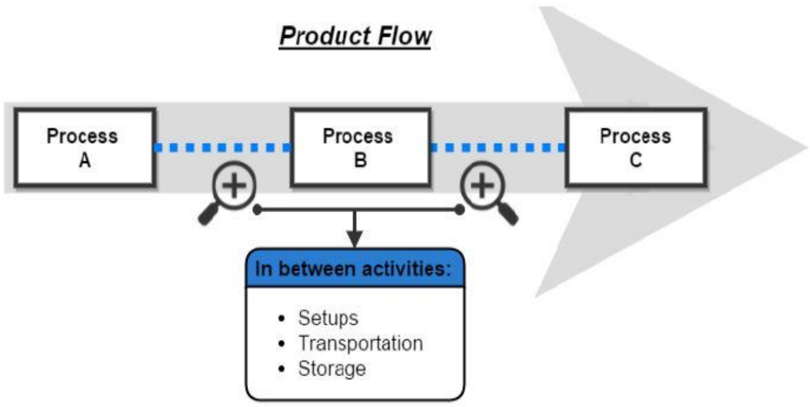


Figure 1-7: Analysis in between productive processes, available in [29]

The suggested KPI calculation process for the MSM 2.0, is then also focused on reducing the wastes associated with the product flow [29].

The author of the MSM 2.0 suggested that the KPI's proposed can now be calculated by two different formulas (equations (5) and (6)) depending on the type of variable being assessed [29]. Perceiving there are several types of KPI's, depending on the strategy and goals of the company, it is essential to define the direction of improvement for each one of those KPI's, since some should be minimized, like waste time, distances or stock levels, and others should be maximized, like if the number of right items is being manufactured or the time a machine is adding value to a product.

- For KPI's that should be minimized, since the total values are above the designed value pre-defined by the company, the ratio is:

$$\Phi = \frac{Designed\ Value}{Total\ Value} \tag{5}$$

- For KPI's that should be maximized, since the total values are below the designed value of the company, the ratio is:

$$\Phi = \frac{Total\ Value}{Designed\ Value} \tag{6}$$

Where, for both cases:

Φ – Efficiency level of the analyzed KPI

$Designed\ Value$ – Value defined by the company for that KPI

$Total\ Value$ – Current value measured for that KPI

The designed value is usually defined by the company according to its goals and should be as realistic as possible, since with too ambitious targets will outcome a low efficiency level that can wrongly indicate a system is with a minor performance.

The MSM 2.0, by being a recent methodology, was not tested in several case studies.

3. Case study and methodology

The present work consists on applying the MSM methodology to one of the MAESTRI's partners, Manuel Conceição Graça (MCG) company, which includes several activities and types of manufacturing processes, and therefore, allows the application of the MSM. The MSM will be used with two strands, one of characterization, and the other of monitoring the production system by setting strategic goals and KPI's to improve the production efficiency.

The global aim is to test and validate the MSM 2.0 methodology and support decision-making for a production system, considering not only the operational performance, but also environmental and economic concerns.

Chapter 3 will look at the necessary background for this case study with a description of the approach used to test and validate the MSM in this production system.

3.1. Case Study

Manuel Conceição Graça, MCG mind for metal, is a manufacturing private industry with more than 60 years of history, located at Carregado, Portugal.

The company produces metal components, used in different projects such cars' front seats, recycling trash bins, charge boxes, coffee machines and heating devices.

It has more than 400 workers, five manufacturing areas (automotive, tooling, laser, solar and transports), is composed by five manufacturing sites, Metal1, Metal2, Metal3, Metal4 and Metal5, where its products are developed and manufactured (figure 3-1).

The production system to be studied will focus on the heating devices production line. The processes involved in this production are laser cutting, bending, welding, shot blast, painting and assembly (sequentially).

The case study system is currently spread in three different locations in the MCG site. The laser cutting is located at Metal 3, the Painting at, Metal 1, and the others processes at Metal 5, the main site of this production system.

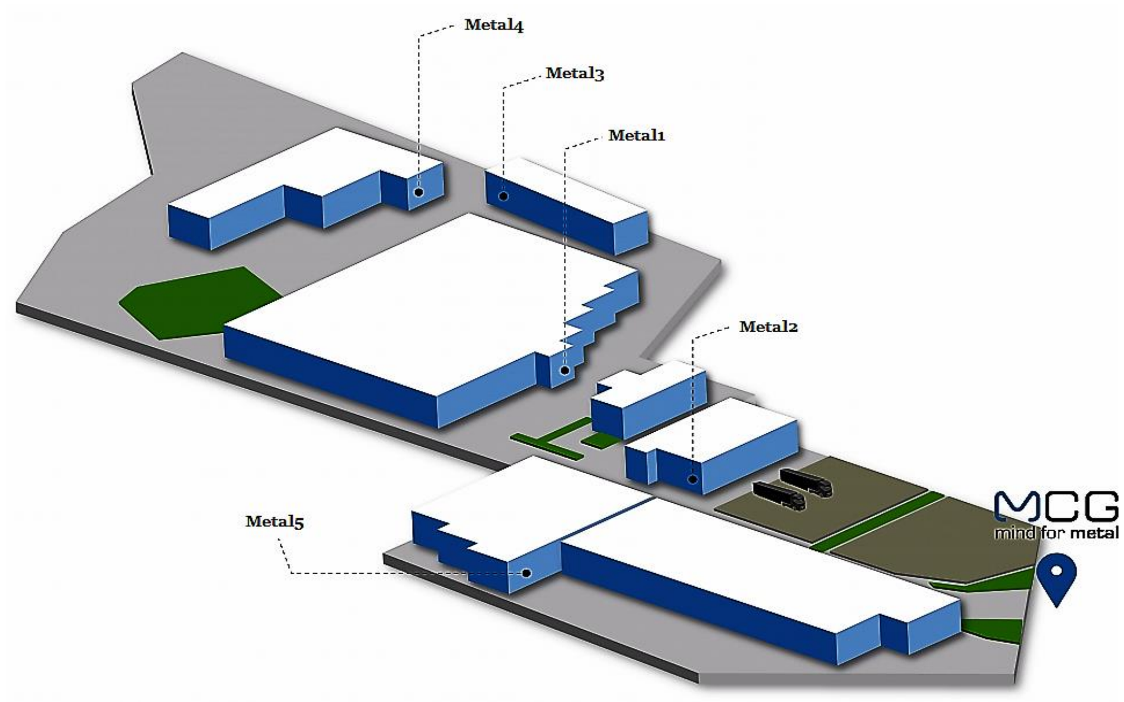


Figure 3-1: MCG site's plant

3.2. Work Developed

The study for the application of the MSM 2.0 in the described production system and the resulting diagnosis required a presence in the MCG company for about three months. During that period, it was possible to learn about the MCG history, values and strategy and improve the relationship with the operators and all the teams of the different departments. In addition, a comprehensive assessment of all the activities involved in the production of heating devices was done, to allow a complete and integrated diagnosis of the production system.

The data used to build up the VSM and MSM 2.0, was gathered by visual observation, time measuring, operators interviews, metering devices and records analysis without destabilization of the involved people functions in the company. These methods study techniques were very useful for a structured decomposition of the different phases and variables of the system such as time, resources consumption or inventories, that will be the inputs of the MSM.

To understand the scope and potential of the MSM methodology was first used the VSM, that allows a macro analysis of both, add value and non-add value activities, necessary to create the product.

Considering the purpose of this work, the MSM 2.0 methodology was then developed to fully evaluate, in a more detailed perspective, the production system, combining the productive processes and logistics operations with the environmental and economic dimensions, and with that deriving conclusions and identifying possible needs of improvement in the heating devices production line.

The main focus of the case study is the in-between processes activities, which includes storages, transports and waitings, having the new MSM 2.0 approach a necessary utility for the analysis, and, for the MAESTRI project, an opportunity to test it in another production system and perhaps improve this methodology.
In the succeeding chapters the production system will be deeply characterized, and an improved methodology of the MSM 2.0 will also be presented for a better diagnose of the production system and better support the decision-making process.

Also, having established these lines to the development of the case study, proposed improvement solutions are presented, and some of them were already implemented in the company.

Finally, a future state of the process can be estimated. The following step is to check that future state and repeat the diagnosis process and solutions development to act again on the production system and follow a continuous improvement approach and by that mitigating all the wastes in all the processes and activities inside MCG.
The flowchart for the development of this work is presented in figure 3-2.

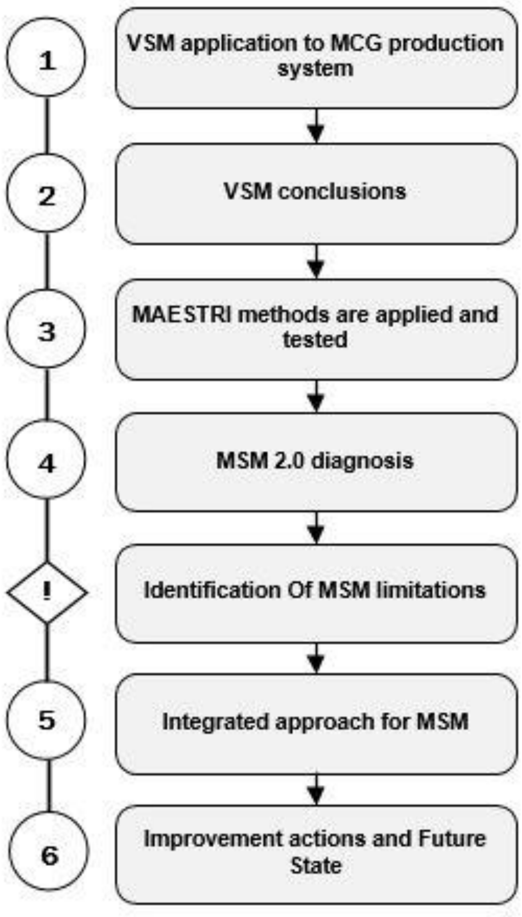


Figure 3-2: Methodology for the current work

4. MSM 2.0 methodology application

This chapter will present an in-depth characterization of the production system at MCG for a better comprehension of the case study and a complete analysis of the system. By characterizing and decomposing the production system in the several different phases, a detailed understanding of the heating devices production system is achieved, and so, the MSM 2.0 methodology can properly be applied to this case study.

By completing the analysis of the case study, the major misuses of the production system could be identified resorting the MSM. With the present analysis, some limitations of this approach were identified and presented in the following chapter.

4.1. Production system characterization

The production system in MCG is characterized by a multi-production system, where a high variety of products, all from different clients, is manufactured.

The current system uses a make-to-stock logic and it is essentially based on push production. The orders made from the customers have an erratic demand, rarely having the same quantity in every order. Managing such unpredictable demands without affecting the performance of the system is a very challenging and difficult task, because this variability in demand and in product mix contributes to long lead times and bottlenecks along the production line.

The system to be studied consists in:

- the six manufacturing processes (previously mentioned in chapter 3)
- an auxiliary operation in which all parts required to one process are manually grouped together and placed into one or more kit containers to progress in production, Kits
- two safety stocks where the unfinished inventory wait for the next process, denominated W1 and SKI
- all the resources necessary to promote a balanced service level and satisfy the customer needs, that involves all the operators, machines, one diesel van and five electrical forklifts.

A schematic diagram of the current system is shown in figure 4-1.

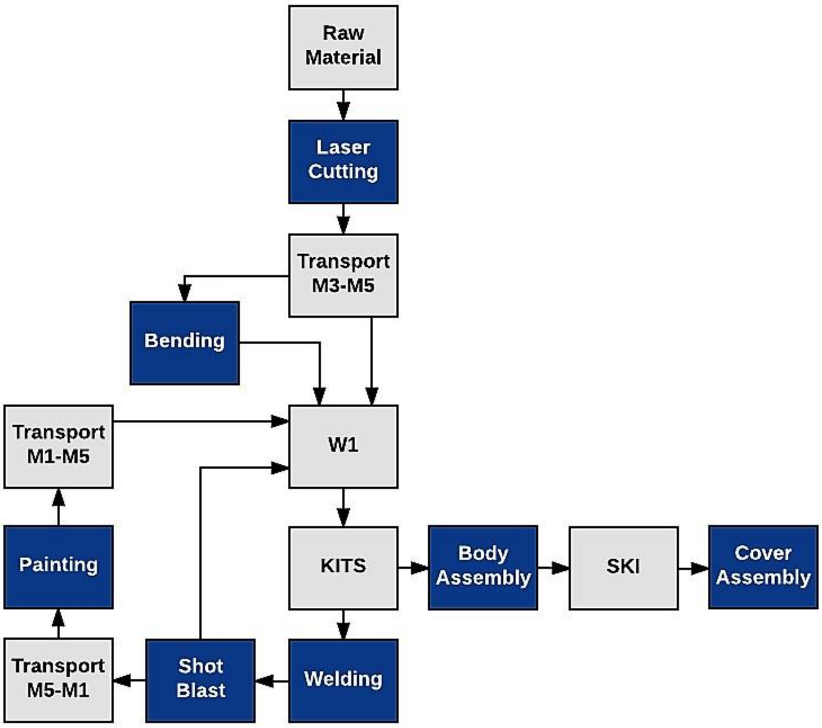


Figure 4-1: Activities within the production system

4.1.1 The product

Each heating device produced at MCG is composed by two distinctive elements: one body and one cover, both constituted by several different parts. The body structure is where the combustion takes place and the cover is the outside structure that provides the aspect of the heating device.

Since there is a great variety of heating devices models being produced at MCG, it is essential to choose one that good represents the production system, in order to study it and accomplish the goals of this work. The chosen model was the “P46-mini fusion glass door”, presented in figure 4-2.

Within this model, a more specific part was selected to follow through the shop floor and collect information about the actual state of the system. This part is a component of the body structure and was guaranteed that it goes through all the process units in the company to perform a full study of the production system (see figure 4-3).

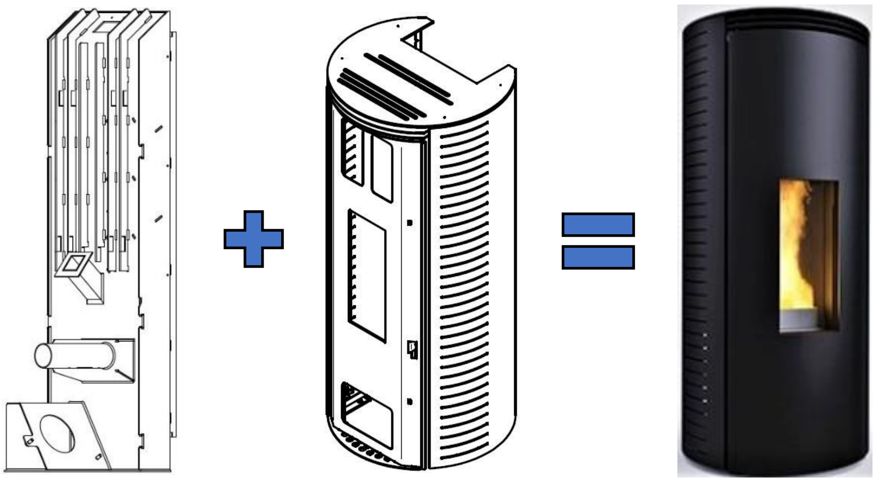


Figure 4-2: Mini fusion glass door made of one cover and one body structure

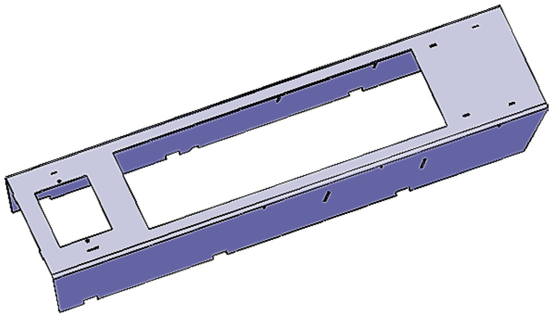


Figure 4-3: Part chosen for the production system characterization

4.1.2 Add value activities

Although the processes are not the main target off the current work, they are the most crucial operations in any production system. Even more, since the original approach of the MSM methodology contemplates the add value activities, it is essential to present the different processes within MCG. In a further analysis, with the new approach of MSM 2.0, the add value activities will be integrated with the non-add value activities to fully evaluate the production system

The necessary processes to produce a heating device are resumed below:

Laser Cutting – The laser cutting process is where the raw material is cut into different components by a generated laser beam of a high-power machine. The laser workstation has two different machines, being the Trulaser 5040 used to produce the chosen part by the time of the observation. In this process, the company resorts on some necessary gases, used as resources, for a good quality of the parts. MCG uses helium, nitrogen and carbon dioxide, for formation and stabilization of the laser beam, and oxygen and liquid nitrogen for an efficient clean cut with relatively low laser power. The laser workstation is presented in figure 4-4.

Figure 4-4: Laser workstation with the Trulaser 5040

Bending – The bending process shapes the parts into its final configuration by the action of a high-power machine. The machine observed to produce the chosen part was the Trubend 5130, although it has more three bending machines.

This process only requires energy as input and the operator to position the work piece over a die block to press the part and form the necessary shape.

The bending process is in figure 4-5.

Figure 4-5: Bending workstation with two high-power machines

Welding – Workstation where the parts are joined together to form sub-assemblies. For the product studied, this is an outsource process, due to the inability of MCG manufacture so many different type of products in its facilities.

The type of welding observed in the outsourcing was metal active gas, MAG, with a carbon dioxide/argon mixture. This gas mixture has, as primary function, the protection of the weld region, from the atmospheric gases contamination.

Shot Blast – The shot blast process consists on throwing very thin metal grains at high speed against the product in order to remove oxidation and other dirtiness, and to prepare the parts for the painting process.

Liquid Painting – Workstation where the different parts are painted by using a liquid ink, white or black. After the operator applies the ink, the parts must go to an oven for ninety minutes to dry and increase the quality of the painting. The drying process also improves the properties of the material to support high temperatures without degradation.

Assembly – Manual process, that combines all the parts together to form the final product. On a first phase, all the parts from the body structure are assembled and then, the cover parts are assembled to the body making the final heating device product. The assembly workstation can be seen in figure 4-6.

Figure 4-6: Assembly workstation

4.1.3 Non-add Value Activities

The non-add value activities, i.e., the waste phases, are the central activities to be studied in this work. They are very important to MCG's production system, because is where the company have costs without adding value to the final product, and must be organised and reduced in an efficient way, since they are always necessary to answer the customer needs.

The waste phases of the heating devices production are described below:

Setup – Preparation and adjustment of the machines, material or tools by the operators inside the workstation. Most of the times is a necessary operation, and in the case study is done in every process due to the high variability of products and the need to adjust the machine to switch from producing one product type to a different product type. Although it affects the performance of the production system, the setup will not be studied in this work, being considered an integrated part of the manufacturing/assembly phases, and not an in-between processes activity (the main focus of the present work).

Storages – Places where the semi-finished material is stored until later need in other process. The main storages are the raw material storage, W1, in figure 4-7, and SKI. The manufactured parts are kept in physical structures, and, although they have associated cost, the company chooses to use them to prevent stock breaks and maintain the product flow controlled.

Figure 4-7: W1 storage

Transports – Movement of parts from one activity to another. From the laser cutting to the bending and from the shot blast to the liquid painting the transport is made by van. All the other transports are made by forklifts (see figure 4-8). These transports don´t have schedule routs being, most of the times, made by the emergency of the order. Currently, for this production system, MCG is using five electrical forklifts and one diesel van.

Figure 4-8: Example of an electrical forklift used for transports

Waitings – Periods of time, in the processes workstations, where the parts wait to go in or out of each process. The places where the boxes with the product wait are marked in the floor. If the parts are about to enter in the process, they are placed in the "in" area, or in other case, if they are already machined and ready for the next activity, they are placed in the "out" area.

Auxiliary Process (Kits) – Since there is a wide variety of models, MCG uses the kitting method to organize and sub-assemble the parts that go to the welding, painting and assembly process. Kits are prepared manually in a specific workstation, asking the needed parts to the W1, and is the main handler to a continuous production flow. At this stage, all the parts required to weld, paint or assemble one unit of the final product are grouped together and placed in one kit container. Although it is a non-value added activity, a work-in-process, the main advantage of kitting is that the material flow is simplified, as only kits need to be moved instead of innumerous individual parts boxes. The Kits workstation can be observed in figure 4-9.

Figure 4-9: Kits workstation

4.2. VSM diagnosis

The VSM consists in presenting the current state of the case study's production system in order to identify all the processes units as well as the existing wastes.

The product was followed through the shop floor, from the moment of the laser cutting until the expedition, where the value-added activities and wastes were registered. Per process unit, characteristics such as cycle time, setup time, uptime (percentage of working time in which a machine is working properly) and add value time were measured. Regarding the non-add value activities, waiting times, transport times and the amount of stock in the storages were also registered to perform the analysis of the system. All this information characterizes every activity in the company being possible to identify operational wastes existing in the production system and simplify the perception of eventual development actions. During this period, there were also several meetings with the top management teams of MCG and MAESTRI to discuss the results and define strategies to improve the production system. The case study's VSM can be seen in Attachment A1 – Value Stream Mapping.

The production lead time is the period between the beginning of production until the product is ready for expedition, that involves all the add value and non-add value activities given by equation (7). The shorter production lead time, the shorter the time between paying for raw material and getting paid for the product manufactured from those materials [39].

$$Production\ Lead\ Time = Process\ Time + Inventory\ Time + Waiting\ Time + Transports\ Time \qquad (7)$$

Where:

Production Lead Time: period between the beginning of production until it's ready for expedition

Process Time: period of time the product is in a manufacturing/assembly process

Inventory Time: lead time for inventory quantity is calculated by the equation (8) [39]

Waiting Time: period the product is waiting to go in or out of each activity

Transports Time: period to take the product from one activity to another

$$Inventory\ Time = \frac{Inventory\ Quantity}{Avarage\ Daily\ Customer\ Requirement} \tag{8}$$

In table 4-1 are presented the sums of hours of every stage of production and respective percentage regarding the production lead time. Results show the main inefficiencies are almost exclusively due to the amount of inventory, 79,8%, and waitings before and after the processes, 17,2%. The process time, 2,94%, that should be the highest in the production system, as it is what add value to the product, represents an insignificant period comparing to the other non-add value activities.

Table 4-1: Sums of hours and respective percentage regarding the Production Lead Time

	Production Lead Time	Process Time	Inventory	Waitings	Transports
[h]	**1513,2**	44,5	1208	260	0,7
Total	**100%**	2,94%	79,83%	17,18%	0,05%

Respecting the focus of this work, the in-between processes activities, detailed results of inventory time, waiting times and transport times are presented on table 4-2.

The discriminated results of the waste times indicate that the bending – welding and liquid painting – cover assembly phases are critical within the production system, due to the inventory in the storages W1 and SKI, and waiting times.

What should be a continuous flow, is actually a system with too many "freezes" between the add value activities, because:

- The transport of the product is bad planned, not being done in the right schedule
- The material waits to be manufactured because the processes are already working on full capacity
- The batch (or batches from other products) is not with the right quality or right quantity
- Excess of inventory

Table 4-2: Detailed results for the different in-between processes activities of the case study

	Inventory [h]	Waitings [h]	Transports [h]
Laser - Bending	-	17,7	0,1
Bending - Welding	264,9	116,2	0,2
Welding - Shot Blast	-	2,8	0,2
Shot Blast – Liq. Painting	-	0,7	0,1
Liq. Painting - Body Assemb.	109,6	108,2	0,1
Body Assemb. - Cover Assemb.	833,5	13,3	0,04
Cover Assemb.- Exp.	-	1,2	0,01

Concluding, the VSM is an effective method to clearly distinguish the productive and non-productive time among the production of a product. Although the VSM is an important reference to study the current state of a production system it does not give information about environmental and costs performance of a production system.

Following the Total Efficiency Framework, of apply and validate principles such as eco-efficiency and waste reduction, the MSM methodology, presented in the next chapter, brings a more ample and high-level assessment of environmental and economic concerns, overcoming the VSM tool for a more complete description of the heating devices production line.

4.3. Key Performance Indicators for the case study

At this stage, is performed the assessment of the MSM 2.0 methodology using all data previously collected for the product's specific conditions. The global objective is to support the decision making and identify the production system limitations, considering not only the operational performance, but also environmental implications and economic issues.

4.3.1 Key Performance Indicators

Following the steps described in sub-chapter 2.4.2 for the MSM methodology, the first phase is the “identification of the system boundaries, processes and relevant KPI’s". As identified in the VSM, the production system comprehends several stages, from laser cutting to expedition.

The key performance indicators for the case study, and their type, were selected according to the different studied activities, problems identified in the VSM diagnosis and were created to describe the in-between processes activities.

The selected KPI’s used for the MSM 2.0 applied to the MCG’s production system were proposed to and validated by the company industrial manager. They are grouped in four different categories, flow, resources, costs, and informative performance variables that should allow the easy understanding of how is the system currently performing.

4.3.2 Flow KPI’s

The flow KPI’s are used in the MSM 2.0 to understand the movement of products through the production process. KPI’s like Time, Distance or 4 R’s for Right Part, Right Quantity, Right Quality and Right Place (criteria required for a Just in Time production) are indicators that help defining the system and must be quantified and analysed to improve the production system.

The data used for this KPI’s was gathered by observation and time measures.

- **Time**

The KPI Time, in minutes, was already analysed in the VSM. Gives the information of how much time is being wasted in the different operations and is the main indicator, to characterize the different activities over the production flow. It is also an indicator to assess if the product is in one location at the right moment.

Calculation formula for efficiency in equation (9):

$$\Phi = \frac{Designed\ Time}{Total\ Time} \tag{9}$$

- **Distance**

Distance, in meters, is the total amount of length between two activities. It was studied on how far the product travels from one process to another. This will allow to see potential improvement actions to reduce transport time. Reducing the distance will decrease the value of the variable time and resources used during transports.

Calculation formula for efficiency in equation (10):

$$\Phi = \frac{Designed\ Distance}{Total\ Distance} \tag{10}$$

- **Right Quantity**

At MCG, the right quantity of parts in the different activities is not always correct. In some cases, the company produces more parts than it should, because the stock of semi-finished parts in the different storages is not considered. Also, some parts are lost during production and so, the quantity needed in other process is not the right one. This situation should be prevented to promote a continuous flow.

Calculation formula for efficiency in equation (11):

$$\Phi = \frac{Total\ Quantity\ of\ parts}{Designed\ Quantity\ of\ parts} \tag{11}$$

- **Right Part**

This KPI measures if the parts in each activity are the right ones. Since they may be from another reference that not the one needed, this situation must be studied to avoid disturbances that can affect the process flow, such as waitings or unnecessary transports of items.

Calculation formula for efficiency in equation (12):

$$\Phi = \frac{Total\ amount\ of\ parts}{Designed\ nº\ of\ right\ parts} \tag{12}$$

- **Right Quality**

The right quality KPI measures if all the parts in each activity are with the required quality. Products with defects require the effort of detect, remove, repair, and retest, increasing process time and cost. Also, defects that escape detection and repair before the product is sent to the customer reduce user satisfaction.

Calculation formula for efficiency in equation (13):

$$\Phi = \frac{Total\ amount\ of\ parts}{Designed\ nº\ of\ good\ quality\ parts} \tag{13}$$

- **Right Place**

In the analysed case study, the part must follow a defined path through the production flow. Since the parts have different precedencies it should be guaranteed that they are in the right place and not at any other activity.

Calculation formula for efficiency in equation (14):

$$\Phi = \frac{Total\ amount\ of\ parts}{Designed\ nº\ of\ parts\ in\ the\ right\ place} \tag{14}$$

4.3.3 Resources KPI’s

These types of KPI’s involve all the resources used within the production, such as the used area, diesel or electrical energy consumed in transports. These energy related KPI’s will allow to understand if the resources used in the production of heating devices are being efficiently allocated in the different activities during the useful time of production.

- **Electrical Energy**

The electrical energy, in KWh, was measured to assess the forklifts efficiency used in transports inside Metal 5. The electrical energy consumption was collected using metering devices, and was despised the building electrical energy consumption. The results are presented in the time interval studied and are directly indexed to it. The consumed electrical energy also has an environmental impact that must be studied to assess the eco-efficiency ratio.

Calculation formula for efficiency in equation (15):

$$\Phi = \frac{Forklift\ power\ x\ Designed\ Time}{Total\ electrical\ energy\ consumption} \tag{15}$$

- **Diesel**

Diesel, in Litres, is a resource used in transports of parts between Metal 1, Metal 3 and Metal 5. The carbon emissions from this activity must be then studied to assess the eco-efficiency of the production system. The results are presented in the time interval studied and are directly indexed to it.

Calculation formula for efficiency in equation (16):

$$\Phi = \frac{Diesel\ consumption\ x\ Designed\ Time}{Total\ diesel\ consumption} \tag{16}$$

- **Area used**

The used area, in m2, is an important variable for the present case study, since there are limited locations on the shop floor for storages and locations where the container waits, that have associated significant costs per m2. The area occupied by the container of the case study part was measured and compared with the total area of each activity. This measure is important to understand how the available area is being used and how much is considered waste.

Calculation formula for efficiency in equation (17):

$$\Phi = \frac{Designed\ area}{Total\ area} \tag{17}$$

- **Box Volume Empty**

One of the misuses detected during observations, was that the boxes/containers were excessively large for the parts in production. An assessment of this KPI show how the volume is being occupied in one box/container for the case study. This may result in smaller boxes/containers, and consequently a smaller area needed for work-in-process and storages. The box volume that is empty is not allocated to the variable time.

Calculation formula for efficiency in equation (18):

$$\Phi = \frac{Designed\ Empty\ Box\ Volume}{Total\ Box\ Volume} \quad (18)$$

4.3.4 Costs Associated

This analysis, in the MSM methodology, presents the results not with the multi-layer layout, but in a graphical way where the green colour represents the costs associated with the designed value and the red colour with the waste value.

Measuring how and where a company is spending money and relating this to causal factors is important to understand and control the costs of an activity and often leads to recognizing the need for better methods, better layouts or better operators' skills [40].

The cost analysis was performed for the several different phases of the production system, where the costs of the KPI's Diesel, Electrical Energy, Used Area and Labor were studied, and are directly associated to the specific duration of each activity.

4.4. MSM 2.0 Efficiency Results

Continuing to follow the steps for the MSM methodology presented in chapter 2.4.2, the following phase is the "analysis of the results and identification of the inefficient processes".

The first step to create the MSM is to collect the data needed regarding the several KPI's created to describe the production system. The necessary data was collected by time measurements, metering devices, observations or records analysis. The designed values were chosen with the MCG industrial manager to identify the most preponderant deviations from a target value that the company intends to have in the future. Consequently, these designed values allow a clear visualization of where are the major misuses that must be improved.

Therefore, it is necessary to introduce the collected data in the MSM extended results, where is possible to analyse the designed values and the waste values of each stream in the several activities, where the deviation from the designed value can be quantified. The final step is the construction of the MSM output to be analysed – dashboards where is shown the efficiency of each variable in each stage of the production system, calculated by the ratio between the designed value and the total value observed.

4.4.1 Value add activities

Although the proposed work is to study the activities between processes, it is essential, in a first step, to diagnose the add value activities for a complete assessment of the production system efficiency. Since the KPI's previous mentioned were created and all data was collected to study the in-between processes activities, it was defined with the company industrial manager that the Time, Electrical Energy and Area are the most relevant parameters for enhancing the processes efficiency.

The data required as input to the MSM for the most relevant parameters was collected in-situ by time measurements and metering devices. All data is presented according to the functional unit, which in this case refers to the production of one part of the case study. Table 4-3 presents the data gathered for the relevant KPI's, and the designed values for the processes that are the minimum time observed, energy consumed or area used to complete an operation. In Attachment A2 – Processes' Collected Data are presented tables with detailed data regarding wastes within processes, such as setups, movimentations and idle times in each activity.

The extended results, the framework behind the efficiency dashboards, are presented in figure 4-10, and the processes efficiency dashboard can be observed in figure 4-11.

Table 4-3: Time, energy and area data for the observed, designed and waste values per/part

	Laser	Bending	Welding	Shot-Blast	Liq. Painting	B. Assemb.	C. Assemb.
Total Time [min]	47	29	592	57	1697	84	166
Designed Value [min]	35	5	64	32	143	50	39
Waste Value [min]	12	24	528	25	1554	34	127
Total Energy [KWh]	38	1,8	2,3	11	7	-	-
Designed Value [KWh]	32	0,8	1,6	6	7	-	-
Waste Value [KWh]	6	1	0,7	5	0	-	-
Total Area [m^2]	616	320	462	216	153	65	50
Designed Value [m^2]	55	20	15	50	49	30	30
Waste Value [m^2]	561	300	447	166	104	35	20

		Laser	Bending	Welding	Shot-Blast	Liq. Painting	Body Assemb.	Cover Assemb.
Time [min]	Designed	35	5	64	32	143	50	39
	Waste	12	24	528	25	1554	34	127
	Total	47	29	592	57	1697	84	166
		74%	17%	11%	56%	8%	60%	23%
Electrical Energy [KWh]	Designed	32	0,8	1,6	6	7		
	Waste	6	1	0,7	5	0		
	Total	38	2	2,3	11	7		
		85%	45%	71%	56%	100%		
Area [m2]	Designed	55	20	15	50	49	30	30
	Waste	561	300	447	166	104	35	20
	Total	616	320	462	216	153	65	50
		9%	6%	4%	23%	32%	46%	60%

Figure 4-10: Processes MSM Extended Results

Processes Analysis

	Laser	Bending	Welding	Shot Blast	Liq. Painting	B. Assemb.	C. Assembly	
	1	1	1	1	1	1	1	Process Parameter Efficiency
Unit Process Efficiency	56%	23%	29%	45%	47%	53%	42%	
Time	74%	17%	11%	56%	8%	60%	24%	14%
Electrical Energy [KWh]	85%	45%	71%	56%	100%	-	-	80%
Area [m2]	9%	6%	4%	23%	32%	46%	60%	14%

Efficiency < 40% — Efficiency 69 - 40% — Efficiency 89 - 70% — Efficiency 100 - 90%

Figure 4-11: Processes efficiency dashboard for time, electrical energy and area

The evaluation of the value add activities performance reveals that the bending (23%) and welding (28%) are the least efficient processes, mainly due to operation time and area used.

Regarding the Process Parameter Efficiency, the production time (14%) and area used (13%) are critical, while the electrical energy has an efficiency of 80%.

In terms of the KPI Time, an overall analysis revealed that the machines are not working in their full operating performance and the time wasted by the operators in movimentations is fairly substantial. Regarding the KPI Area, it was measured the occupied area of the machine involved in the production of the case study part and compared with the total area of the process workstation (that has more machines and space for movimentations of the operators and products). The results evidence that the layout is misfit for the production of this part and that can be altered to avoid excessive movimentations of the operators and products.

The costs analysis for the add value activities was based in values provided by the company, presented in table 4-4. The fabrication costs, in €/h, can be divided into two main cost groups: workstation costs, which includes electrical energy consumed by the machine, water, auxiliary gases, ink and area, and manpower which is the cost of the operator per hour.

The results allow a simple cost analysis that distinguish the costs associated with the designed and waste values of the different activities, respectively with green and red colour.

Table 4-4: Costs of the workstation and manpower provided by MCG for the different processes

Machine - Process	Workstation	Manpower
	[€/h]	[€/h]
Trulaser - Laser Cutting	60,89	9,19
Trubend 5130 - Bending	30,85	9,84
MIG - Welding	18,07	10,44
Shot-Blast	7,53	9,86
Liquid Painting	57,78	9,86
Assembly	1,61	7,61

The cost analysis reveals that 69% of the generated costs are spent in waste operations, illustrated by the red colour, and 31% is spent on designed activities, illustrated by the green colour (figure 4-12). The waste costs are mostly due to area costs and idle times of the machines (also with associated costs).

In this case study, the liquid painting process has the highest contribution to the waste costs. By the time of the observation the operator was away of the liquid painting workstation, being the product stopped in this process with workstation costs associated.

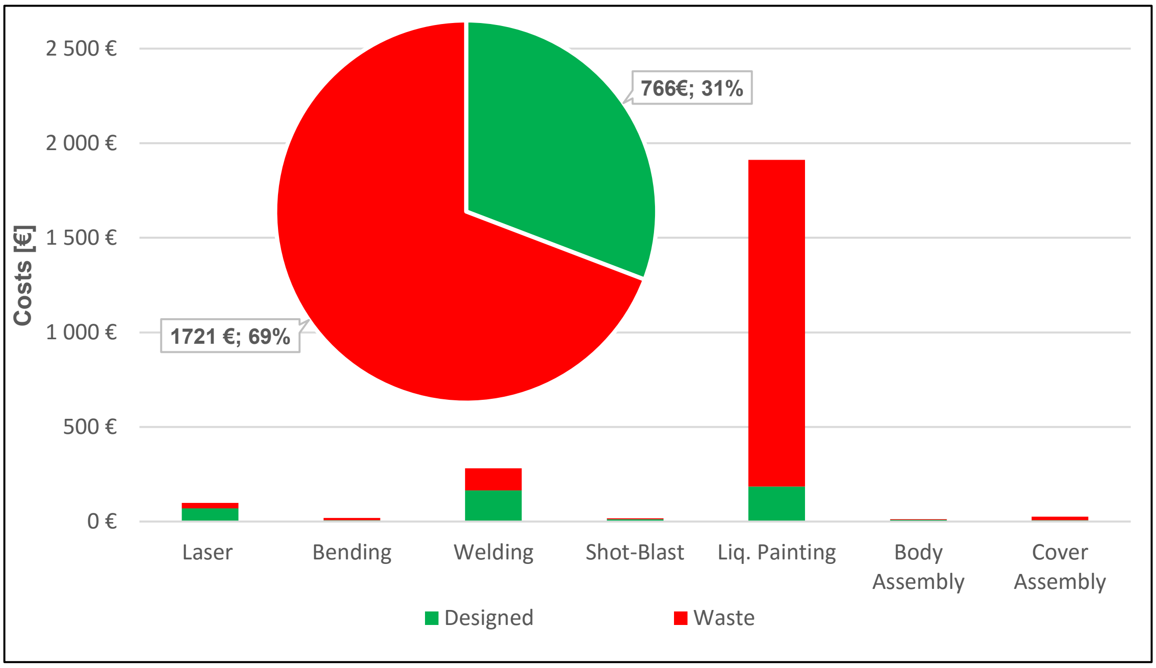


Figure 4-12: MSM processes costs analysis

4.4.1 In-between Processes activities

For the analysis of the in-between processes activities, the data required as input to the MSM was also collected in-situ and is presented in table 4-5. Data regarding activity time, was collected by time measurements. The electrical energy consumption, distance and area was collected using metering devices. Diesel consumption was estimated by doing an average of the values observed in the company records of the last 6 months. The other KPI's were assessed by observations.

The designed values for the activities between processes were chosen with the MCG industrial manager with the objective of establishing benchmarks for these activities in order to fulfil the strategic goals of the company and are presented in table 4-6.

The extended results for the in-between processes activities can be observed in Attachment A3 – MSM Extended Results for the In-between Processes Activities. Detailed results regarding the flow efficiency of the production system are presented in figure 4-13.

Table 4-5: Data collected for the in-between processes activities

	Laser - Bending	Bending - Welding	Welding - Shot Blast	Shot-Blast – Liq. Paint.	Liq. Paint. - B. Assemb.	B. Assemb. – C. Assemb.
Waitings Time [min]	1060	750	165	43	489	320
Transports Time [min]	4,15	13,5	12	5,3	4,5	2
Storages Time [min]	-	19490	-	-	12575	50491
Kits Time [min]		2620	-	-	-	-
Distance [m]	710	5110	5000	715	710	265
Right Quantity [units]	19	48	48	48	48	1
Right Part [units]	19	48	48	48	48	1
Right Quality [units]	19	48	48	48	48	1
Right Place [units]	19	48	48	48	48	1
Electrical Energy [KWh]	-	0,355	-	-	0,17	0,581
Diesel [L]	0,04	0,3	0,13	0,06	0,04	-
Area [m^2]	197	561	18	21	334	625
Box Volume Empty [m3]	0,8	0,8	0	0	0	-

Table 4-6: Designed Values for the in-between processes activities

KPI	Designed Value
Waitings Time [min]	60 min
Transports Time [min]	Minimum time possible for the designed distance
Storages Time [min]	Minimum time observed during the presence at MCG
Kits Time [min]	3 working days
Distance [m]	All processes must be in Metal 5
JIT [units]	All items of the order less inventory units
Energy [KWh] / Diesel [L]	Minimum energy/diesel consumed for the designed time and distance
Area [m^2]	Area occupied by the box with the items
Box Volume Empty [m3]	Maximum of 25% volume empty

Flow Analysis	Laser → Bending	Bending → Welding	Welding → Shot Blast	Shot Blast → Liq. Paint.	Liq. Paint. → B. Assemb.	B. Assemb. → C. Assemb.	C. Assemb. → Exp.	Process Parameter Efficiency
	1	1	1	1	1	1	1	
Unit Activity Efficiency	69%	70%	59%	71%	60%	71%	98%	
Time [min]	11%	41%	34%	100%	29%	14%	86%	24%
Distance [m]	1%	2%	1%	4%	8%	42%	100%	3%
Right Quantity [units]	100%	74%	21%	21%	22%	67%	100%	51%
Right Part [units]	100%	100%	100%	100%	100%	100%	100%	100%
Right Quality [units]	100%	100%	100%	100%	100%	100%	100%	100%
Right Place [units]	100%	100%	100%	100%	100%	100%	100%	100%

Efficiency < 40% Efficiency 69 - 40%

Efficiency 89 - 70% Efficiency 100 - 90%

Figure 4-13: Flow efficiency dashboard

The Unit Activity Efficiency results, for the flow analysis, show that the Laser – Bending (69%), Welding – Shot Blast (59%) and Liquid Painting – Body Assembly (60%) are the least efficient phases within the production system, mainly due to several misuses related with the KPI's time, distance and right quantity of units. The Process Parameter Efficiency results indicate that the time (24%) and distance (3%) are the most inefficient KPI's, exposing that the time wasted in the several activities and the distance travelled from one activity to another diverges a lot from the designed value of these KPI's.

Analysing the time efficiency, the major misuses along the production system are due to time wasted in waitings between processes (see Attachment A3 – MSM Extended Results for the in-between Processes Activities), due to bad scheduling of transport from one activity to another, and inventory time, consequence of the company "make to stock" strategy.

The variable Distance has a low performance, because the laser cutting and liquid painting processes are in different sites of production and the welding process is not done at MCG. The welding is an outsource process as result of the company ineptitude to manufacture so many different type of products, from several different clients, during the available working time.

The efficiency of the KPI Right Quantity of material is also low since the batch is divided in kits of ten to go to the welding process, one kit at a time (all the parts should go to the welding at the same time to promote a continuous flow). In contrast the quality of production is excellent, illustrating that the desired quality standards along production are being achieved.

In terms of resources efficiency, the dashboard for this analysis is presented in figure 4-14.

Resources Analysis								
	Laser → Bending	Bending → Welding	Welding → Shot Blast	Shot Blast → Liq. Paint.	Liq. Paint. → B. Assemb.	B. Assemb. → C. Assemb.	C. Assemb. → Exp.	
	1	1	1	1	1	1	1	Process Parameter Efficiency
Unit Activity Efficiency	17%	31%	38%	62%	68%	40%	55%	
Electrical Energy [KWh]	-	84%	-	-	90%	80%	100%	85%
Diesel [L]	24%	8%	8%	75%	80%	-	-	27%
Area [m2]	1%	1%	6%	10%	1%	0%	10%	1%
Box Volume Empty [m3]	25%	30%	100%	100%	100%	-	-	44%

Efficiency < 40% Efficiency 69 - 40%

Efficiency 89 - 70% Efficiency 100 - 90%

Figure 4-14: Resources efficiency dashboard

The results reveal that the most critical non-add value activities are between laser cutting and shot blast, due to the Diesel, Area and Box Volume KPI's. Regarding the process parameter efficiency, the Diesel and Area KPI's are the most inefficient, with efficiencies of 33% and 1% respectively.

The diesel consumed for the welding process represents an evident source of waste (for a longer distance, more diesel is required). Furthermore, the overall used area efficiency is critical since the limited area on the shop floor for the work-in-process is considerable superior than the currently designed, especially in the storages W1 and SKI.

For the economic analysis, the total costs were estimated based on the values provided by MCG for electrical energy, diesel (average value of the last 6 months), area and labor (table 4-7).

The costs are estimated based on the designed and waste values of each activity.

Table 4-7: Costs associated with electrical energy, diesel, area and labor

Electrical Energy [€/KWh]	Diesel [€/day]	Area [€/m^{2}day]	Labor [€/day]
0,055	5,2	0,22	60,9

The overall cost evaluation for the in-between processes activities reveals that 96% of the production costs are waste, expressed by the red colour, where only 4% of the total costs the company is willing to spend, illustrated by the green colour (figure 4-15).

The results also show that the main portion of the costs supported by MCG is between Body Assembly and Cover Assembly, due to the vast area of the storage SKI. In terms of resources efficiency, since the most critical aspects are related with area, consequently the overall area costs will have a critical impact on the system.

It is also important to notice that a bad quality part, defect or error in the process will have different costs depending on how advance is the production. So, a deteriorated part in an activity, will not have only the costs of the corresponding activity but also all the accumulated cost of the preceding activities.

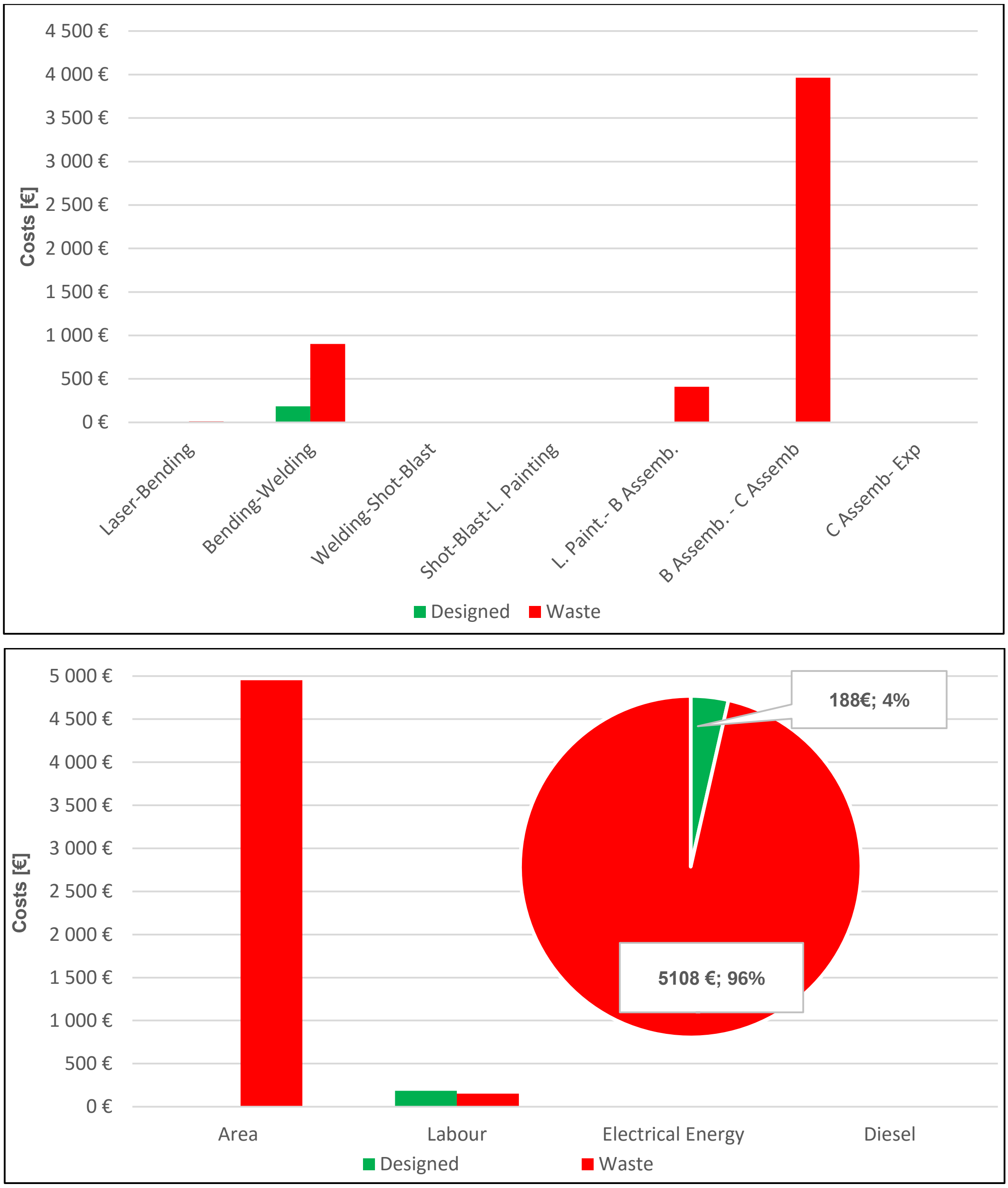


Figure 4-15: MSM cost analysis for the in-between processes activities

In order to complete the analysis of the production system, is presented a summary table 4-8 with the main critical aspects and causes identified through the different phases of production.

Table 4-8: Critical Aspects - MSM efficiency - Identified causes

Activity	KPI	MSM critical Efficiency	Causes
Laser - Bending	Time	11%	Bad schedule of transports
	Distance	1%	Layout (processes in different sites)
	Area	1%	Limited area for waitings
	Box Volume	25%	Container too large for the parts
Bending - Welding	Distance	2%	Outsourcing process
	Diesel	8%	Related with distance travelled
	Area	1%	Storage area
	Box Volume	30%	Container too large for the parts
Welding - Shot Blast	Time	34%	Bad schedule of transports
	Distance	1%	Outsourcing process
	Right Quantity	21%	Batch is divided in kits of ten
	Diesel	8%	Related with distance travelled
	Area	6%	Limited area for waitings
Shot Blast - Liq. Paint.	Distance	4%	Layout (processes in different sites)
	Right Quantity	21%	Batch is divided in kits of ten
	Area	10%	Limited area for waitings
Liq. Paint. - B. Assemb.	Time	29%	Inventory time
	Distance	8%	Processes in different sites
	Right Quantity	22%	Batch is divided in kits of ten
	Area	1%	Storage area
B. Assemb. - C. Assemb.	Time	14%	Inventory time
	Area	0%	Storage area
C. Assemb. - Exp.	Area	10%	Limited area for waitings

5. MSM improvements

Being a recent methodology under development, the MSM can be object of improvements to overcome its limitations, with the aim of being useful for all types of companies and support the decision-making process in a more effective way.

In this chapter, a complementary and new analysis is proposed, to help in the decision-making process and establish prioritizations for future improvements, where the MSM efficiency of the different variables will be related with the effective contribution to the waste dimension of the values observed.

Also a study for a future proper collection of data is made to incorporate in the MAESTRI Total Efficiency Framework with also the integration of new simple dashboards to be analysed by the MCG top teams.

5.1. Integrated approach for prioritization of improvements

The MSM methodology focuses on the overall efficiency and performance assessment of production systems, being able to identify all the add value and non-add value activities as well as all types of waste, giving the information of how much an activity can improve its performance and where the company should act to reduce the operational, environmental and economic inefficiencies along the production system.

The outcomes from MSM are isolated efficiency results of each singly activity, distinguishing the respective designed value and waste value and recognizing priorities to improve the production system. By setting designed values to the different KPI's chosen, the MSM measures the deviation of the current value from the designed value (for each manufacturing step) and assist the decision-making process to reduce the inefficiencies within the production system.

The MSM approach contemplates that efficiencies inferior than 40% reveal critical situations within the production system, where the deviation of the current value from the designed value is quite significant, and, by the MSM methodology, should be the first targets of improvement actions in order to improve the overall system performance.

However, through the interpretation of the MSM results, it was perceived that the MSM is assessing efficiency/inefficiency values, but "camouflages" the contribution of the physical quantity dimension of each variable.

A complementary analysis is then proposed that contemplates the physical quantities of each stream and allows a more complete visualization and intuitive interpretation of the results, to support, in a better way, the decision-making process in terms of prioritization of improvement actions. In the end, more than identify the critical activities within the production system, the results are integrated in the MSM efficiency dashboard for a complete evaluation of the production system.

Therefore, the analysis, that also includes the processes, considers the “weight” of the physical waste contribution of each process/activity, and correlate it with the MSM efficiency. The Effective Contribution to Waste (ECW) of each process/activity is calculated by the equation (19).

$$ECW\ (\%) = \frac{\sum_{i=1}^{n}(Waste\ values)_{phase\ i}}{(Total\ waste\ values)_{stream\ j}} \tag{19}$$

Where:

∑ (Waste values) phase i : Physical contribution to the waste dimension of each process/activity

(Total waste values) stream j : Total waste contribution of each stream

Just like the MSM approach, a set of colours to illustrate and ease the interpretation of the different levels of the ECW can be created, but following the concept of waste and promoting its reduction, where the green colour represents a low percentage of ECW and the red colour a high percentage of ECW.

Taking now these considerations, all the required information to quantify the ECW of each phase and compare it with the corresponding MSM unitary efficiency is present, and a graphical analysis of these two dimensions can be mapped (MSM efficiency vs ECW) – Figure 5-1.

Contemplating the MCG strategy of free capacity hours for production, it is essential to reduce the time wasted in the several activities of the production system. So, an analysis of the ECW of the KPI Time and respective MSM unitary efficiencies through the different production processes is performed and is presented in figure 5-11.

The X axis characterizes the ECW and the Y axis represents the MSM efficiency. Each circle represents the different processes/activities within the production system, with the colour scale of the MSM methodology to illustrate the corresponding efficiency value, and the graphic’s background illustrates the different zones of the ECW level (green for a reduced ECW and red for a high ECW).

[1] Due to business factors, the cover assembly will not be done any more at MCG, and consequently, the Body Assembly – Cover Assembly phase will not be part of the production system any longer and so the study of these activities would not contribute to the future objectives of the company.

The final result enables an ample evaluation of the overall production system, through a simultaneous analysis of the MSM efficiency, that can include the functional, environmental or economic dimensions, and the respective physical Effective Contribution to Waste allowing the identification of phases with greater impact in the production system and an important resolution for the decision-making process.

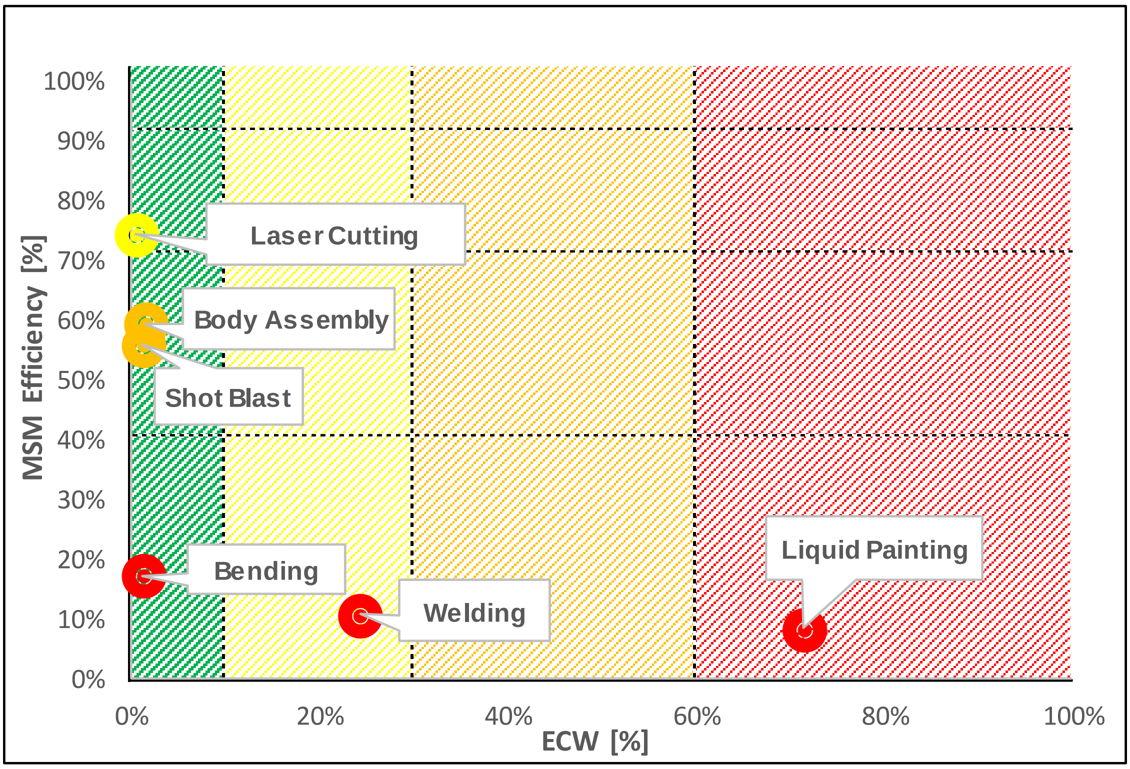


Figure 5-1: Graphical comparison between MSM efficiency and ECW of each process

Regarding the process units, the outcome allows to see a combined reading of the MSM efficiency and ECW level. This new approach evidences that the critical process pointed by the original MSM methodology (Liquid Painting) is in fact the process that has the highest Effective Contribution to Waste, and by that should be target of analysis and imperative improvement actions. On the other hand, it is concluded that the bending process misuse is the current observed value being far from the designed value, since it has a diminutive contribution to the waste dimension of the variable time.

Considering now the in-between processes activities, the same analysis can be made. It is presented in figure 5-2.

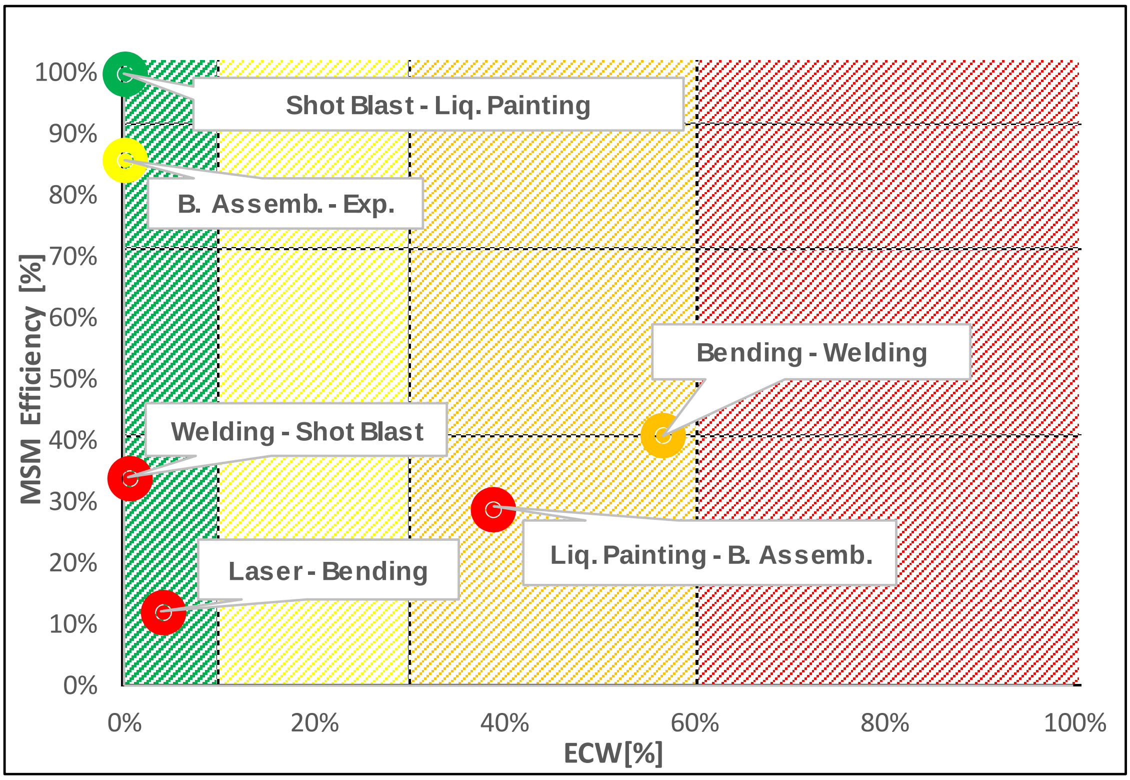


Figure 5-2: Graphical comparison between MSM efficiency and ECW of each in-between processes phase for the variable time

First, regarding the MSM perspective, it is crucial to improve the laser – bending, liquid painting – body assembly and welding – shot blast phases, since these activities have critical efficiencies of 11%, 29% and 34%, respectively (red colour). According to the MSM methodology, the other activities, are not yet so urgent to improve.

However, the results of this analysis show that the time wasted in the bending-welding phase is more significant than the time wasted in other activities, contributing with a high percentage (57%) to the waste dimension of the KPI time (due to inventory time).

Despite of not be the phase with lowest MSM performance, the elimination of the time wasted in the bending – welding phase frees more capacity hours for production than the elimination of the time wasted in the laser – bending (4%), welding – shot blast (0%) and liquid painting – B. Assembly (39%) phases combined.

So, regarding the company strategy, it may be essential to first improve the bending – welding phase for the MCG's future objectives.

Continuing the same analysis for the particular activities between bending and welding, that incorporates transports, waitings, and Kits, an equivalent scenario is observed. Once more, activities with lower performance shown by the MSM, may not be urgent to improve in the near future. Although this activity has not a critical MSM efficiency of 40%, the time wasted by the product in the storage W1 is what contributes more to the waste dimension of the variable time

(90%), due to inventory time, and for that should be the first target of improvement solutions (figure 5-3).

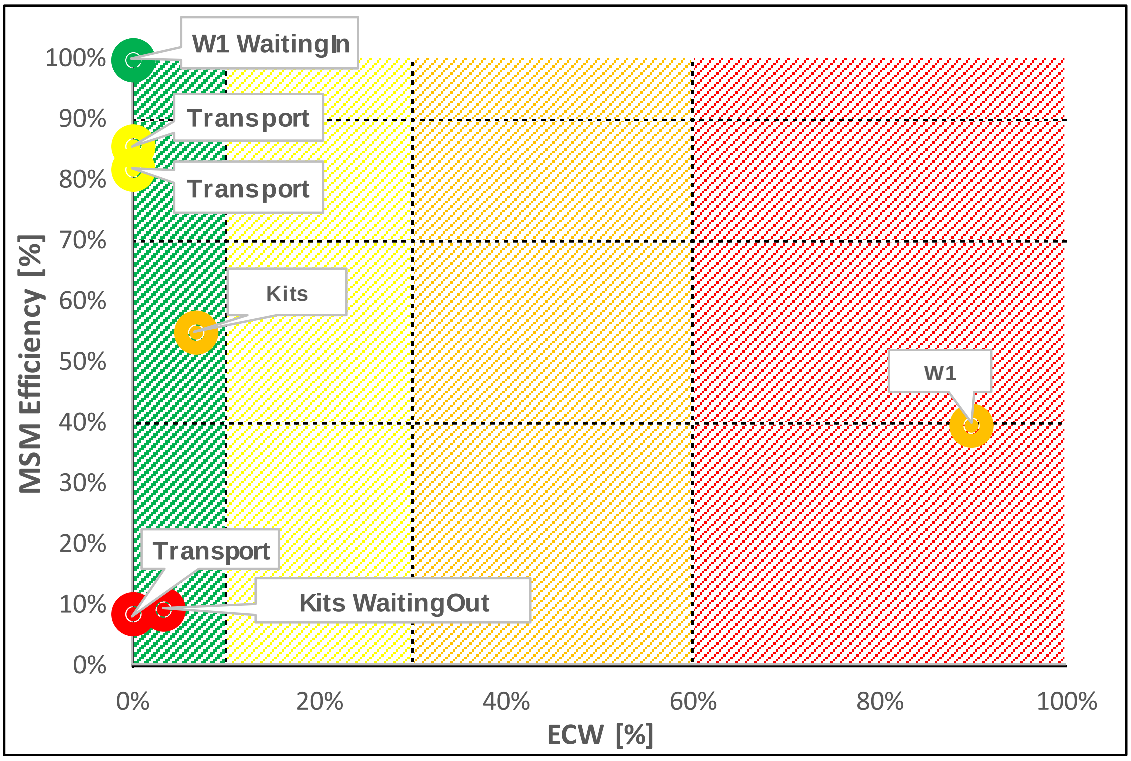


Figure 5-3: Graphical comparison between the MSM efficiency and ECW for the Bending-Welding activities for the variable time

The study of the ECW is proposed to be integrated in the MSM methodology and can be applied for all the streams (figure 5-4). For example, in terms of the stream Distance, the results show that it should be better, in a first stage, to make the welding process at MCG than reduce the distance between all other phases since it has a higher ECW level of the KPI Distance.

This mapping allows a clear "prioritization of improvement actions" (next step of the MSM methodology presented in chapter 2.4.2), since the MSM approach, as demonstrated, cannot fully reflect the impact of the different activities in the production system, hence one activity denoted as more efficient than other, may be urgent to improve, since it can have a much higher negative impact to the company than other inefficient activity.

Flow Analysis

	Laser → Bending		Bending → Welding		Welding → Shot Blast		Shot-Blast → Liq. Paint.		Liq. Paint. → B. Assemb.		B. Assemb. → Exp.	
	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]
Time [min]	11%	4%	41%	57%	34%	0%	100%	0%	29%	39%	86%	0%
Distance [m]	1%	6%	2%	42%	1%	41%	4%	6%	8%	5%	100%	0%
Right Quantity	100%	0%	74%	9%	21%	36%	21%	36%	22%	18%	100%	0%
Right Part	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%
Right Quality	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%
Right Place	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%

Resources Analysis

	Laser → Bending		Bending → Welding		Welding → Shot Blast		Shot-Blast → Liq. Paint.		Liq. Paint. → B. Assemb.		B. Assemb. → Exp.	
	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]
Electrical Energy [KWh]	-	-	84%	78%	-	-	-	-	90%	22%	100%	0%
Diesel [L]	24%	11%	8%	40%	8%	41%	75%	5%	80%	3%	-	-
Area [m2]	1%	0%	1%	9%	6%	36%	10%	36%	1%	18%	10%	0%
Box Volume Empty [m3]	25%	0%	30%	0%	100%	0%	100%	0%	100%	0%	-	-

Efficiency < 40% | Efficiency 69 - 40% | ECW < 10% | ECW 59 - 30%

Efficiency 89 - 70% | Efficiency 100 - 90% | ECW 29 - 10% | ECW 100 - 60%

Figure 5-4: Integrated analysis of the ECW in the MSM methodology

5.2. Future data gathering

The implementation of the MSM methodology within an industry environment is not yet a reality, with several obstacles that need to be thoroughly studied and overtaken to reach the final objective. The major limitations of the MSM approach are related with data quality and with the innumerable assumptions that can be made to define the value of the waste portions. If these are not well established and justified the results interpretation may be misleading.

In the current work, for the data collection stage, it was necessary to follow the product through the shop floor, time measuring, operators' interviews and record analysis, emphasizing difficulties about "easily done" data acquisition, data quality or the lack of the organization's structured methods to collect information for defining parameters and control the several activities along the production system.

With the current technology within the company, the MSM was used to diagnose the system, with manual data collection for the defined KPI's, setting objectives to see how the global system performance is and to support the decision-making process for improvement solutions.

To allow a proper and automated collection of data and consequent evaluation, it is proposed the integration of metering devices and sensors along the production system, being then able to associate the information with the MSM methodology to support control and decision making.

Moreover, with the emergence of the concept of Industry 4.0, a set of trends and technologies that will reshape the way things are made and controlled in the industrial environment, the MSM can be a tool integrated in that near future scenario, combining information with operational aspects and carefully monitor the entire production system in real time. Furthermore, a new frame of presenting results, with new touchscreens dashboards for the MSM methodology can be developed to keep up with this progress. The dashboards should be directed to the hierarchical level of the person is watching those dashboards. The top management teams of MCG, should see several efficiencies, resources consumption, costs and activities performance, while the operators should only see information that can guide them through the manufacturing process, such as units produced and operation time efficiency.

The dashboards must preferably graphical information for an easy visual analysis of the most useful and relevant information of the MSM. More important, with a future continuous control and information updates by the metering devices and sensors, the proposed dashboards can show the evolution of a KPI performance along time and help to predict future situations based on the identified trends.

In figure 5-5 is presented a scheme relating the process of data reading equipment, the MSM and the dashboards visualization with the Total Efficiency Framework of the MAESTRI project, to be implemented at MCG.

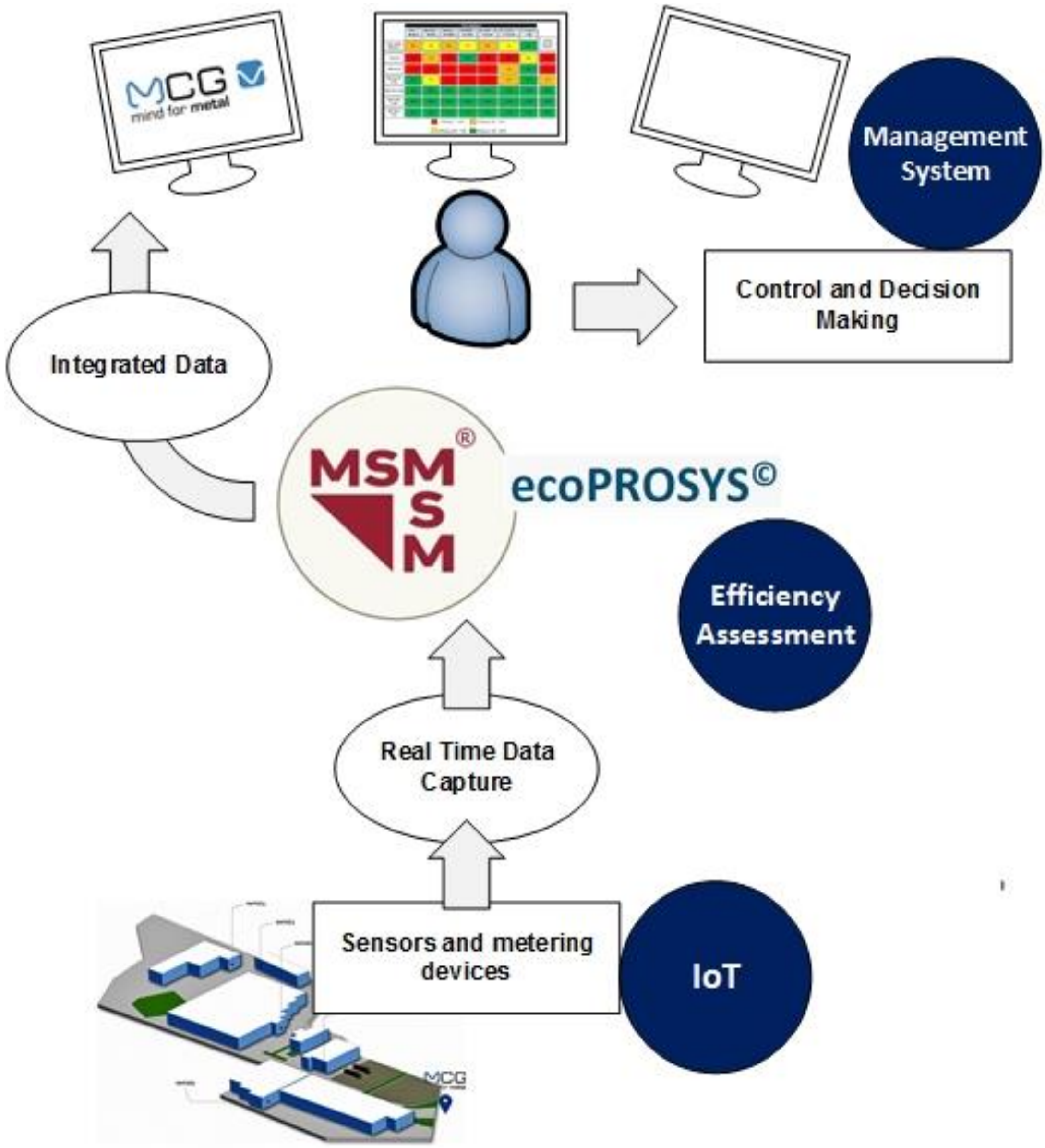


Figure 5-5: Integrated approach for the implementation of the Total Efficiency Framework in MCG

6. Lean improvement actions and Future State

The last step of the MSM methodology, presented in chapter 2.4.2, is the “implementation of the improvement actions and collect results of the efficiency improvements”.

In this chapter, some improvement solutions are presented, based on the problems identified in the MSM.

After the implementation of solutions, the Future State of the company is also estimated to see the production system development and future situations of concern that need to be improved.

Other improvement actions were suggested to problems that were not identified in the MSM, but by observations and operators interviews, and are presented in Attachment A4 – Other Improvement Actions

6.1. Improvement Actions

Following the MSM diagnosis, several reasons for the misuses along the production system, such as the company’s layout, absence of scheduled transports or excessive inventory were possible to identify.

The problems identified were presented to the MCG’s management teams and after some meetings, important improvement actions were developed according to the company strategy and vision, with the objective of reducing and perhaps eliminate the most important inefficiencies of the production system. Some of them were analysed and immediately implemented by the top teams at MCG. The lean improvement actions act in the activities between processes and try to be solutions that not require a big investment.

In the future, the company may continue this process of continuous improvement, based on this study, implementing more new solutions, not only in the product flow, but also in the add-value activities, and try to reach a system with no inefficiencies.

6.1.1 New Layout

According to the MSM results, it can be seen that the Distance is a critical variable with an overall efficiency of 2% (see figure 4-13), leading to high transport time, diesel consumption and consequently pollutant emissions.

This is because laser cutting and liquid painting workstations are in different sites of production, and welding is an outsourcing process. The results from the ECW analysis show that the outsource welding process is what contributes most to the waste dimension of the variable distance and by that should be the first target of improvement solutions (see figure 5-4). However, under the current conditions, MCG first needs to free capacity hours within the production system to do the welding process of the case study part at its facilities.

By the Lean philosophy, movimentations of components, transports and big distances should be decreased to reduce wastes like transport time, diesel consumption and increase the production availability.

Under this logic and resorting the MSM extended results, the activities between the Laser and Bending Workstations, which involves waiting for transport after the laser process is complete, transport to Metal 5 and waiting to proceed for the bending process, can be analysed in detail (figure 6-1). The results show, for the Transport activity, the transport time, distance and diesel consumption have critical efficiencies of 24%, 1% and 24% respectively.

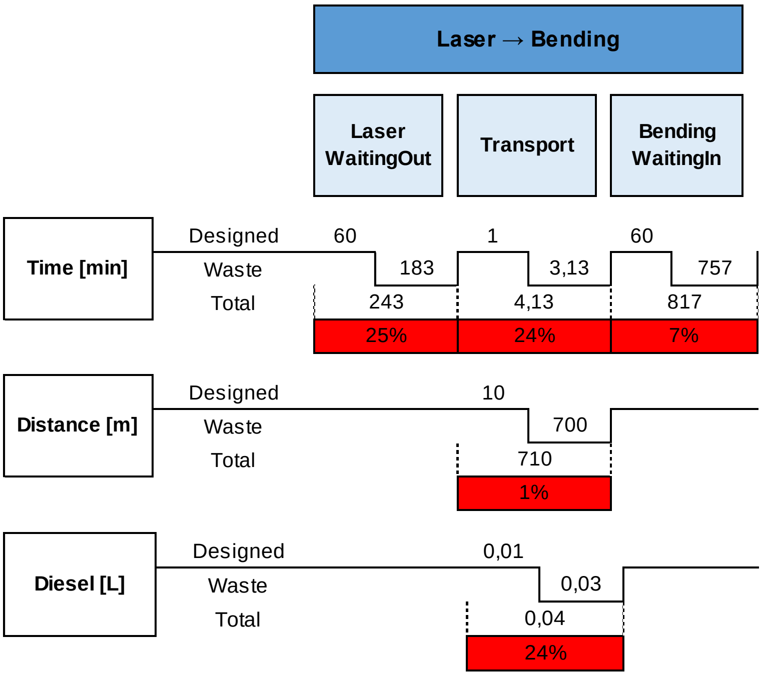


Figure 6-1: MSM extended results for the Laser-Bending phase

Therefore, a new layout was then suggested and discussed where the laser cutting process is moved from Metal 1 to Metal 5, near the bending process, to decrease the distance between these two processes and consequently the transport time and diesel consumption.

With this proposed solution, the distance between the two process units will be reduced 700 m, eliminating the transport time between Metal 1 and Metal 5 and diesel consumption, allowing an increased product fluency and a more efficient and solid interaction of the laser process with the others at Metal 5. The new layout of Metal 5 can be observed in figure 6-2.

This proposed solution is currently implemented at MCG. In the future, the company can also move the painting workstation to the central production site, Metal 5.

In table 6-1 the real impact of the proposed solution in the Transport activity between Laser Cutting and Bending can be observed. Moving the Laser workstation to Metal 5 increased both transport time and distance efficiencies to 100% (the designed value was achieved), and eliminated diesel consumption, since the transport is now made by electrical forklift.

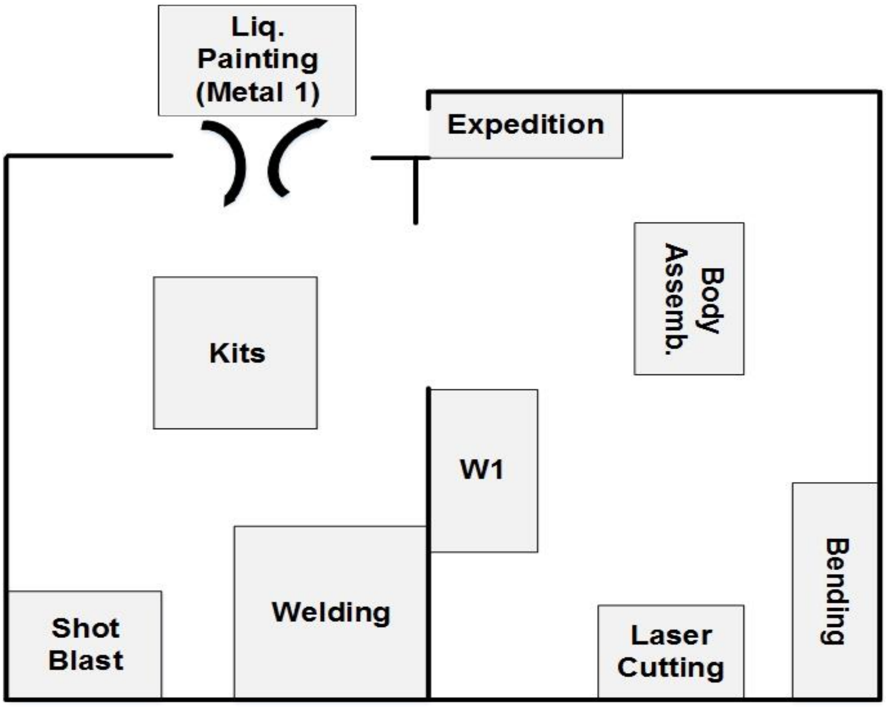


Figure 6-2: New Layout Metal 5

Table 6-1: Real impact of the proposed solution in the Transport activity between laser and bending, in terms of transport time, distance and diesel consumption

	Before Solution		After Solution	
	Quantity	MSM Efficiency [%]	Quantity	MSM Efficiency [%]
Transport Time [min]	4,13	24%	1	100%
Distance [m]	710	1%	10	100%
Diesel [L]	0,04	24%	-	-

6.1.2 Make to order

From the MSM efficiency results and ECW analysis, it was concluded the inventory time is a major misuse within the production system. Regarding the MSM results, the time efficiency between body assembly and cover assembly is critical (14%), as it can be observed in figure 4-13. Analysing the storage SKI, for this stage of production, it can be seen there is a lot of time wasted in this storage. This is mainly due to the substantial amount of inventory, consequence of the company "make to stock" strategy. Regarding the ECW analysis, it was observed that the time wasted in W1 storage, for the Bending-Welding phase, is what contributes more to the waste dimension of the time in this phase (90% of ECW, from figure 5-3), also due to excessive inventory (note that the body assembly – cover assembly phase was not included in this analysis).

By the time of production, when the laser cut was being programed, if there was some empty space for more parts in the sheet metal plate, MCG would produce more to stock, to avoid raw material wastes. Although it may be a good policy to reduce scrap rates, when a new order was received, MCG did not consider for production the quantity of extra parts existing in stock, producing the exact quantity of parts of the order. So, the inventory quantity was always increasing, representing a cost that has not yet generated a revenue from a sale, with the risk of becoming obsolete or lose quality.

The solution presented to MCG, was to change the strategy to a make-to-order policy and evolve the system into a pull production (one of the Lean principles in table 1-2) to reduce the inventory quantity, and consequently the inventory time and storages area (less inventory, less area needed for storage). With the new solution, the high costs related to inventory maintaining and time dispended on producing extra parts will be mitigated.

Although the new solution was already implemented, MCG chooses to have a minimum amount of stock in storages to prevent stock breaks.

From table 6-2, it can be observed the real impact of the proposed solution in inventory time and storage W1 area. The inventory time is now ninety-one hours, because MCG choose to have a minimum amount of the case study's part as safety stock. The area of the storage W1 also suffered a considerable reduction, since this solution was applied to all the products that are being manufactured at MCG, so the overall quantity of stock decreased, and therefore it is not necessary so much space in the shop floor to inventory maintaining.

Consequently, both Time and Area efficiency suffered a raise. Table 6-3, show that between bending and welding, the Time efficiency raised from 41% to 56%, and area efficiency had an improvement of 1%. Between Liquid Painting and Body Assembly, the Time efficiency raised from 29% to 39% and the Area efficiency improved from 1% to 5%.

Table 6-2: Real impact of the proposed solution in inventory time and storage W1 area of the Bending-Welding and Liq. Painting – B. Assembly phases

	Before Solution		After Solution	
	Inventory Time [h]	W1 Area [m2]	Inventory Time [h]	W1 Area [m2]
Bending -Welding	264,9	300	91	50
Liq. Painting - B. Assemb.	109,6	300	91	50

Table 6-3: Real impact of the proposed solution in the Time efficiency and Area efficiency between *the* Bending-Welding and Liq. Painting and B. Assembly phases

	MSM efficiency before Solution [%]		MSM efficiency after Solution [%]	
	Time	Area	Time	Area
Bending -Welding	41%	1%	56%	2%
Liq. Painting - B. Assemb.	29%	1%	39%	5%

6.1.3 **Introducing Mizusumashi**

The MSM results show that the overall time efficiency is critical, 24 % (see figure 4-13). It was diagnosed that the time wasted in waitings is one main reason for this inefficiency (as it can also be seen in figure 6-1, where the waitings have an efficiency of 25% and 7% between laser and bending). This situation occurs due to bad scheduling of the transport from one activity to another.

Currently, MCG is using five electrical forklifts to provide the necessary material to the different workstations, but without any defined routes and schedules. Without a suitable model for the material supply through the different phases of production, unnecessary waitings are created and unnecessary resources are consumed, such as electrical energy of the five forklifts.

So, the Lean concept of Mizusumashi (figure 6-3) is suggested to replace the five electrical forklifts. The mizusumashi is an internal transport with the purpose of collecting material from the different workstations and deliver it in the following processes of production. With the Mizusumashi a cyclical standard work is created where the logistic operator executes all the necessary movimentations through metal 5, collecting and providing the necessary material to the processes when it is needed, and by that, eliminate waitings in the processes' in and out areas, "empty" travels, excessive use of resources and also free capacity hours for production.

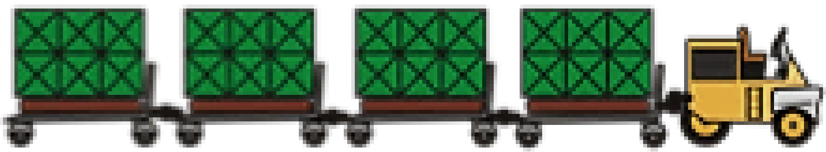


Figure 6-3: Mizusumashi

For a correctly work of the mizusumashi, providing the right material, in the right place at the right time, it is necessary to define routes, mizusumashi dimensions and schedules, to avoid variability in the process, idleness or overload work of the production lines and enabling a high productivity of the system.

A route for the mizusumashi is proposed in figure 6-4, based on the production flow through the new layout of Metal 5.

The schedule of the mizusumashi must be defined every week depending on the production plan for that period. The mizusumashi dimensions are proposed according to the average weekly production of the case study's part, which is 13 units. Since one container can have 7 heating devices inside, the mizusumashi should be able to transport two containers of $1m^3$.

This proposed solution was not yet implemented, but in table 6-4 is estimated its impact on the variable Time. This study also takes into account the previous solutions, i.e. the current "new" state of the production system.

Since the objective is to eliminate waitings between processes, the overall MSM efficiency of the KPI Time would considerable increase. However, this solution is proposed for the presented case study. A deeper analysis should be made in order to consider all the manufactured products at MCG.

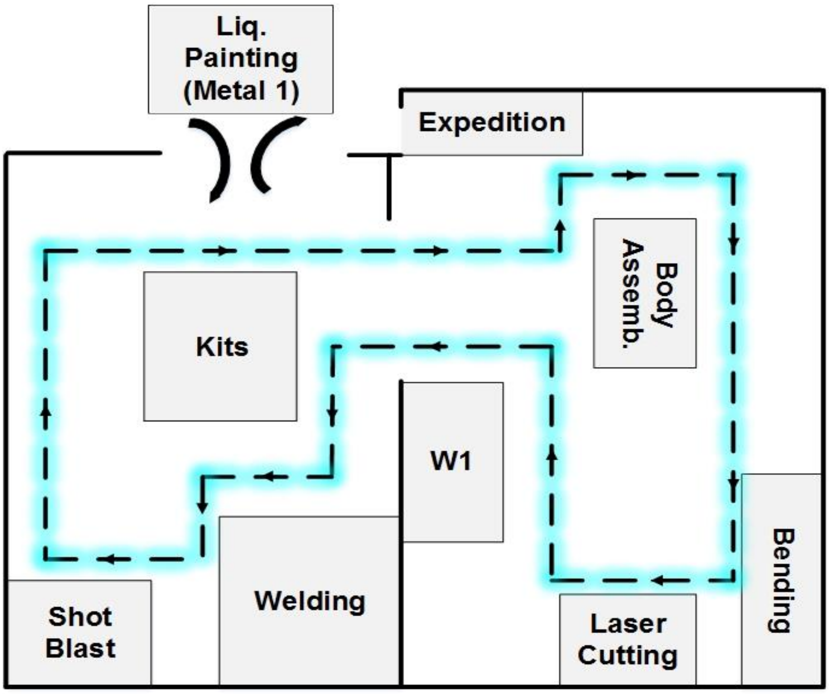


Figure 6-4: Mizusumashi proposed route in the new layout

Table 6-4: Expected impact of the implementation of the mizusumashi solution on the production of the case study's part

	Before Solution		After Solution	
	Time [min]	MSM efficiency [%]	Time [min]	MSM efficiency [%]
Laser-Bending	871	11%	141	86%
Bending-Welding	16583	41%	16003	58%
Welding-Shot-Blast	162	34%	82	74%
Shot-Blast-L. Painting	48	100%	48	100%
L. Painting- B. Assemb.	9593	29%	9314	41%
B. Assemb.- Exp.	70,85	86%	60,85	100%

6.2. Future State

Following a continuous improvement strategy denoted by the Lean philosophy it is necessary to estimate the future state of the company and start a new cycle of planning the following necessary objectives, execute the new diagnosis process, check results and act on the necessary activities, with the aim of zero defects within the production system.

The MSM dashboards for the “real future state” of the in-between activities can be consulted in figure 6-5 where the impact of the implemented improvement actions can be observed. Comparing with the diagnosis made in sub-chapter 4.4, it is expected a general improvement as it was shown in tables 6-1, 6-2 and 6-3. The efficiency of the KPI distance, between Laser and Bending, had a major increasing (from 1% to 99%), and the overall Time efficiency along the different phases also had an increment. These results show that MCG should now adopt strategies to increase the used area performance, also with significant costs to the company, and free more capacity hours to mitigate the outsource operation by acting in the bending welding phase due to the high ECW level of the variable Time.

The MSM dashboards for the estimated future state can be consulted in Attachment A5 – MSM dashboard for the Estimated Future State.

Flow Analysis

	Laser → Bending		Bending → Welding		Welding → Shot Blast		Shot-Blast → Liq. Paint.		Liq. Paint. → B. Assemb.		B. Assemb. → Exp.	
	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]
Time [min]	14%	3%	56%	69%	38%	0%	100%	0%	39%	27%	86%	0%
Distance [m]	100%	0%	2%	44%	1%	44%	4%	6%	8%	6%	100%	0%
Right Quantity	100%	0%	74%	9%	21%	36%	21%	35%	22%	18%	100%	0%
Right Part	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%
Right Quality	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%
Right Place	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%

Resources Analysis

	Laser → Bending		Bending → Welding		Welding → Shot Blast		Shot-Blast → Liq. Paint.		Liq. Paint. → B. Assemb.		B. Assemb. → Exp.	
	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]
Electrical Energy [KWh]	100%	0%	84%	78%	-	-	-	-	90%	22%	100%	0%
Diesel [L]	-	-	8%	46%	8%	46%	75%	5%	80%	3%	-	-
Area [m2]	1%	0%	2%	9%	6%	36%	10%	36%	5%	18%	10%	0%
Box Volume Empty [m3]	25%	0%	30%	0%	100%	0%	100%	0%	100%	0%	-	-

Figure 6-5: MSM dashboard for "Real Future State" of the in-between processes activities

7. Conclusions

In the scope of the MAESTRI project, the presented work had as main focus to test and validate the Multi-Layer Stream Mapping methodology, using as case study a production system with several manufacturing processes, such as laser cutting, bending, welding, shot-blast, painting and assembly.

In order to properly diagnose this production system, was first performed an analysis resorting the VSM tool to identify the several wastes along production and recognise opportunities for improvements.

The VSM has proved to be a simple and useful tool to identify the current add value and non-add value activities within the production system. However, with the nowadays concerns, the VSM is not capable of enhancing the important economic and environmental dimension to completely identify and quantify each stage of the production system.

The MSM approach was then applied to overcome some of the limitations of the VSM tool. When applied to the case study, this methodology revealed capable of assess the overall performance of the production system, while evaluating the resources efficiency, as well as the costs generated along production. The MSM application allowed to perform a full diagnosis of the production system, where aspects like activities time, distance between processes, used area and diesel consumption revealed to be inefficient within the organisation.

The MSM diagnosis also enabled to identify some limitations in this methodology. An important limitation identified was that the results presented by the MSM, efficiency ratios, hide an essential dimension to help the decision-making process: the quantification of the different wastes along the production system. So, it was suggested a new and complementary analysis to quantify every waste in every stream in order to prioritize improvement actions. It was also proposed the implementation of metering devices and sensors to allow a proper and effective collection of data and associate automatically the collected information with the MSM methodology.

By detailing the strengths and weaknesses, defining which activities of the overall production system have higher inefficiencies, which sections and KPI’s need the highest level of control regarding operational, environmental and economic aspects, and what activities contribute more to the total waste dimension of the production system, it allows the company to outline an improvement strategy, and focus in activities where there is highest potential to increase the performance of the system. So, several improvement actions were proposed to reduce the most important inefficiencies identified in the previous diagnosis. At the end, the future state of the company was presented to quantify the impact of the proposed solutions in the production system.

The MSM 2.0 methodology was successfully applied to this production system. The MSM proved to be fundamental in the development of this work being able to diagnose the several misuses throughout production, although some of the identified limitations in this methodology.

All the developed work, since data collection, to the obtained results and MSM validation revealed to be of great importance for MCG, the MAESTRI project and the future application of the Total Efficiency Framework in the company.

8. Future Work

Future research work can take place to improve, even more, the MSM methodology and test it in other environments, not only in manufacturing industries, but also in hospitals, transports, agriculture or services sectors, to realize the real impact of this methodology in multiple business systems.

It is also suggested, instead of a linear analysis of the overall system, a statistically prediction analysis integrated in the MSM methodology to facilitate the process of decision making and create improvement actions revealed by the prognosis.

Other suggestion for future works involves the concept of “Efficiency Paradox”, introduced by Niklas Modig in “This is Lean – Resolving the Efficiency Paradox”. It would be interest to study on how much the inefficiencies of the add value activities can be reduced without compromising the flow efficiency, and vice-versa.

Finally, is proposed a study and comparison of different sensors and metering devices to install in the company facilities in order keep up with the industry 4.0 progress and simplify the data collection to the MSM methodology, and promote an in-line performance analysis.

9. Bibliography

[1] L. D. Caprio, Director, *Before the Flood.* [Film]. 2016.

[2] MAESTRI, “MAESTRI project to European Union, Part B,” 2015.

[3] Y. Monden, Toyota Production System - An Integrated Approach to Just-in-Time, Chapman &. Hall, 1994.

[4] D. P. Jorge, Desenvolvimento de Soluções Lean Manufacturing aplicadas num sistema produtivo de moldes, Instituto Superior Técnico, 2016.

[5] “Organisation for economic co-operation and Development - Eco-Efficiency,” 16 March 1998. [Online]. Available: http://www.oecd.org/.

[6] A. J. Baptista, E. J. Lourenço, E. J. Pereira, F. Cunha, B. Marques, E. J. Silva and P. Peças, “Eco-efficiency Framework as a Decision Support Tool to Enhance Economic and Environmental Performance of Production Systems,” in *Energy-related Technologic and Economic Balancing and Evaluation – Results from the Cluster of Excellence eniPROD, 3rd workbook of the cross-sectional group ‘Energy-related technologic and economic evaluation’ of the Cluster of Excellence eniPROD*, Auerbach, 2014.

[7] A. Schneider, A. J. Baptista, M. Holgado, E. J. Lourenço, S. Plebanek and E. Lezak, “Deliverable 1.1 - MAESTRI platform usage scenarios,” 2015.

[8] A. J. Baptista, E. J. Lourenço, E. J. Silva, S. Plebanek, E. Pawlik and M. Gil, “Deliverable 2.1 - Efficiency Framework concept description,” 2016.

[9] Z. Masluszczak, M. Fiarkowska-Filipek, M. Holgado, S. Evans, E. J. Lourenço, A. J. Baptista, E. J. Silva and M. Estrela, “Deliverable 2.2 - Methods for Efficiency Framework for resource and energy efficiency description,” 2016.

[10] M. Holgado and S. Evans, “Deliverable 4.1 - Report on challenges and key success factors and gap analysis for industrial symbiosis,” 2016.

[11] M. Borucke, A. Galli, I. Katsunori, E. Lazarus, S. Mattoon, J. C. Morales, P. Poblete and M. Wackernagel, “Accounting for demand and supply of the Biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework,” 2013.

[12] A. Sproedt, J. Plehn, P. Schonsleben and C. Herrmann, “A simulation-based decision support for eco-efficiency improvements in production systems,” Elsevier, 2015.

[13] P. R. Ehrlich and J. P. Holdren, “Impact of Population Growth,” *Science, New Series, vol.171, No. 3977,* 26 March 1971.

[14] M. Lehni , S. Schmidheiny and B. Stigson, “Ecoefficiency: creating more value with less impact.,” in *World Business Council for Sustainable Development*, Geneva, 2000.

[15] K. Madden, R. Young, K. Brady and J. Hall, Eco-Efficiency Learning Module, Five Winds International, 2006.

[16] “Ecoeficiência na Vida das Empresas, Business Council for Sustainable Development Portugal,” in *Become Eco-Efficient*, 2012, p. 7.

[17] M. Ichimura, S. Nam, S. Bonjour, H. Rankine, B. Carisma, Y. Qiu and R. Khrueachotikul, “Eco-efficiency Indicators: Measuring Resource-use Efficiency and the Impact of Economic Activities on the Environment,” United Nations Economic and Social Commission for Asia and the Pacific, 2009, p. 4.

[18] H. Verafaillie and R. Bidwell, “Measuring eco-efficiency - a guide to reporting company performance,” 2000. [Online]. Available: http://www.gdrc.org/sustbiz/measuring.pdf..

[19] “Eco-Efficiency - creating value with less impact,” 2000. [Online]. Available: http://www.wbcsd.org.

[20] K. D. Zylstra, “Lean Distribution - Applying Lean Manufacturing to Distribution, Logistics, and Supply Chain,” John Wiley & Sons, p. 1.

[21] “Industry 4.0 - The new Industrial Revolution,” March 2014. [Online]. Available: https://www.rolandberger.com/en/Publications/pub_industry_4_0_the_new_industrial_revolution.html.

[22] A. L. Helleno, A. I. Moraes and A. T. Simon, “Integrating sustainability indicators and Lean Manufacturing to assess,” Elsevier, 2016.

[23] J. P. Womack, D. T. Jones and D. Roos, “The Machine that Changed the World,” Macmillan Publishing Company, 1990, pp. 48-51.

[24] T. Melton, “The Benefits of Lean Manufacturing - What Lean Thinking has to Offer the Process Industries,” in *7th World Congress of Chemical Engineering*, Glasgow, 2005.

[25] L. A. Brito, Melhoria de Processos utilizando metodologias Lean, Instituto Superior Técnico, 2014.

[26] A. Brown, J. Amundson and F. Badurdeen, "Sustainable value stream mapping (Sus-VSM) in different manufacturing system configurations: application case studies," Elsevier, 2014.

[27] E. J. Lourenço, A. J. Baptista, J. P. Pereira and C. Dias-Ferreira, "Multi-Layer Stream Mapping as a Combined Approach for Industrial Processes Eco-efficiency Assessment," in *Re-engineering Manufacturing for Sustainability - Proceedings of the 20th CIRP International Conference on Life Cycle Engineering*, Singapore, 2013.

[28] E. J. Lourenço, J. P. Pereira, R. Barbosa and A. J. Baptista, "Using Multi-layer Stream Mapping to assess the overall efficiency and waste of a production system: a case study from the plywood industry," 2016. [Online]. Available: www.sciencedirect.com.

[29] M. Gomes, Multi-Layer Stream Mapping applied to a productive system - Study on new approaches to integrate the logistics management operations on the MSM, Instituto Superior Técnico, 2016.

[30] A. J. Baptista, E. J. Lourenço and J. P. Pereira, Multi-Layer Stream Mapping - a new approach for total efficiency management, efficiency and productivity analysis of a production system, 2014.

[31] A. J. Baptista, E. J. Lourenço and J. P. Pereira, "Multi-layer stream mapping - Uma ferramenta para a avaliação e gestão da eficiência global de sistemas," *INGENIUM - A Engenharia Portuguesa em Revista,* Novembro/Dezembro 2014.

[32] A. A. Fraga, Aplicação do Multi-Layer Stream Mapping para Gestão da Eficiência de Recursos e Produtividade de um Sistema de Produção, Instituto Superior de Engenharia do Porto, 2014.

[33] "Multi-Layer Stream Mapping - Ferramenta para a gestão da eficiência de recursos e produtividade de sistemas de produção," *Tecno Metal - Inovação nas Empresas de Matalurgia e Metalomecânica,* Julho/Agosto 2014.

[34] A. J. Baptista, E. J. Lourenço, J. P. Pereira, P. Peças and M. Gomes, *Multi-Layer Stream Mapping - A New Approach for Total Performance Assessment, Value Stream Perspective, Waste Stream Perspective,* 2016.

[35] "100 Production Ratios," [Online]. Available: www.cometis-publishing.de.

[36] D. Parmenter, "Key Performance Indicators - Developing, Implementing, and Using Winning KPIs," John Wiley & Sons, 2007, pp. 1-5.

[37] J. Smith, “The KPI Book - The ultimate guide to understanding the Key Performance Indicators of your business,” Insight Training & Development Limited, 1988, pp. 2-4.

[38] N. Vieira, Aplicação do Multi-Layer Stream Mapping para a Gestão da Eficiência de Recursos e Produtividade de um Sistema de Produção, Faculdade de Engenharia da Universidade do Porto, 2014.

[39] M. Rother and J. Shook, Learning to see - Value Stream Mapping to Add Value and Eliminate Mudda, Massachusetts, USA: The Lean Enterprise Institute, 1999.

[40] A. J. Baptista, E. J. Lourenço, M. Estrela, M. Holgado, E. Pawlik, K. Nagorny, G. Grobe Hovest, P. Brizzi and A. Schneider, “Deliverable 1.2 - Technology Watch Report,” 2015.

[41] R. N. Bravo, Analysis of influence of design factors in Eco-efficiency of the Injection Moulding Process, Instituto Superior Técnico, 2015.

[42] M. Schmidt and M. Nakajima, “Material Flow Cost Accounting as an Approach to Improve Resource Efficiency in Manufacturing Companies,” 3 September 2013. [Online]. Available: www.mdpi.com/journal/resources.

[43] K. L. Christ and R. L. Burrit, “Material Flow Cost Accounting: a Review and Agenda for Future Search,” Elsevier, 2014.

[44] K. Kokubu, T. Enkawa, Y. Furukawa, Y. Kawano, K. Kitagawa, T. Mizuguchi, Y. Murata, M. Numata, H. Tachikawa and M. Yoshikawa, Material Flow Cost Accounting: MFCA Case Examples, Ministry of Economy, Trade and Industry, 2010.

[45] D. E. Perry and L. G. Votta, “People, Organizations, and Process Improvement,” IEEE Software, 1994, pp. 36-45.

Attachments

Attachment A1 – Value Stream Mapping

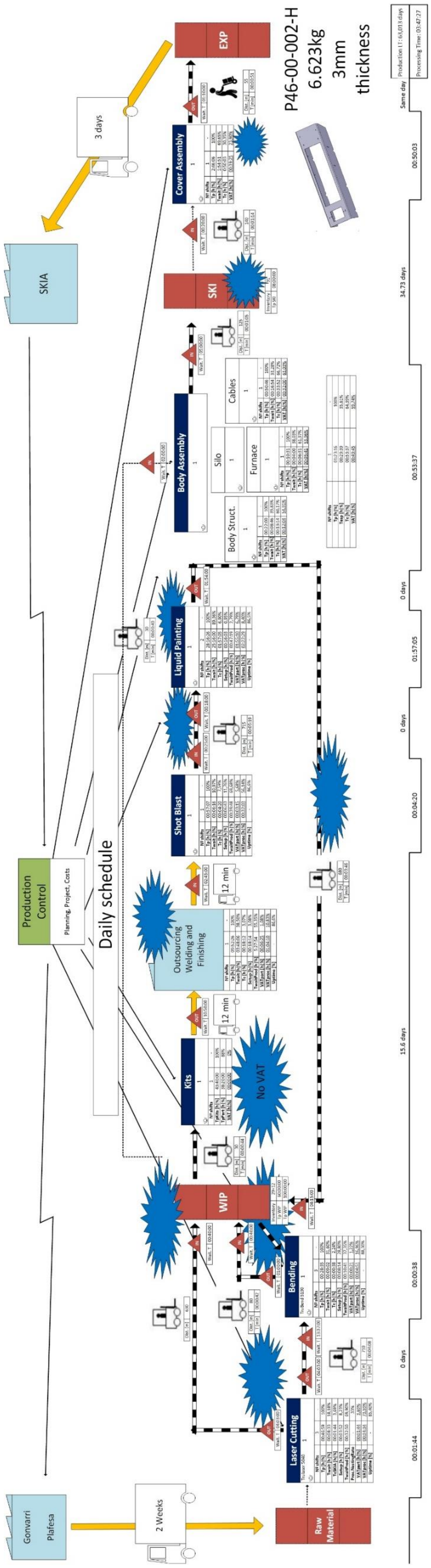
Attachment A2 – Processes' Collected Data

Attachment A3 – MSM Extended Results of in-between Processes Activities

Attachment A4 – Other Improvement Actions

Attachment A5 – MSM for the Estimated Future State

Attachment A1 – Value Stream Mapping



FigureA1-1: Value Stream Mapping of the production system

Attachment A2 – Processes' Collected Data

Table A2-1: Collected Data for the Laser Process

Laser Cutting			
Setup A	Setup in machine	Alline nozzle with lens	
[8,23%]	19,68%	31,84%	
Setup B	Table Change	Control	Maintenance
	22,11%	4,50%	21,87%
Tw	Operator away/talking	Non-application of SMED	
[18,18%]	48,84%	51,16%	

Table A2-2: Collected Data for the Bending Process

Bending		
Setup A	Setup	
[28,8%]	55,00%	
Setup B	Control	
	45,00%	
Tw	Print tags/registers	Operator away/talking
[31,6%]	43,00%	57,00%
Others	Transports	
[total time]	22,64%	

Table A2-3: Collected Data for the Shot-Blast Process

Shot Blast		
Setup	Equipment	Movimentations (turn furnaces)
[11,76%]	81,55%	18,45%
Tw	Operator away/talking	
[10,97%]	100,00%	
Others	Transports	Remove metal grains left overs
[total time]	9,79%	11,34%

Table A2-4: Collected Data for the Liquid Painting Process

Liquid Painting					
Setup	**Equipment**	**Movimentations**		**Ink Loading**	
[0,95%]	33,68%	40,00%		26,32%	
Tw	**Print tags/registers**	**Work in another models**	**Operator away**	**Waiting for oven**	**Others**
[89,36%]	1,03%	0,79%	73,55%	24,16%	0,47%
Others	**Transports**				
[total time]	1,29%				

Table A2-5: Collected Data for the Body Assembly

Body Assembly		
Tw	**Operator away/talking**	
[35,61%]	100,00%	
Others	**Movement for component**	**Movement for tool**
[total time]	3,92%	0,73%

Table A2-6: Collected Data for the Cover Assembly

Cover Assembly				
Tw	**Work in another product**	**Waiting for necessary components**	**Waiting for Packaging**	**Operator away/talking**
[69,95%]	6,19%	20,91%	16,41%	56,49%
Others	**Movement for component**		**Movement for tool**	
[total time]	4,66%		1,79%	

Attachment A3 – MSM Extended Results for in-between Processes Activities

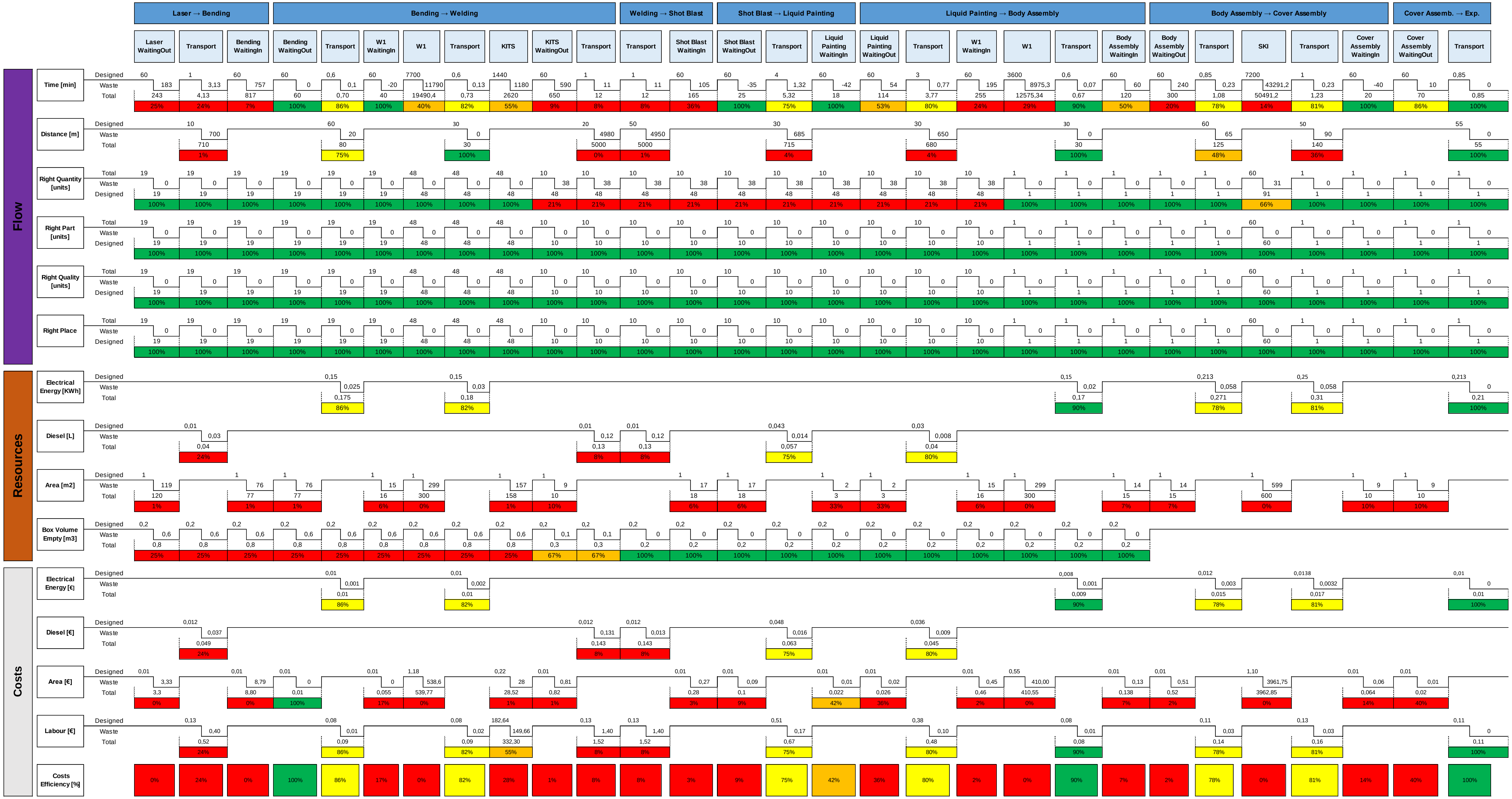


Figure A3-1: MSM Extended Results for the In-between Processes Activities

Attachment A4 – Other Improvement Actions

Table A4-1: Improvement Solution for Production Flow

<u>Problem:</u> Quantity in the Kanban card does not match with the quantity in the box

Description:

Quantity declared in the kanban card does not match the quantity in the box. Happens essentially in small parts that fall to the floor through the spaces of the laser table This situation creates problems in the following processes and costs for producing more parts

Location:

Laser – Metal 3

Proposed improvement actions:

- Operators must count all the parts before printing the kanban card, but not fully reliable
- Weighting machine to count the parts
- Introduce a treadmill under the laser table that will take the parts that fall through the table to a small container. With the new situation, the operators, at the end of each cut, can verify if there are missed parts that should be inside the box

Weight machine “count parts” - Industrial

Consequences:

- Reduced costs and time to produce new parts
- In the bending process, there will be no problems related
- Lead Time reduction

Table A4-2: Improvement Solution for Bending Process

<u>Problem:</u> Lack of support for the heavier parts in the bending process	
Description: • When dealing with heavier parts, opeators have difficulty lifting them off the floor so they stop their work more often because they get tired	
Location:	
Bending – Metal 5	
Proposed Improvement Measures:	
• Acquire trestles to support heavier parts, on all machines (already exists in one machine)	 *Cavalete para ajudar aperadores*
Consequences:	
• Improved operator performance and safety (prevent muscles pain)	

Table A4-3: Improvement Solution for Kits

<u>Problem:</u> Kits	
Description: • Non-add value process, but essential to the production flow	
Location:	
Kits/W1 – Metal 5	
Proposed improvement actions:	
• Create a data base of each KIT to being made and organize all the references of each KIT as close as possible in W1	
Consequences:	

• In the W1, if the bottom box is needed to build a KIT, avoid wasting time taking the box from the top, then the bottom, and then put the top box again in the shelve. With this, the operator could take both at the same time, with the forklift, for the KITS

Table A4-4: Improvement Solution for Inventory in storage W1

<table>
<tr><th colspan="2"><u>Problem:</u> Obsolete inventory in W1</th></tr>
<tr><td>Description:
• The system first-in-first-out is not applied</td><td rowspan="3"></td></tr>
<tr><td>Location:</td></tr>
<tr><td>W1 – Metal 5</td></tr>
<tr><td colspan="2">Proposed improvement actions:</td></tr>
<tr><td>• Apply the first-in-first-out</td><td>
</td></tr>
<tr><td colspan="2">Consequences:</td></tr>
<tr><td colspan="2">• Reduces damaged parts by oxidation or other external factors for have been in W1 storage for a long time</td></tr>
</table>

Attachment A5 – MSM for the Estimated Future State

Flow Analysis	Laser → Bending		Bending → Welding		Welding → Shot Blast		Shot-Blast → Liq. Paint.		Liq. Paint. → B. Assemb.		B. Assemb. → Exp.	
	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]
Time [min]	86%	3%	58%	69%	74%	0%	100%	0%	41%	27%	100%	0%
Distance [m]	100%	0%	2%	44%	1%	44%	4%	6%	8%	6%	100%	0%
Right Quantity	100%	0%	74%	9%	21%	36%	21%	35%	22%	18%	100%	0%
Right Part	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%
Right Quality	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%
Right Place	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%

Resources Analysis	Laser → Bending		Bending → Welding		Welding → Shot Blast		Shot-Blast → Liq. Paint.		Liq. Paint. → B. Assemb.		B. Assemb. → Exp.	
	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]	MSM [%]	ECW [%]
Electrical Energy [KWh]	100%	0%	84%	78%	-	-	-	-	90%	22%	100%	0%
Diesel [L]	-	-	8%	46%	8%	46%	75%	5%	80%	3%	-	-
Area [m2]	1%	0%	2%	9%	6%	36%	10%	36%	5%	18%	10%	0%
Box Volume Empty [m3]	25%	0%	30%	0%	100%	0%	100%	0%	100%	0%	-	-

Figure A5-1: MSM dashboard for the Estimated Future State