Incorporation of Material Flow Cost Accounting in Life Cycle Engineering for product and process design

Patrícia Alexandra Leal Paiva

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Supervisors: Prof. Paulo Miguel Nogueira Peças

Profª. Inês Esteves Ribeiro

Examination Committee

Chairperson: Prof. Rui Manuel dos Santos Oliveira Baptista

Supervisor: Prof. Paulo Miguel Nogueira Peças

Members of the Committee: Profª. Elsa Maria Pires Henriques

Prof. Uwe Götze

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Resumo

A fase de design de produto e de processo, é uma etapa que influencia o desempenho económico e ambiental ao longo de todo o ciclo de vida do produto. No decorrer da última década, da emergente preocupação ambiental sobre os crescentes problemas ecológicos, por parte da população, surgiu a necessidade de integração de métodos que avaliem o impacto ambiental na fase de conceção do produto. Esta integração mostra-se fundamental para que as empresas consigam manter a sua competitividade no mercado, controlando desta forma, o impacto ambiental das suas práticas. A presente dissertação foca-se na incorporação do *Material Flow Cost Accounting* (MFCA) no *Life Cycle Engineering* (LCE) aplicado na fase de design de produtos e processos. A integração de ambos métodos, promove a conceição de produtos mais ecológicos e rentáveis, sendo um ferramenta de apoio à decisão.

A fim de atingir os objetivos expostos, a metodologia do MFCA é, em primeira instância, aplicada a uma unidade de produção que se caracteriza por um processo de injeção de plásticos. Esta aplicação permite o reconhecimento dos benefícios do MFCA, assim como as limitações inerentes à sua utilização numa fase inicial do projeto. Com vista alargar o seu campo de aplicação, algumas modificações são propostas e um Modelo de Processo é desenvolvido. O modelo não só possibilita o cálculo dos recursos necessários para produzir os componentes e os custos associados ao processo de fabrico, como também fornece as informações necessárias para a avaliação do impacto ambiental.

A nova abordagem da metodologia do MFCA; em conjunto com o Modelo de Processo desenvolvido, é aplicada com o intuito de comparar e avaliar várias alternativas de produção do processo de fabrico em estudo. Além disso, é ainda utilizada para avaliar diferentes designs ao longo do ciclo de vida, seguindo a abordagem do LCE.

Por fim, o estudo descrito possibilitou o desenvolvimento de uma metodologia, proposta, para incorporar o MFCA na análise LCE. Esta metodologia poderá auxiliar as organizações a compreender melhor os potenciais impactos ambientas e financeiros das suas praticas. Nomeadamente da utilização de materiais e de energia, assim como procurar oportunidades para melhorar ambos os desempenhos, através da melhoria da eficiência dos recursos.

Palavras-Chave: *Material Flow Cost Accounting, Life Cycle Engineering, Life Cycle Costs, Life Cycle Assessment*, Modelo de Processo; Injeção de Plásticos.

Abstract

The design phase of a product or a process influences the economic and environmental impacts throughout its entire life cycle. In the last decade, ecological problems have emerged as an important public concern. Hence, the integration of environmental methods on the early design phase become essential for the companies to maintain their competitiveness in the market. The present dissertation is focused on the incorporation of the Material Flow Cost Accounting (MFCA) in the Life Cycle Engineering (LCE) for products and processes design, to promote the design of ecological and cost-effective products and support decision-making.

To achieve that goal the MFCA methodology is first applied to a production unit characterised by the Injection Moulding process. This allows the recognition of the MFCA benefits, as well as the inherent limitations to be used in the early design phase. To extend its scope, some modifications are proposed and a Process Based Model (PBM) is developed. It not only enables the calculation and forecasting of the necessary resources for the manufacture of the components and their associated costs but also provides the necessary information for the assessment of the environmental impact.

The new approach of the MFCA methodology, together with the PBM, is applied to compare and evaluate several production alternatives of the manufacturing process in study. Furthermore, it is also used to appraise different designs throughout the entire lifecycle following the LCE approach.

This enabled the development of a methodology, proposed, for integrating the MFCA in the LCE analysis. This methodology can assist organisations to better understand the potential environmental and financial consequences of their material and energy use practices, and seek opportunities to enhance both performances through the efficiency of the resources improvement.

Keywords: Material Flow Cost Accounting, Life Cycle Engineering, Life Cycle Costs, Life Cycle Assessment, Process Based Model, Injection Moulding.

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Nomenclature

LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCE	Life Cycle Engineering
EI	Environmental Impact
EMA	Environmental Management Accounting
SEM	Environmental Management System
EoL	End of Life
MFCA	Material Flow Cost Accounting
MEFCA	Material and Energy Flow Cost Accounting
OEE	Overall Equipment Effectiveness
PBM	Process Based Model
PDCA	Plan-Do-Check-Act
PP	Polypropylene
QC	Quantity Centre
SUW	Solid Urban Wastes
WM	Waste Management

1. Introduction

Nowadays, in a modern and competitive production context, the companies are under an increasing pressure to achieve a higher productivity with reduced environmental impact [1]. An effective resources management is vital to meet the economic and ecological goals [2]. Material Flow Cost Accounting (hereafter referred to as MFCA) is one of the major tools for environmental management accounting, which allows the achievement of the harmony between profitability and sustainability [1].

The MFCA is a method aimed to reduce the costs and the environmental impacts, at the same time, through the improvement of resources efficiency and as a tool for decision-making [3]. The Life Cycle Engineering (LCE) is also typically used and understood as an approach to support decision making considering environmental impacts, technical and economic performance addressing the whole life cycle of a product [5]. It incorporates life cycle tools as Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) to evaluate the environmental and the economic aspects respectively [6]. Though LCC and LCA are based on the same type of objects and information, they are often applied independently of each other. The possibility of integrating the LCC and LCA may contribute to a detailed evaluation based on a common foundation and enhance the global evaluation significance [4], [2].

From the fact that the MFCA provides detailed information about the environmental variables and the production costs, arises the hypothesis of extending the Material Flow Cost Accounting scope to a life cycle perspective and integrate it in the Life Cycle Engineering of a product.

Therefore, on a first approach the present dissertation applies the MFCA methodology to a Plastic Injection Moulding System in a Portuguese company. Then, to support the hypothesis and extend the MFCA scope, a Process Based Model is developed for the appraisal and comparison of different design configurations. To test the hypothesis the MFCA is integrated in the LCE approach to evaluate different production alternatives of the Product used as a case-study in the present work. Finally, a methodology to incorporate the MFCA in the LCE for process and products design is proposed.

This work starts with a brief description about Material Flow Cost Accounting and its current applications, as well as the Life Cycle Engineering concept and principles, presented in Chapter 2.

The main goals description and the approach followed on the dissertation are presented in Chapter 3, together with the company's framework, the products and the productive unit used as a case-study. The Injection Moulding Process characteristics are also briefly described in this Chapter.

In Chapter 4, the methodology followed for the application of the MFCA is described, as well as the calculation model developed for the diagnosis of the production system. Still in this Chapter, the diagnosis of to the case-study's manufacturing unit is performed and the obtained results are presented. At the end of the Chapter, some inefficiencies in the production system highlighted by the MFCA are discussed and improvement solutions are suggested.

Chapter 5 identifies the primary limitation of the MFCA methodology to evaluate different design configurations, as well as the necessary modification to the original calculation model. Subsequently the developed Process Based Model is presented. With the aim of evaluating and validating the new model, several production scenarios are compared. Moreover, two sensitivity analysis to the production volume and to the product lifetime are performed. The obtained results and the applicability of the MFCA as an early design tool is discussed in the end of the Chapter.

Chapter 6 approaches the ultimate goal of this dissertation, the MFCA integration in the LCE. The environmental impact is calculated through the LCA using the information provided by the MFCA analysis. Furthermore, the MFCA costs results are integrated in the LCC to obtain the economic impact of each alternative. The results are then presented and the MFCA integration hypothesis with the LCE is discussed.

In Chapter 7, the proposed methodology to incorporate the MFCA in the LCE model is presented.

Finally, the conclusions of the present dissertation are presented in Chapter 8 and the suggested future work is described in Chapter 9.

2. State of the art

Companies intend to remain competitive in a global market where a higher sustainability is demanded, due to the growing debate about climate change and materials scarcity [2]. Under pressure to achieve higher productivities with low environmental impacts, managers face the challenge of integrating increasing ecological objectives with economic goals [2]. In consequence, an effective tool that supports the company in the resources management is decisive to meet environmental and economic goals successfully [1]. In this context, Material Flow Cost Accounting is recognised as an essential approach to sustainability and a practical approach to meet such needs [1].

The design of a product or a production process must meet technical, environmental and economic requirements [2]. In the manufacturing industry, the input materials cause the largest share of costs by far [10]. The materials' consumption, together with the energy used, largely affect the environmental performance of industrial companies [2]. Furthermore, a significant share of residual materials is generated in production systems [12].

In many cases, an organisation is unaware of the full extent of the actual cost of material losses because traditional management accounting theories largely fail in the identification and accounting of material and energy inefficiencies [8]. The awareness of these losses is vital for improve the resources consumption, reduce adverse environmental impacts and increase productivity [7]. To overcome this issue, and to meet ecological goals imposed by the environmental management systems, flow oriented concepts were developed [2].

Material Flow Cost Accounting is a specialised accounting method [2] and one of the primary tools of Environmental Management Accounting (EMA) [7]. It is also considered one of the few tools that integrate environmental management and management accounting systems as illustrated in Figure 2-1 [11]. It promotes the transparency of material use practices through a model that traces and quantifies the material flows in physical and monetary units [1], [7]. It seeks to highlight the comparison of the costs associated with products and with materials losses [2].

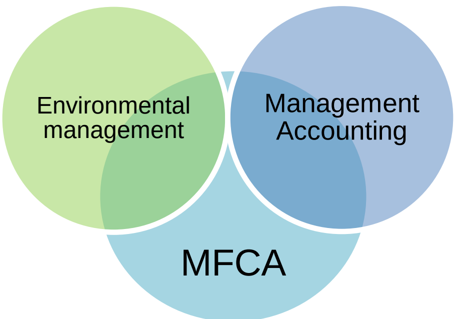


Figure 2-1: Positioning MFCA adapted from [11]

In the following sections of this Chapter, the history, principles and fundamentals of MFCA are described. Then, to better understand the benefits of implementing the MFCA in a company, the differences between MFCA and traditional costs accounting methods are discussed. Subsequently, an implementation methodology is presented.

The material losses generated in a system are often driven, on the one hand, by the materials' quality provided by the supplier and, on the other hand, by the specifications of the product requested by the client. The extension to the supply chain, upstream or downstream the organisation, can potentially help to develop an integrated approach improving the efficiency of the resources [7]. The supply chain includes all systems and process involved in the products' production from the supplier to the customer. The challenges and benefits of extending the MFCA scope to the supply chain are also discussed further in this Chapter.

The extension of its scope to future states evaluations and as a tool of decision-making in the early design phase of a product or a process, lead to a life cycle perspective approach. In this context, the concept of Life Cycle Engineering, Life Cycle Assessment and Life Cycle Costs are described.

To finish, the existing information about the potential integration of the MFCA in the LCE, which supports the present dissertation hypothesis, is presented.

2.1. History, Principles and Fundamentals of MFCA

2.1.1. History

The original concept of MFCA was developed at *Institut für Management und Umwelt* in Augsburg, Germany, in the late 1990s. However, MFCA's real breakthrough happened in Japan [2] where the initial concept was modified. With the aim of increasing the facility of use and favour the improvement plans, it was proposed segmenting the materials into raw materials and energy sources as well as measuring them by process [3]. Since the vast success of the firsts implementation cases in the year 2000, it has been actively promoted by the Japanese Ministry of Economy, Trade and Industry. More than 300 Japanese companies adopted the methodology [2].

In parallel, MFCA's methodology was refined and the final version of the standard, ISO Standard 14051, was published at the end of 2011 [2]. The aim of the International Standard is to offer a general framework for its application, common terminologies, objectives and principles, provide fundamental elements and implementation steps. However, calculation procedures and techniques for enhancing the material and energy use are outside of its scope [7].

MFCA methodology was primarily designed for a single facility or organisation; however, it is possible to extend it to multiple organisations within a supply chain, and some successful examples can already be found [7]. Nevertheless, this integration leads the companies to share their accounting information and technical details which raise confidentiality issues. To overcome the implementation difficulties and serves as a guide, a new standard ISO 14052 is being developed since May 2014 [12].

2.1.2. Principals and Fundamentals

MFCA, as it was referred, is a flow oriented accounting method which objective is to support a company to enhance the environmental and financial performance through the improvement of the material and energy use [7]. It allows the recognition of the primary waste sources, simplifying the identification of the problem and thereby, the solution [3].

MFCA is independent of the industry type and scale; i.e., is applicable to any system that uses materials and energy, even if they lack environmental management systems in place [7].

The MFCA analysis divides the process in quantity centres [7]. The quantity centres are selected parts of a process where the inputs and outputs are quantified, first in physical units and then, in monetary units. The materials' movements and the use of energy for all the quantity centres should be described by a flow model. Figure 2-2 depicts a simplified example of a flow model only considering materials movements [8].

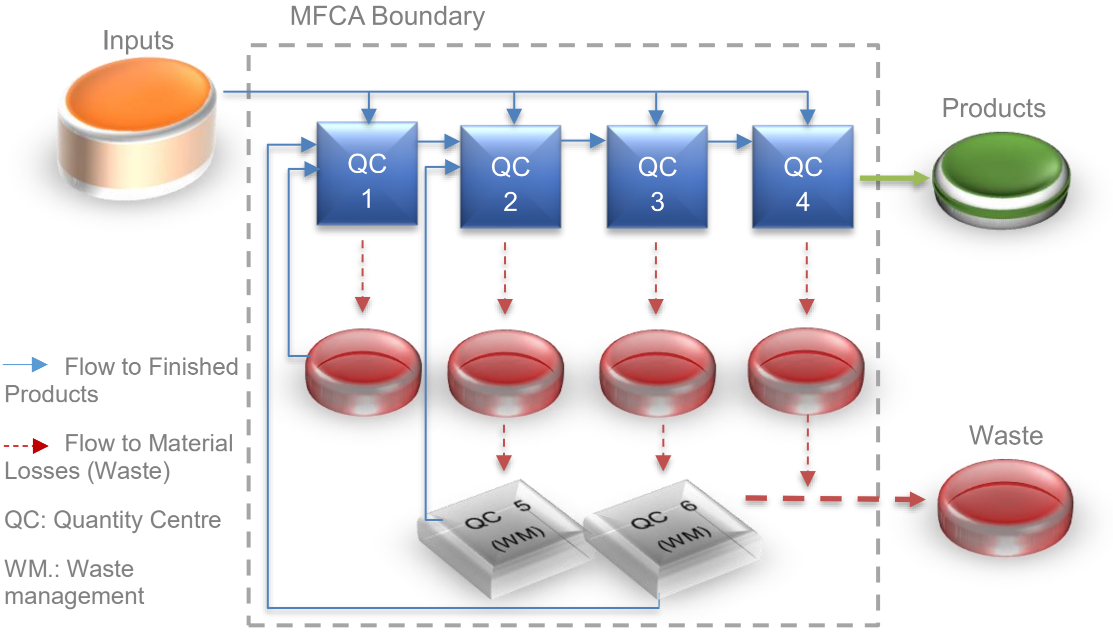


Figure 2-2: Material Flow Cost Accounting - Flow model example adapted from [8]

The flow model should illustrate the overall movement of materials and energy within the boundary chosen for the analysis as well as provide an overview of the entire process, identifying potential points where losses can occur [8]. Further, should evidence the financial effect of the losses, what subsequently will allow managers and engineers to focus on the more critical points and to develop technical and organisational improvements [2].

The mass and energy conservation laws state that mass and energy can neither be created nor destroyed, only transformed. Based on this principle and to ensure that all materials flows are accounted, a mass balance should be performed to the system and individually to each quantity centre. It must consider the material inputs, outputs and changes in inventory, Equation (2.1), [7].

$$Input = Output = Product + Material\ loss\ (Waste) + (Initial\ inventory - Final\ inventory) \quad (2.1)$$

In practice, the intake of air or moisture, complex chemical reactions or measurement errors can lead to inaccuracies in the previous Equation (2.1). The significant and unexplained irregularities must be further investigated [7].

As it can be noted in Equation (2.1), the MFCA considers the production of goods as a system of flows that can be divided in [2]:

- Desired material flows (products);
- Undesired material flows: movement of unintended material outputs or material losses (waste).

MFCA considers as undesired flows [3]:

- Material loss during processing and defective products;
- Materials remaining in the equipment after set-ups;
- Auxiliary materials as solvents, lubricants, detergents, etc.;
- Raw materials, work-in-process and stock products rejected due to deterioration or other reasons.

In manufacturing industries, all the steps of the manufacturing process may be sources of waste and loss [3]. The subsequent decrease of undesired outcomes entails a reduction of demand for input materials, leads to positive economic and ecologic effects, increases productivity and reinforces the competitive capacity of the company [2].

In conclusion, MFCA traces and appraises the material flows with the aim of enhancing the resources productivity and resolve wastefulness problems. It subsequently leads to the reduction of the resources demand, simultaneously reducing the environmental impact and the costs [11].

Additionally, MFCA implementation also creates the opportunity to enhance the accounting and the information systems of the company. Consequently, provides more precise data and avoids some manual data collection and analysis in future projects [2].

2.2. MFCA and Traditional Cost Accounting

MFCA is a specific method firstly designed to be applied as an evaluation and redesign tool with the aim of improving the efficiency of the resources [2]. Understand the differences between MFCA and the traditional cost accounting methods can be useful for its implementation [7].

Assuming that the improvements made in a company primarily have to be economically advantageous to generate profit, the evaluation of an existing process chain and the development of alternatives should be based on monetary valuation. The corresponding appraisals, typically refer to economic data that are recorded, analysed and reported by a company’s cost and management accounting system. Traditional management accounting theory already provides a vast spectrum of methods for cost analysis, although largely fail in the identification of material and energy inefficiencies [2].

One of the primary and most evidence differences between the traditional cost accounting and the flow-oriented methods lies in the treatment of the material losses costs and the inefficiencies in the process. Traditionally, those costs are allocated to the product costs and seen as a necessary part of the production process. The material losses are recognised, but the costs are not separated from the goods productions [7]. Often, it is defined a standard value with which actual costs are compared, and the causes for the cost variances are analysed. This variance, rather than reflecting the material losses, only identifies materials used beyond the standards and consequently, only those are considered as a loss. The same logic is applied to the processing costs [3]. Additionally, waste management costs are either incorporated in product costs or hidden in overhead costs. This leads to a lack of understanding of the material losses and inefficiencies along the production process [7].

On the other hand, MFCA traces all the material flows emphasising the material losses. The material losses are treated as a separate cost object that includes all the associated costs (material costs, energy costs, system costs and waste management costs) related to their production and allocated through an appropriate criterion. In opposition to traditional methods, MFCA highlights the costs of material losses and the costs of inefficiencies in the process, making visible the costs associated with undesired flows. The identification of the sources of material loss and the overall inefficiencies supports the company in management and appraisal of environmental impacts [7].

Even though, MFCA embraces and overcomes the traditional methods' weakness regarding the evaluation of material use, some of its objectives and the information that provides are overlapped with those of traditional cost accounting. Both approaches map and document business processes, supply information for planning, monitoring and controlling the operations, assist in the behavioural control of all the employees and support the appraisal of products, intermediates and self-made assets. Nevertheless, they also differ in last use of that information. While traditional cost accounting uses the cost information for a broad range of decisions, generally related to product costing and short-term evaluation of the company, MFCA focuses on process design, appraising the process desired and undesired outcomes to derive conclusions about the resources' efficiency [2].

Hence, from the company's perspective, MFCA can be perceived as a specific part of the cost accounting system. Götze et al. propose a method to integrate MFCA in the cost accounting system on the data level [8]. The integration ensures the comparability of the results and the analysis can be understood as the study of the same object from different perspectives, enhancing the information for decision-making. Additionally, the quality of the traditional costs appraisals will be simultaneously improved by more detailed information regarding material and energy movements provided by MFCA [2].

The benefits and the enhancement of the accounting system obtained by integrating MFCA as a partial system of it should be contrasted with the necessary effort for its implementation. The MFCA is a flow model, hence, requires detailed information about the material and energy movements and an appropriate system of control points for measuring the physical quantities of the different flows separately. Furthermore, the necessary recording is extended to the undesired outcome of the production process. This quality and detail of information are essential for the significance of the analysis' results. An appropriate implementation strategy aims at a meaningful ratio between effort and benefits [2].

Practical experience recommends, in a first approach, to identify the more critical parts and the use of a rough flow model for that purpose. It can be followed by an enhanced stepwise analysis to identify the causes of the inefficiencies. Successful cases show that the initial analysis of the MFCA typically highlights more inefficiency than expected in the process chain and partly shortcomings of the existing management system. The subsequent elimination of the inefficiencies results in significant cost savings [2].

2.3. MFCA Implementation Methodology

The implementation of MFCA method in a company requires the collaboration of multiple corporate departments and several implementation steps [3]. The level of detail and the complexity will depend on the size of the company, the nature of the organisation and its products, the number of processes and quantity centres and the available information [7]. It can be implemented in an organisation with or without Environmental Management System (EMS) in place. However, the implementation process is favoured in those who have it [7].

On the one hand, the MFCA implementation can be understood as a several steps procedure from its introduction to its application to evaluate a productive system [3]. However, it can provide significant information in the various stages of the continuous improvement cycle: Plan-Do-Check-Act (PDCA) [8]. The knowledge of potential environmental and financial impacts obtained from the MFCA analysis can considerably enhance the PDCA evaluation. If the appraisal is performed in an organisation that has within an EMS, the MFCA PDCA cycle can be applied at different phases of the EMS PDCA cycle [7]. Thus, on the other hand, the MFCA implementation benefits will be increased if it is constructed in accordance by the PDCA cycle and became a tool of continuous improvement within the accounting system of the company [8]. Figure 2-3 proposes an outline of the MFCA implementation steps in a company as a PDCA cycle.

In a first approach, the management level personnel should understand the value and practicability of MFCA to achieve the environmental and financial goals. Then, the target products, lines and process should be studied and selected, and therefore, the MFCA boundary should be specified [8]. It is advisable initially, to choose a process with potentially significant impacts. However, the company can choose from a single process to a supply chain boundary [7].

Once determined the boundary, the period for data collection should be defined. It should be sufficiently long to allow the compilation of meaningful data and to consider significant process variation. Depending on the analysis, the appropriate period could be a month, half a year, a year or a lot of production time [7].

Subsequently, the quantity centres are carefully selected [7]. If the quantity centres are defined too roughly a lack of information about the potential material losses' location occur. In opposition, if they are set too finely, data compilation will take too much time [3]. Before proceeding to the next phase, the performance of a rough analysis is recommended, to corroborate the validity and potency of the previous definitions [3].

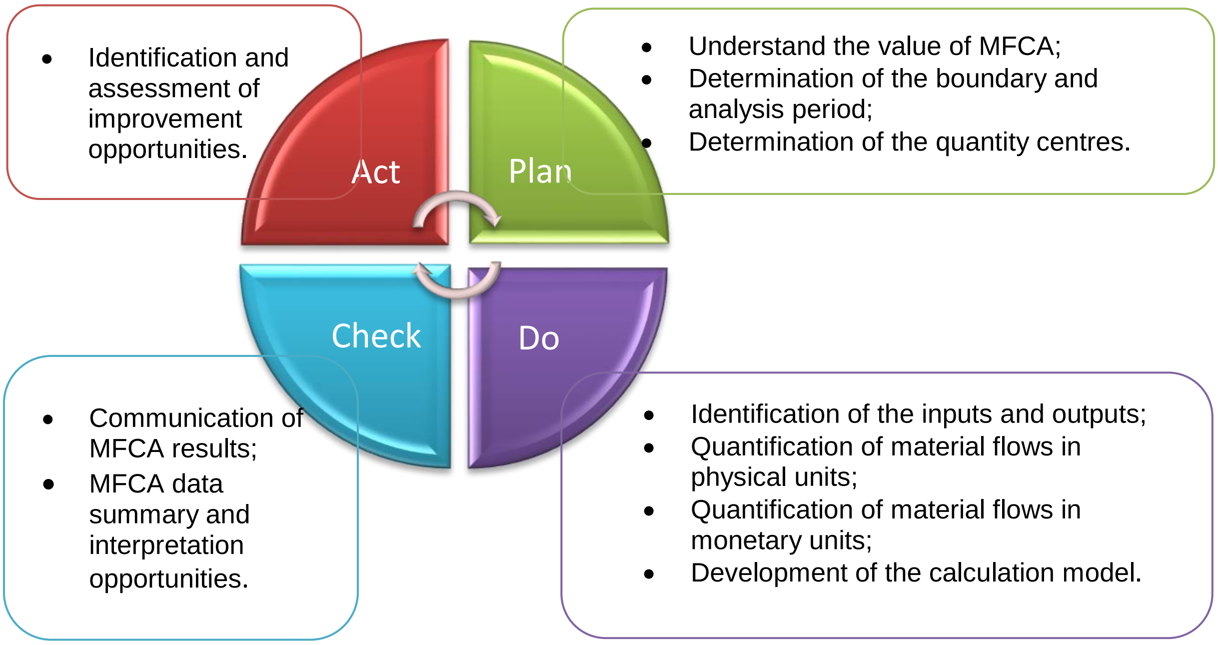


Figure 2-3: MFCA implementation steps, PDCA cycle adapted from [7]

The first phase of the *Do* phase is the identification of the inputs and the outputs for each quantity centre. As mention before, typically the inputs are materials and energy, and the outputs are products and material losses and energy losses. The energy flows can be either included under the material flows or traced separately [7].

Once all the inputs and outputs are identified, they should be quantified in physical units and link the quantity centres within the MFCA analysis boundary. To calculate the material balances, all the physical units should be convertible to a single standardised unit. The inventory changes within the quantity centre should be considered as well as all the materials within the boundary conditions. Nevertheless, materials with minimal environmental or finance significance that are difficult to quantify can be omitted [7].

After the material flow data collection and validation, it should be translated into monetary units to support decision-making [3]. The desired and undesired flows do not carry only the material cost. Since each process requires the input of labour, depreciation, energy, transportation, among other associated costs, MFCA adds all the costs information to the quantity data based on material flows. Thereby, the economic loss can be analysed not only regarding material but also including the entire manufacturing costs [3]. Table 2-1 describes the four types of costs identified by in the MFCA analysis [7]:

Table 2-1: Material Flow Cost Accounting - Types of costs

Material	Costs of main materials, sub-materials and auxiliary materials. The material costs for each input and output flow are quantified by multiplying the physical amount by the unit cost of the material over the period chosen for the analysis [7]. The use of fixed input costs allows a consistent evaluation for all the steps [10].
System	Costs incurred during in-house handling of material such as processing, labour, depreciation, among others, regardless material, energy and waste management costs [7].
Waste Management	Costs associated with handling material losses. These costs should be entirely attributed to the material losses [7].
Energy	Costs related to the energy consumed in each quantity centre. In the cases where the energy costs for individual quantity centres is difficult to measure the most appropriate criterion should be selected for allocate the total energy costs [7].

As other accounting processes, MFCA differentiates between direct and indirect costs. The indirect costs, as structure costs, must be allocated by the more suitable criterion. A two steps procedure is suggested by the ISO standard 14051. First, the indirect costs should be allocated to the quantity centres that they are related to and then, to the outgoing flows by an appropriate criterion [7]. Figure 2-4 represents a typical example of the cost analysis performed to a quantity centre [7].

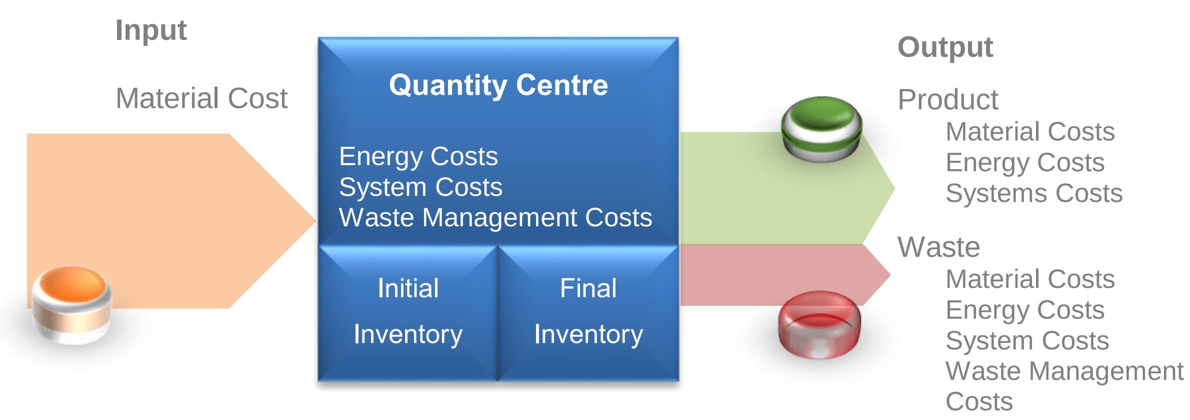


Figure 2-4: Example of a quantity centre's cost analysis adapted from [8]

Once all the information is compiled the allocation rules for the system and energy costs should be defined [3]. To maximise the accuracy of the analysis, the costs should be calculated individually for each quantity centre and individual flows. However, some costs such as system, energy and waste management costs are often available only for the entire process. Therefore, is necessary to define allocation rules in a two-step procedure [7]:

1. Allocate the process-wide costs to different quantity centres;
2. Allocate the quantity centre costs to products and material losses.

The allocation rules should not be general, i.e., for each assignment step an appropriate allocation criterion that reflects as closely as possible the main drivers for costs allocation should be adopted. The first step may include machine hours, labour hours, the number of employees, production volume, floor space, depreciation and the most appropriate allocation criteria should be selected for each type of cost [7].

For the second step, another appropriate criterion should be selected. The criterions more used are the total material distribution percentage and the primary material distribution percentage. All the waste management costs within a quantity centre are attributed to material losses. For the remaining costs, the most appropriate allocation rule is a decision of the company [7].

The environmental performance evaluation of a company is often based on the consumed resources in physical units. In opposition, the financial assessment uses monetary units. To base the decision-making in financial and environmental information at the same time, the calculation model must integrate the material and energy data collected in physical units with their associated costs [7]. The calculation model should be developed by the company based on the requirements, fundamentals and principles of the MFCA methodology, although a guidance for costs calculation is provided in the ISO standard 14051. The calculation model may follow three steps [7]:

1. Calculation of material costs;
2. Calculation and allocation of energy, system and waste management costs;
3. Integrated presentation and analysis of cost data.

The review and interpretation of the results obtained after the MFCA analysis will allow the identification of the quantity centres with the more relevant material losses. Further, can be analysed individually by engineers and managers in more detail to identify the root causes of the inefficiencies and the factors that incur the costs. The general information provided by the MFCA can support a broad range of decisions aimed at the improvement of both, environmental and financial performance [7].

Finally, to better understand the magnitude, consequences and drivers of the material use and loss, the data must be reviewed to study the potential opportunities for enhancing the environmental and economic performance of the company. The MFCA calculation model can support the appraisal of the cost-benefits measures to achieve the improvements decided by the corporation [7]. Some of the improvements derived from the MFCA analysis can be categorised into three main levels [3]:

- Management of manufacturing site continuously. These improvements are based on production indicators as yield rates, the percentage of defective products or operating rates. The MFCA allow the translation of the indicators in production costs, making more visible the consequences achieved with their improvements.

- Improvements in engineering and production departments. The inefficiencies identified through the analysis, lead to proposed of enhancement of the process design or the substitution of the existing equipment. The cost estimation and changes in the production system can be estimated, in part by the MFCA.
- Improvements in the development and design stages of a new product: MFCA evidences the impact of process yield rates on costs and recognises how the material use efficiency contributes to cost reduction.

The appraisal of alternatives process configurations and technologies require the calculation of future costs that may be out of the scope of the as-is state results obtained by the MFCA evaluation. Some new factors must be considered when the MFCA is used for planning purposes. The ISO standard 14051 mentions that the MFCA can be utilized for planning but does not provide procedures for costs calculations [10].

The alternatives process configurations and technologies may change the flow system and influence the different types of costs (material, energy, system and waste management) and their allocations. Sygulla et al., suggests the following procedure [7], [10]:

1. Categorization of the sub-items;
2. Identification of the cost drivers;
3. Forecasting of the sub-items costs based on the cost drivers.

For the identification and analysis of the costs drivers, a methodical support is provided by the Input-Throughput-Output-Model (ITO-Model) presented by Götze et al. [10]. This subject will be discussed in more detail further in this dissertation.

2.3.1. Energy Flows Analysis

The MFCA methodology should be questioned from a theoretical perspective to evaluate the significance of the results obtained. The main weakness found is related to the lack of knowledge concerning the modelling of energy flows [10]. When the energy costs are allocated under the material flows, the information about the magnitude, consequences and drivers of material losses is neglected, and the appraisal of waste heat or vibrations are ignored. The identification of energy inefficiencies requires the differentiation between desired and undesired energy flows and thus, the energy balance of each process and the efficiency evaluation of every equipment [2].

From an economic and accounting perspective, in the majority of cases, the costs related to the energy consumption are reported as a marginal share of the total production costs. For this reason, the energy use was scarcely questioned in the past [14]. Moreover, the increasing energy prices, energy-related taxes and climate change increasingly require more transparent models to analyse energy consumptions and energy uses [8]. A detailed analysis of internal infrastructures for energy conversion and supply may reveal unknown potentials for cost savings [2].

In opposition, from the ecologic and sustainable point of view, the energy demand is one of the primary drivers to measure the carbon footprint, the most common indicators of the environmental performance [14]. The enhancement of the MFCA methodology regarding the analysis of internal energy flows may contribute to improving material and energy resources, and consequently, the environmental and economic performance of the company [2].

The integration of the energy considerations in the MFCA requires the refinement of the flow structure modelling [10]. The energy flow should be traced and quantified in physical units independently to the material flow, and constitute a Material and Energy Flow Cost Accounting (MEFCA) approach. The general procedure is based on the same steps that MFCA [8]:

1. Modelling the flow structure;
2. Physical quantification of the flows;
3. Monetary quantification of the flows.

During the flow structure modelling, some important considerations must be noted.

On the one hand, the forms of energy are always linked to a material energy carrier. Thus, for some carriers as gas or coal, if the material losses of energy conversion are relevant for the analysis, model the energy flows parallel to a material flow is adequate. On the other hand, for the most common forms of energy used in industry, such as electricity or compressed air, the single trace of energy flows is enough [2].

Moreover, the energy flows are all the energy transmissions between energy-related quantity centres and leave the quantity centres in the form of efficient energy and energy loss. In turn, the efficient energy is used to produce the outgoing products, i.e. goods and material losses. Thus, it must be allocated to the product and the material losses. Consequently, the outgoing material flows are modelled as a joint of material and energy flows. Figure 2-5 exemplifies a simplified flow map example [10].

After that, the energy flows must be quantified. The total amount of energy can be measured with appropriate instruments. However, the output flows in the form of efficient energy and energy loss, will often have to me estimated or calculated by energy balances [2]. To ensure that all the transformations were considered, a balance of the ingoing and outgoing flows should be calculated for each quantity centre [8].

Finally, all the costs associated with the production, from all the categories mentioned before, must be allocated to every material and energy flow described in the flow map. The system costs and the waste management costs are indirect costs that must be allocated firstly to the quantity centres and then to the outgoing flows [8]. The energy is, by definition, quantified in Joule or Watt hour, what will introduce a second non-transferable unit in the MFCA appraisal, raising the necessity of review the allocation criterions [2].

A possible solution is to perform a more detailed analysis of the costs drivers and distinguishing between two types of system costs [8]:

- Material-related system costs: all the expenses incurred by the in-house handling of material flows except for costs of material, energy, energy-related system costs and waste management;
- Energy-related system costs: all the expenses incurred by in-house generation, transformations and transmission of energy, excluding the delivery costs of purchased energies.

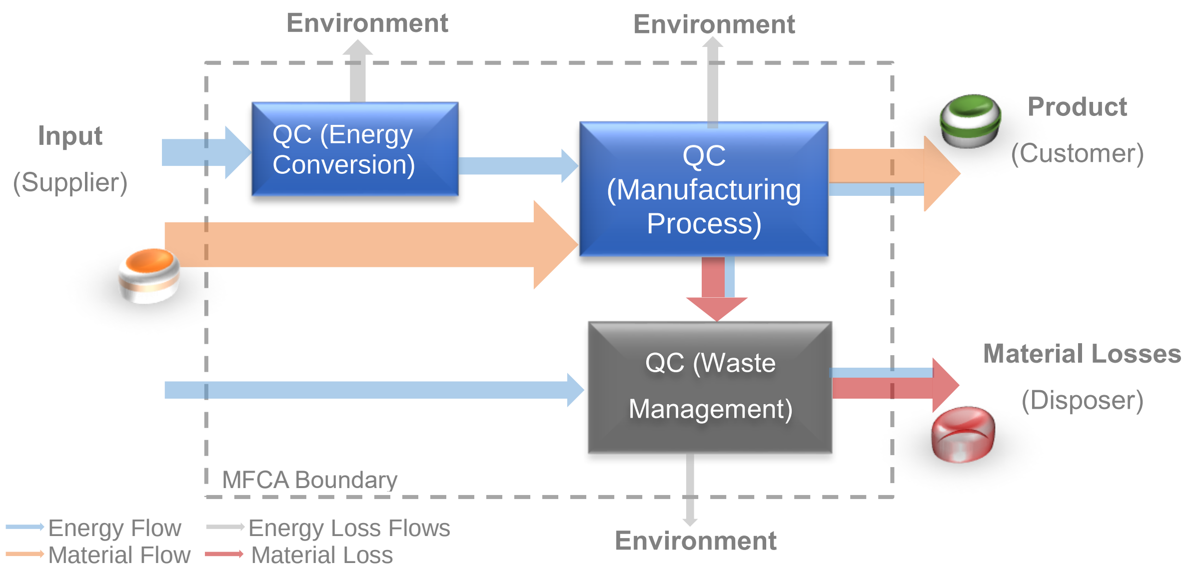


Figure 2-5 Energy and Material Flow Map Example adapted from [10]

Nevertheless, other simpler allocation criterions based on substantial amounts ratios can be applied. One example is the allocation based on the material to energy costs ratios. Furthermore, the quantity centres can be categorised per primitive type of output: energy or material and use the rate of the central physical unit to allocate the costs to the outputs [2].

The results obtained support the appraisal of alternatives process with the enhancement of information about energy use and the possibility of identifying material and energy interdependencies. It supports the improvement of resource efficiency through the highlight of material and energy losses and their financial effect [2]. Withal, the possible benefits of the proposed enhancement depend on the material and energy flows available information and the additional effort to perform the analysis [10]. It is important to note that the MEFCA implementation procedures must be refined. Further researches are required to increase the informative value of energy cost accounting, provide adequate solutions for energy inefficiencies and planning methods to compare alternatives for improving the energy use [8].

The appraisal of the productive system performed in this dissertation, through the MFCA, allocates the energy costs under the material costs. This decision was based on the lack of information about energy flows, the low contribution of the energy costs of the total production costs and the high number of uncertainties that may compromise the significance of the results.

2.3.2. Internal Loops Analysis

In the manufacturing industry, a production unit may include recycling processes, either of the generated scrap or the cutting fluids which lead to material loops. In a first approach, appear economically and ecologically favourable because the amount of input materials and materials to dispose of are reduced. Nevertheless, is important to mention that every material loop is an indication of waste generation and in addition to that a potential starting point for technical improvement. Furthermore, the recycling processes raise additional cost [2].

The challenge of modelling material loops is settled in the interdependency of the material input and output flows and how to appraise the cycle flows. Literature proposes three possible solutions [2]:

1. Calculate the total costs of every material flow;
2. Consider only the additional costs of the material loop;
3. Report the loop costs as an additional costs' category.

The calculation of the total expenses of every material flow entails the simultaneous calculation of the raw material substitute flow and the material loss flow, through the corresponding linear Equation system. The second solution is proposed with the aim of facilitating the first solution appraisal. The particular consideration of the additional costs of the material costs is based on the fact that the material costs of the cycled flows will end up in the output product, thus can be ignored [2].

In opposition to MFCA's philosophy, both solutions assign the loop costs to the material output product and neglect the fact that these expenses are incurred by undesired material flows. Consequently, the material inefficiencies of the process remain invisible. To overcome this issue, Viere et al. suggests to "pull out" the costs of the material loop and to report them as an additional charge [9]. On one hand, it may conflict with MFCA's methodology since the costs of the material flow are pulled out as a cost flow without a physical material cost. On the other hand, evaluates the material loop flows identifying the negative monetary effect of material inefficiencies, which represents the aim of MFCA [2].

Finally, this methodology can also be applied for appraising inventories and solve the problem raised by the stock changes and storing costs [2].

2.4. Application of MFCA in the Supply Chain

MFCA has been developed to be applied to a single organisation; nevertheless, it can be applied to an entire supply chain from the extraction of the resources to the disposal of the products. The enlargement of the application boundary and the extension of the scope to the companies' supply chains will potentially contribute to enhancing the resources efficiency [1].

In a supply chain, the highest material losses, often occur in the manufacturing phases. Beyond the natural reasons related to the manufacturing process, the quality of the materials provided by the supplier and the final product specification required by the client have a significant impact on the amount of waste generated in the entire supply chain [7], [1]. The Ministry of Economy, Trade and Industry, in Japan, from 2008 and 2011 implemented the MFCA in approximately 50 supply chains of different industries with favourable results [1].

The application of the MFCA in a supply chain with the aim of improving the efficiency of the resources requires the collaboration of the partners. To support the implementation and serves as a guide, a new standard ISO 14052 is being developed since May 2014. It will complement the ISO 14051 and help the users that had identified material losses and potentially points of the efficiency enhancement in their supply chain [5].

The primary challenge arises from the necessity of transparency, openness to disclose and discuss topics related to the production process and the cooperation of all the companies along the supply chain. The successful application of the MFCA requires a holistic understanding of the production system, what leads to confidentiality issues regarding sharing technical details and costs information. Both types of information could be misused by one of the partners to take advantage of this knowledge. Furthermore, after the MFCA appraisal, the optimised solutions to increase all efficiency of the supply chain and reduce the material losses, may lead to unequal distributions of the costs and the benefits among the partners [5].

To overcome these difficulties, MFCA experts that are working on the ISO 14052, suggest the settlement of pre-condition requirements and organise the information by type and level of detail for sharing. The different types of information are physical, environmental impact and financial. The degree of detail of shared information may increase with the progress of the project. One essential pre-condition pointed by experts is creating trust in the willingness of all the partners to share the realised benefits. To build trust, a proved success factor is to restrict the sharing of relevant information for the MFCA to the team members in the partnering organisations. The shared information must be exclusively used to reduce material losses and increase the efficiency of the resources in the production system [5].

The application of the MFCA in the supply of a product can start with the collaboration of two companies and from there, grow including more partners upstream and downstream. Hence, ultimately the improvement of the economic and environmental performance is addressed for the entire life cycle of the product [5].

Typically, the Life Cycle Engineering (LCE) is used to support decision-making considering environmental impacts, economic aspects and technical performances [5]. Since the MFCA aims at the enhancement of the economic and ecological efficiency of a product or a process, its extension to the supply chain and its similarities with the LCE raises the hypothesis of integrating both analysis methods.

To better understand the potential benefits of incorporate the MFCA in the LCE, the following sections describe the LCE and the two major approaches used to assess the environmental and economic impacts, the Life Cycle Assessment and the Life Cycle Costs, respectively.

2.5. Life Cycle Engineering

The concept of Life Cycle Engineering is introduced by Alting and Legarth in 1995 as “the art of designing the product life cycle through choices about product concepts, structure, materials, and processes” [15]. It emerges in response to the necessity of considering from the early design phase of a product its entire useful life, causing the lowest environmental impact and offering economic viability [6].

The LCE is a decision support methodology, which assesses technical, economic and environmental performance, considering all the life cycle stages of the product [16], [6]. The integration of these three dimensions provides a solid foundation for decision-making in the design process, development and use [17]. Furthermore, represents the primary characteristic that differentiates the LCE from other life cycle methodologies [6].

Hence, this method enables the development of a study with the purpose of minimising both environmental impact and production associated costs while guarantying technical requirements of a product throughout its useful life [18]. The product’s life cycle includes all the phases, from the raw material acquisition, through production, use, end-of-life treatment, recycling and final disposal [19].

Traditionally, each dimension of the LCE is analysed separately [16]. To perform this evaluation, LCE includes conventional tools, as technical performance analysis, as well as life cycle tools to appraise the environmental and economic performance. Then, the three dimensions are aggregated into a single analysis framework for the global evaluation of the alternatives [6]. Figure 2-6 illustrates an overview of the life cycle engineering model.

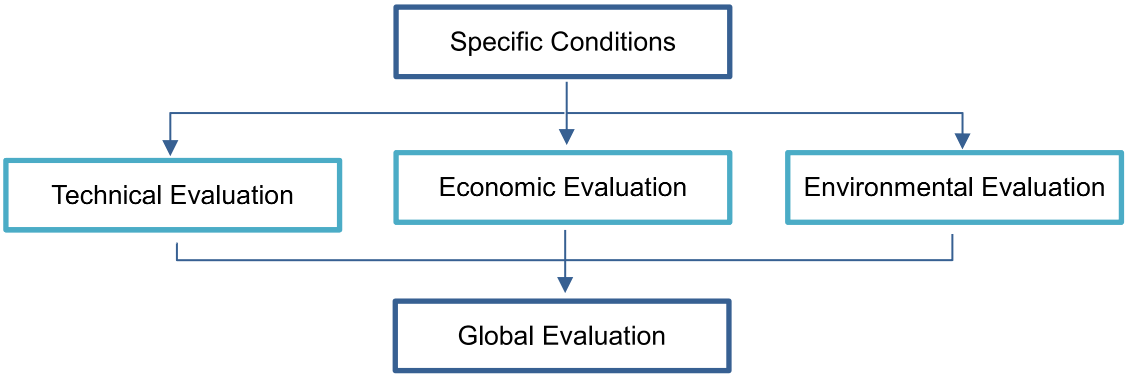


Figure 2-6: Overview of the life cycle engineering model adapted from [6]

There are different proposed methodologies to integrate the three dimensions into a single value [16]. The primary difficulty of this step is related to the materialisation of the relative importance of the three dimensions, describing as close as possible the business strategy of the company and the sensibility of the results. To overcome this issue, Ribeiro et al. propose the development of a ternary diagram, where each axis represents one dimension of analysis [6], [16]. The diagram maps the best solution according to a set of weights, as well as the domain of weights for each best option.

Therefore, the LCE supports the communication between costs, environmental impacts and engineering requirements, allowing the comparison of alternatives on a sustainable and life cycle perspective.

In the context of sustainable decision-making, the most common methods to evaluate the economic and environmental effects of products and production systems throughout their life cycle are the Life Cycle Costs (LCC) and the Life Cycle Assessment (LCA) respectively [4]. Both approaches are presented in the following sections.

2.5.1. Life Cycle Cost

The LCC is a cost management method for the evaluation of all economic consequences and financial trade-offs occurring throughout the life cycle of a product [4].

The LCC analysis is a method of economic evaluation of different alternatives [20]. It assesses the total costs associated with the product's useful life in a cradle-to-grave perspective [16]. Therefore, integrates research and development costs, as well as production, construction, operation, support, retirement, treatment and disposal costs for all the producers, suppliers and customers related to the product [20]. Thus, includes costs often not expressed in the product market price as the costs incurred during the usage and disposal phases [18].

The expenses incurred during the overall life cycle of a product are equal to the sum of the several costs inherent to the successive stages. Each phase includes different types of equipment, consumables, energy, labour, scrape and generated wastes with different costs rates [21].

Nevertheless, this is not a standard analysis, and there are a vast number of approaches with different scopes and methodologies. Greene and Shaw (1990) proposed a guided approach for the LCC analysis, which principles have been used by various authors [22]. Figure 2-7 represents a sequence of general steps.

Figure 2-7: Life Cycle Costs Analysis procedure [22]

Therefore, LCC can be defined as an evaluation and comparison tool, supporting the appraisal of the most cost-effective solution from a set of alternatives [18]. It contributes to cost-oriented decision-making concerning multiple life cycle phases and can be applied to identify primary costs drivers, as well as for product and production technology design and strategies comparisons [4].

2.5.2. Life Cycle Assessment

The LCA is an environmental management technique, which enables the evaluation of potential environmental impacts of a product throughout its life cycle [19], [23]. The Standard ISO 1040 describes the principles and framework for LCA [19], and ISO 1044 specifies the requirements and guidelines for executing the LCA [23].

The LCA analysis aims at the recognition of the life cycle related environmental burdens of a product. It identifies and quantifies the ecological impacts of the processes and resources used throughout the entire life cycle. Therefore, supports the development of ecologically intended improvement measures and the design of eco-friendly products and production processes [4].

The LCA analysis can be divided into four primary phases [24]:

- Definition of the goal and scope of the study;
- Development of a model of the product life cycle, defining all the environmental inflows and outflows, often referred as Life Cycle Inventory (LCI);
- Evaluation of all the inflows and outflows environmental relevance often referred as Life Cycle Impacts Assessment (LCIA);
- Interpretation of the results.

The primary motivation of LCA analysis is the enhancement of the environmental performance through the minimization of the pollution magnitude, conservation of non-renewable resources and ecological systems, development and use of cleaner technologies, improving the efficiency of the resources and reducing the wasteful materials and energy [19].

This method supports the comparison of different designs alternatives for a product; nevertheless, it can also be used to identify opportunities to improve the environmental performance of goods in their life cycle.

2.5.3. MFCA, LCC and LCA integration

The underlying intentions of the LCC and LCA evaluation are different, and thereby their calculation models are addressed to economic or ecological objectives. Thus, even when the LCC and LCA are used as appraisal tools of the same object within the LCE assessment, they are applied in parallel, or with little integrations. However, several similarities can be found between both methods.

On the one hand, LCC and LCA analysis contribute to the identification of favourable alternatives. Their overall objective is largely the same, albeit differing in the addressed dimension, economic or ecological. Thus, the integration of the LCC and LCA results can support the identification of trade-offs between the main purposes of both dimensions [4].

On the other hand, both approaches are based on the modelling of systems, subdividing the life cycle into phases and decomposing the entire system into simpler processes. This requires the data compilation of inputs, outputs, technologies and impacts of influencing factors over time. LCC and LCA integration may reduce the efforts of modelling and data collection, once the modelled systems and the necessary data are similar [4]. Often, this represent the most time-consuming activities in both studies.

Furthermore, a product is often inserted in a complex production system and shares many of the resources with other products; consequently, allocation criterions are required to model the systems and assign accurately the data collected. The application of the same method and a shared database contributes to a standard definition of underlying assumptions and, consequently to develop a consistent basis for the final decision-making [4].

Therefore, in the last several years, researchers attempt to integrate both analysis with the aim of increasing the consistency of their results [25]. In an integrated study, both dimensions should be evaluated in detail based on a common foundation. Thus, economic and ecologic targets should be calculated using mutual goals, scope, life cycle definitions, system models and a widely shared database.

The MFCA, as it was already referred, aims at the improvement of the economic and environmental performance of a company, and provides information about resources consumption and material flows in physical and monetary units. Hence, it is suggested as a potential link between LCC and LCA analysis [4].

The MFCA flow models, structure and data have already been pointed as a starting base for LCA assess since it requires similar primary data [4], [5].

The MFCA concept of separate the value of products and losses can also add a new dimension to the results of LCC and LCA analysis, quantifying and highlighting the contribution of material and energy losses to upstream and downstream processes, physical flows, environmental impacts and costs [26]. Hence, the life cycle economic and ecological performance can also be evaluated concerning losses, providing a deeper comprehension about resources efficiency [4]. Although, this advantage requires new allocation rules to distinguish the contribution of each flow to the total result, and implicates new challenges for modelling and quantifying the life cycles of a product [4], [26].

Nevertheless, its application improves considerations of inefficiencies, and the consequent identification of target points to reduce the losses, thereby reducing environmental impacts and enhancing economic performance throughout the life cycle of the product [4], [26].

Moreover, if the MFCA is used for modelling the life cycle flow and quantify it to perform both appraisals, also contributes to the development of a shared database and criterions for the assignment of economic and ecological effects, thereby increasing the consistency of the results. However, this requires the extension of the MFCA scope to the life cycle, to compute the environmental dimension to the appraisal step, to adapt the calculation units and to model future states [4]. Though, this extension supports the harmonisation of the system models, stabilising a common database. It also increases the relevance of LCA and LCC results for business decision-making.

Thus, it is possible to conclude that MFCA components enable the calculation of material and energy flows, flow properties, components and stocks for a given time [27]. This data can be used to perform life cycle assessment and cost accounting evaluation, pointing the MFCA as a potential instrument to integrate LCA and LCC analysis. However, an integrated calculation procedure should be developed for the determination of all relevant variables related to environmental impacts and cost accounting instruments based on a single material and energy flow model.

3. Case study and Approach

The primary objective of the present dissertation consists in the analysis of the MFCA applicability to the design phase of a product or a process and subsequently, the integration of the MFCA in the life cycle engineering.

To achieve the proposed goals, the present work was partially developed in an industrial environment to perform the MFCA analysis and collect the necessary data to develop MFCA calculation model and flow map.

The following sections describe the industrial framework of the company and the approach followed to develop of the present dissertation.

3.1. The Industrial Framework and Case-Study

This section describes the industrial framework of the Company, the product used as a case-study and the production system characteristics. Due to a confidential agreement, the name of the company is not mentioned, and the real product cannot be described; therefore, a product similar to the case study's real product will be presented. At the end of the section, a brief description of the injection moulding process is presented to provide a more comprehensive understanding of the production process analysed.

3.1.1. The industrial framework

The Company where the present work was partially developed started as a family business of manufacturing parts and elements of moulds. The Company was founded at the end of 80's as a moulding manufacturing company, producing moulds of small and medium dimensions. Around the year 2000, the Company expanded his business and incorporated a Plastic Injection Moulding production division. At present, the Company Group integrates several business units.

The work for this dissertation was developed in the Plastic Injection Moulding business unit. It integrates 36 injection machines and nearly 150 employees. It is specialised in the thermoplastic injection of parts for a wide range of industries, such as electronics, automotive, electrical and food industry. It has bi-material injection machines and machines with robotic arms to produce parts with metal inserts. To complement the injection moulding process, the company provides assembly and packing units, artificial visual monitoring and quality control systems, and laser engraving.

3.1.2. The Case-study Product

The Product used as a case-study for this dissertation is composed of two parts, Part A and Part B. Both parts, are produced separately through the plastic injection moulding process. Figure 3-1 as it was referred, due to a confidentiality agreement, illustrate two parts similar to the case-study real parts. The material injected to produce the parts is polypropylene (PP), one of the most common thermoplastics processed in injection moulding [28]. Bellow, Table 3-2 describes the general dimensions and characteristics of both parts.

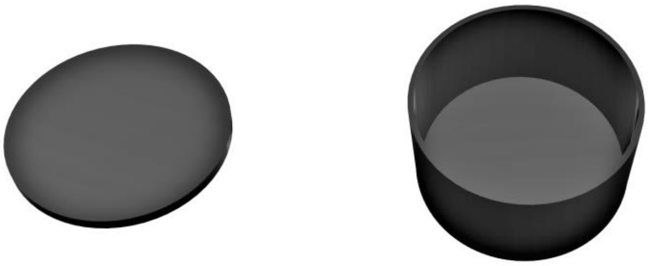


Figure 3-1: Left: Part similar to Part A; Right: Part similar to Part B

Table 3-1: General dimensions of the case-study's similar parts

	Maximum thickness [mm]	Projected Area [mm]	Volume [mm^3]	Weight [g]
Part A	1,50	1 140	2 275	2,35
Part B	1,25	1 206	4 012	4,20

3.1.3. The productive system characterization

The Product studied for the present work has an independent production line within the Company Injection Moulding installations with particular characteristics and configurations. It is characterised for being a continuous production line, i.e. a daily non-stop production. In oppositions to the other productions of the company, it has dedicated machines and employees.

To provide an overview of the entire production system and to the easy understanding of the production flows, a step by step description is presented in Figure 3-2. It illustrates the major productive activities involved in the manufacture of each components of the Product. The production flow of both parts is similar, involving the same main steps.

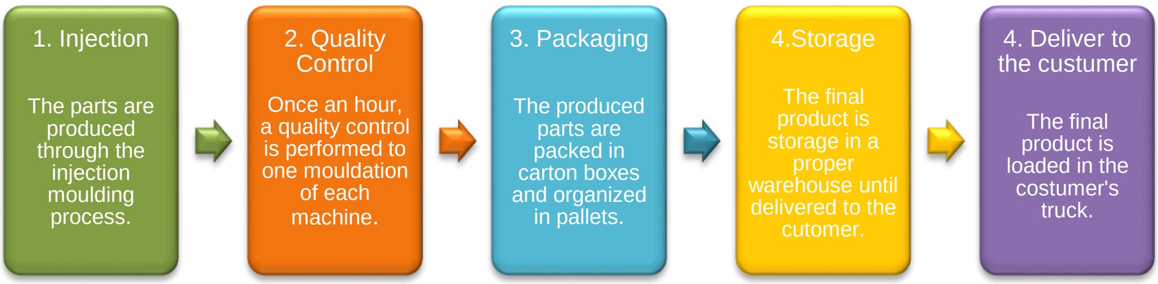


Figure 3-2: Main productive activities of each part production system

Consequently, the productive system is organised in the following areas:

- Raw Material Warehouse: is the warehouse where the raw materials needed for the injection moulding are storage and is located, one floor below the rest of the areas. There is a warehouse worker, not dedicate to its productive system, responsible for receiving and organising the materials;
- Shredding Zone: it is a particular area located in the Raw Material Warehouse where the rejected and the defective parts are stored and shredded. It has its dedicated worker;
- Injection: it is the zone where the injection machines are located, and consequently, where the parts are produced. There are six injection machines, three to produce the Part A and three to produce the Part B, organised in pairs. There are two pairs of moulds of 32 cavities and one pair of 16 cavities;
- Packaging: it is the area near the injection zone where the produced parts are packaged and organised in pallets;
- Quality Control: it is a specific area of the production system near the injection zone where the quality control tests are performed;
- Final Product Warehouse: is the warehouse where the pallets that contain the parts packaged are palletized and storage until being delivered to the client. This work is performed by the dedicated employees of this warehouse. The workers are organised in three shifts of eight hours per day, with one dedicated employee per shift;
- Plastic Collection Area: is the zone where the material discharges and contaminated parts are stored before being sold.

The support equipment, such as forklifts, stackers, palletizing machines and grinding machines, are not dedicated to a production unit. They are used by all the production processes of the company. Thus, their utilisation time and costs will be, further, appropriately allocated.

The dedicated employees due to the continuous character of the production system, are organised in three shifts. Each shift has one team leader responsible for the production and the coordination of four employees. The main tasks of both types of workers are described in Table 3-2.

Table 3-2: Main identified tasks of the productive system dedicated workers

Team Leader	Change the raw material's Big Bags perform the injection machines maintenance, coordinate the team, control and solve problems and coordinate the shift change.
Dedicated Employee	Check the big bags of raw material, perform the quality control tests, package the parts, check the cycle time and the size of pillow of the injection machines.

The proper characterization of the production system is fundamental for the successful application of the MFCA methodology. It is also important to understand the phases of the manufacturing process to assure the identification of all the material flows. Next, the injection moulding process is described.

3.1.4. Injection Moulding Process

The injection moulding process is one of the most common techniques for manufacturing plastic parts, enabling the production of complex parts, multicolour products, multi-components, hollow, macro and micro products as well as the production of several identical or different parts in the same cycle [31]. It is used for mass production through moulds and the application of heat and pressure [33].

The injection moulding process was first developed in the late 1800s to produce simple objects. Later, in 1946, James Hendry revolutionised the plastic manufacturing industry building the first screw injection moulding machines with an auger design, which still is the technique used by most injection machines nowadays [32].

The following Figure 3-3, describes the main stages by which the injected material passes during the injection moulding process [33].

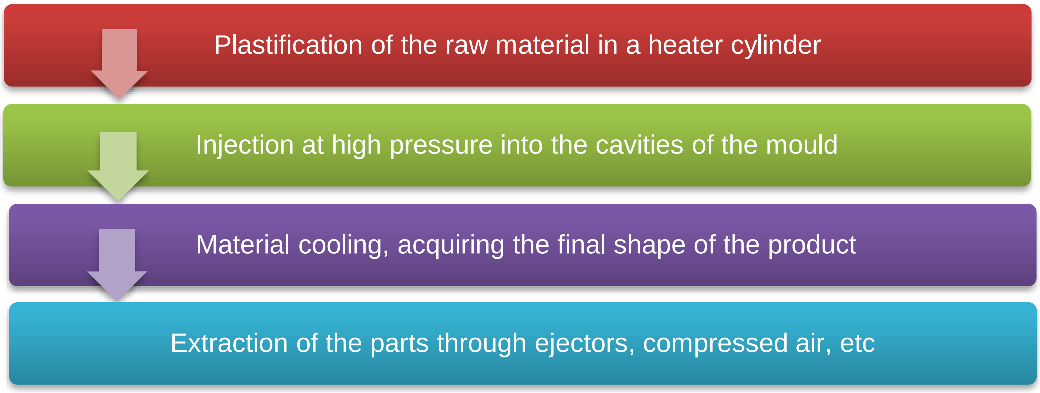


Figure 3-3: Description of the Injection Moulding Process

The raw material, often in the form of plastic pellets or powder, is fed into a hopper and from there to a heater cylinder. In the heater cylinder is melted into a viscous fluid. When the material reaches a certain temperature, the screw inside the cylinder starts rotating mixing the material, moving it forward and injecting the material into the mould. When 95-99% of the mould's cavities volume is fulfilled, the screw maintains a predetermined pressure during a defined period, allowing the material to solidify in the cavities without receding to the cylinder. The mould contains a cooling system composed by channels where cooling liquids, often water or oil, flow, cooling the mould and the parts. When a certain temperature is reached, the final parts are ejected from the mould through a set of ejectors pins, or a compressed air system among other techniques. The extraction temperature is controlled by the time that the material remains in the mould and depends on the material, the thickness of the part, the cooling fluid and the design of the cooling system. After the ejection of the part, the mould is closed and the process is repeated to produce a new set of components [33].

The entire process described is commonly designated as moulding cycle [39]. The cycle time is one of the most important parameters in injection moulding. Not only because it determines the necessary time to produce a set of parts, but the quality of the parts depends on it [36].

From the injection machine's perspective, the cycle can be decomposed in five subsequent events: filling, packing and holding, part cooling, opening and ejection of the part and closing the mould. The time distribution typically required for each step is represented in Figure 3-4 [39].

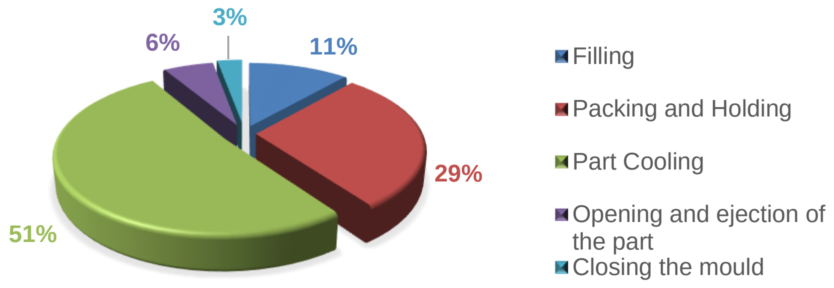


Figure 3-4: Typical time distribution of the injection moulding cycle

The injection moulding process requires several system elements: the mould, the injection moulding machine, devices for regulating the mould temperature and additional components, e.g. dryers and robots that should be carefully designed and selected [31].

The mould is the main tool of the injection moulding process, typically constituted by two parts: core and cavity. It is a sophisticated device that should be properly designed, operated and maintained [34]. Often, is made of stainless steel or aluminium [35]. It can have one or multi-cavities that can be identical or different. Furthermore, both types can include inserts, often metallic, with which the plastic will bond and form the final part [31].

Apart from the cooling system already referred, the mould also contains a feeding system responsible for the filling process. There are two types of feeding systems: cold runners and hot runners [33]. On the one hand, in the cold runners' system, the material inside the feeding system is cooled and ejected along with the part. The system is composed by the gate, the runners and the sprue. This type of system is simpler and cheaper. On the other hand, in the hot runners' system, the runner is inside the mould and is kept at a temperature above the melting point of the plastic. Thus, the material remains melted, allowing the elimination of the runners' material loss, the reduction of the cooling time, and thereby the reduction of the entire cycle time. This system is specially used in high production, with moulds with diverse cavities to avoid excessive material expenses and in high-quality products due to the minimal vestiges left by this system. However, is more complex and expensive [37]. The production process studied in this dissertation uses a hot runners' system for the reasons listed above.

The injection moulding machines have different configurations, horizontal and vertical in concordance with the injection position, and distinct components. Regardless the configurations, both types, are composed by the following units [34]:

- Injection unit: promotes the transport, heating, melting, injection and packing of the material;
- Clamping unit: guarantees the attachment and movement of the mould and should keep it close during the filling and holding stages;
- Control unit: includes the devices to ensure and monitor the variables in the process;
- Power unit: provides the adequate power to the different actuators.

Depending on the driving system used, the injection machines can be classified into three groups: all-hydraulic, all-electrical and hybrid machines [24]. The last types combine hydraulic and electric devices. The all-electrical machines allow energy savings from 30 to 70%, higher injection speeds and clamp motions, as well as faster start-ups, shorter stabilization times and 20% faster cycles due to the ability of overlap the screw recovery and clamp movements. It also increases the precision and repeatability due to higher positioning accuracy, and avoids cleaning oils allowing cleaner operations and lower maintenances [38]. The energy savings represent the principal advantage of these machines and the main driver for its purchase.

The case-study production system has five electric machines and one hybrid machine. In Chapter 5, when several production scenarios are compared, the impact of using electric or hydraulic machines to produce the parts is studied.

3.2. Approach

The developed work aims to meet the initial goals of the thesis by proposing some enhancements to the original MFCA methodology, allowing the appraisal of future states. The proposed modifications intend to extend the MFCA scope to the design phase and its integration as a tool of decision-making in the LCE of a product or a process. Figure 3-5 describes the approach followed.

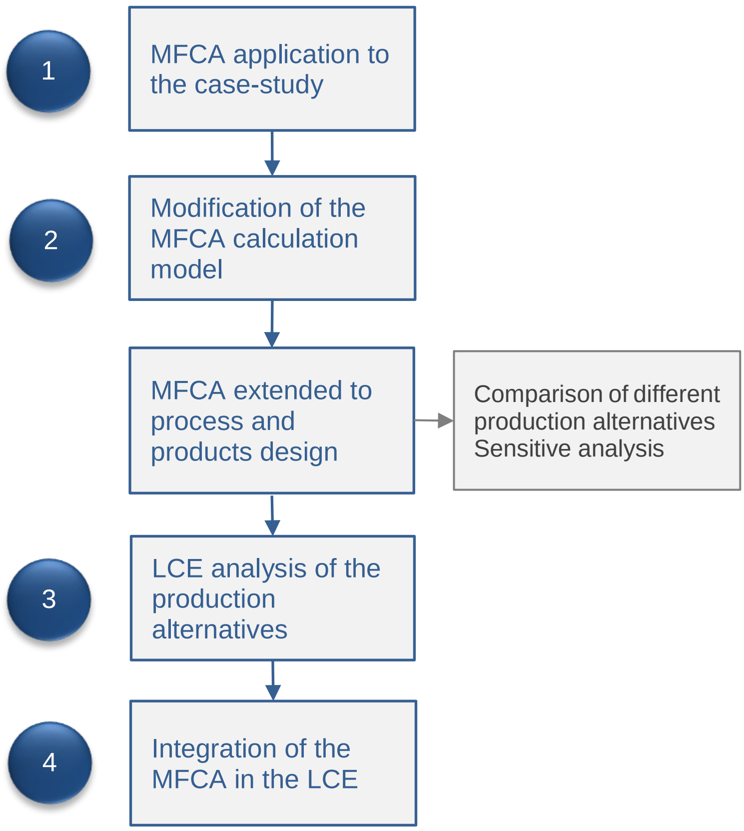


Figure 3-5: Approach followed in the present dissertation

The first phase consists in the application of the MFCA to the Product's production process described above. The application of the MFCA methodology requires the characterization of the production system and the compilation of the necessary data to quantify in physical and monetary units the material flows for develop the calculation model and perform the analysis. Consequently, it was necessary the physical presence in the Company Group for three months. The results quantify the material losses of the production system, helping the company to understand their monetary value and identify the main sources of loss. Furthermore, it also contributes to recognise other inefficiencies in the production system and potential improvements. The results and the corresponding methodology are described in the following Chapter 4.

The MFCA application allows the identification of inherent limitation and weakness of the methodology to be used as an appraisal tool in the design phase of a product. These restrictions are mainly related to the fact that it evaluates the process as-is state and design decision-making require the appraisal of future states. Some modifications to the original model are proposed, as well as the development of a Process Based Model, to enhance it for the assessment of future states. To analyse the practicability of the new calculation model, several production alternatives are compared through the MFCA methodology. Moreover, to verify its dynamic character, two sensitive analysis are performed: of the production volume and of the product lifetime.

Then, the economic and the environmental impacts of the different alternatives are analysed in a life cycle perspective. The life cycle analysis includes the appraisal of the production and then end of life phases, through the MFCA methodology or using the information extracted from it. This allows the creation of a common database use to evaluate the environmental and the economic performance and improve the significance of the results comparison.

Finally, in the last phase, the applicability of the MFCA as a tool of the LCE is discussed and an integration methodology is proposed. This represents the ultimate goal of the presented work.

4. MFCA methodology application

The MFCA methodology is applied to the production system of the Product to appraise its current performance in economic and environmental terms. This Chapter describes the methodology followed for the application of the MFCA, the calculation model developed for the production evaluation, as well as the obtained results. Furthermore, the MFCA also helps to identify inefficiencies in the production system; thus, after the analysis of the results, some enhancements are suggested.

4.1. Case-study characterisation

As the MFCA methodology suggests, the first step should be the characterization of the system to clearly define the company's sector where the implementation of the tool will occur, the following three parameters should be determined:

- The boundary conditions;
- The analysis and data collection period;
- Quantity centres.

To define the analysis frontiers a full understanding of the entire production system and the departments involved in it is required. Since the product is entirely produced by the company, the analysis should include all the activities related to the manufacture of the part. Therefore, the boundaries are defined at the limits of the manufacturing process of the Product, including all the operations and departments involved in it.

Furthermore, the period selected to compile meaningful information is one month. After the definition of the boundaries of the analysis and the data collection period, the quantity centres should be determined.

4.1.1. Quantity Centres determination

To determine the quantity centres, it is necessary to identify and characterise all the activities and processes that occur during the production, including non-value adding activities and the ones that contribute to the value creation, within the boundaries of the analysis.

To facilitate the activities recognition procedure, the production system is analysed by its organisational areas: raw material warehouse, injection and adjacent areas, final product warehouse, shredding area and plastic's collection area. The main activities of each zone are described in *Annex B -*.

The quantity centres should divide the production system in process or parts to further calculate and analyse their inputs and outputs. Subsequent processes that do not produce material losses or have any important variable should be integrated in a single quantity centre. Thus, the quantity centre can be determined on the basis of the operations identified in each zone and the analysis of the materials movements through the entire manufacturing process, within the boundaries conditions.

Figure 4-1 illustrates a material flow map where all the quantity centres are identified, as well as the material movements.

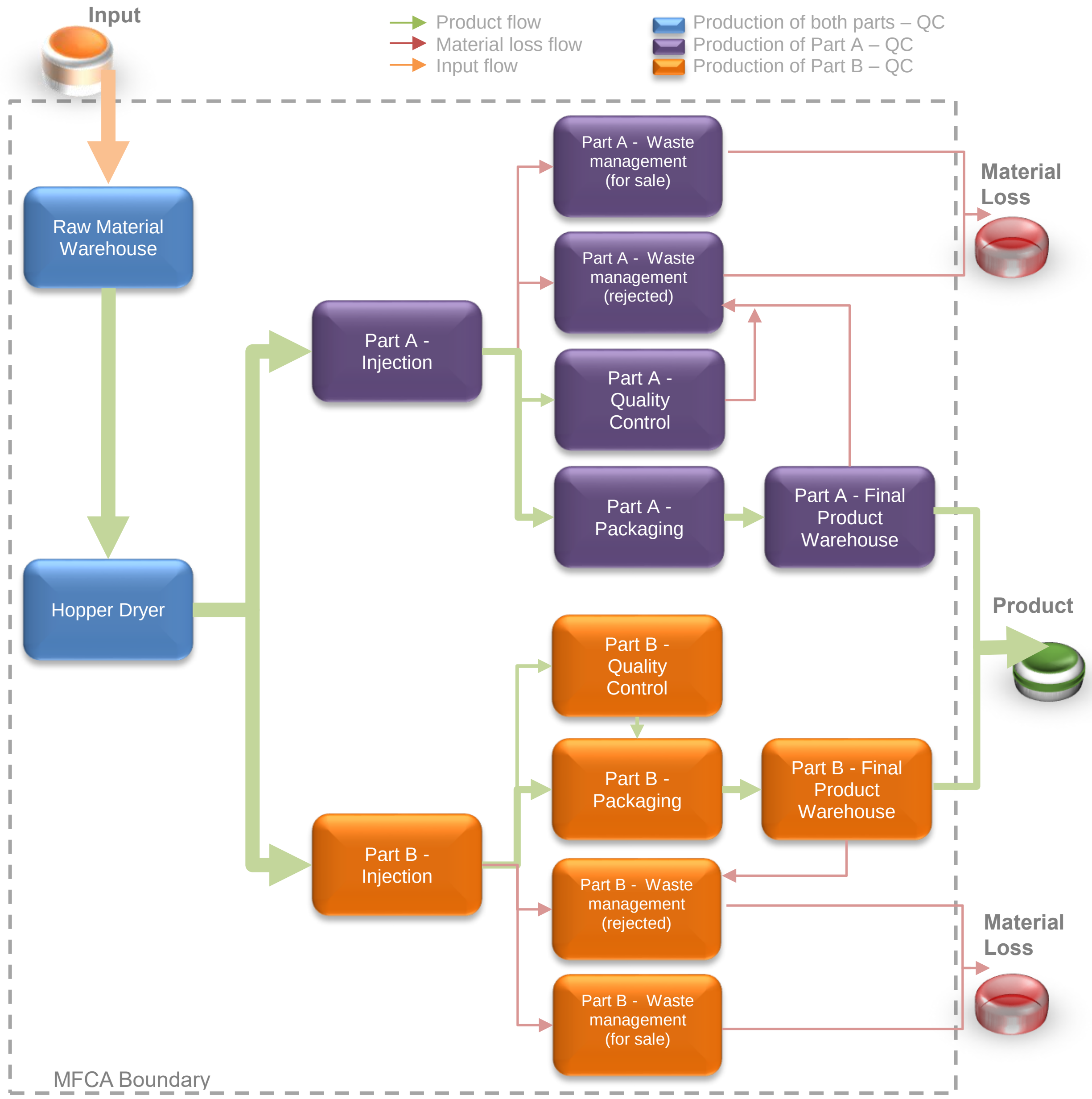


Figure 4-1: Material Flow Map

4.2. Material flows quantification

Once defined the MFCA quantity centres, their inputs and outputs should be quantified in physical and monetary units. As mentioned before, the energy and the energy losses are included under the material and the material losses respectively. Therefore, the inputs are material flows and the outputs are products and material losses flows.

To quantify the inputs and outputs flows the approach used follows a three steps procedure:

1. Identification and classification of all the materials;
2. Data compilation to quantify the flows in physical units;
3. Quantification in monetary units.

4.2.1. Identification and Classification of Materials

There are two types of materials:

- Materials that are intended to became part of a product, as raw materials or auxiliary materials;
- Operating materials: materials that do not become part of goods.

The overall system has only one input material, polypropylene, used by the injection moulding process to produce both parts of the product. The raw material follows a sequence of processes until being transformed into finished products. Throughout the processes, there are material losses that are further treated in waste management quantity centres. The polypropylene material losses are:

- Discharges of material after step-up maintenance and non-programmed stops;
- Off-specification components produced after maintenance step-up and non-programmed stops;
- Destroyed parts due to the destructive quality control test performed to Part A;
- Contaminated parts;
- Returned components from the customer;

The designated operating materials are outlined in the Table 4-1, however a more detailed description can be consulted in *Annex A -.* They are respectively allocated to the quantity centre where are consumed and to the output flow they are related to.

Table 4-1: Operating materials

Quantity Centre	Operating material and corresponded output flow
Part A – Injection Part B – Injection	Materials used for the injection machine maintenance, like alcohol and cleaning solvents. Their cost is assigned to the material losses output flow.
Part A – Packaging Part B – Packaging	Carton boxes, plastic bags and pallets used to package the produced parts. Their cost is entirely assigned to the product output flow.
Part A – Final product warehouse Part B – Final product warehouse	Palletizing film used to palletize the final product boxes. Its cost is assigned to the product output flow.

4.2.2. Data compilation methodology

After identifying the material inputs and outputs of each quantity centre, each flow is quantified in physical units. In *Annex B -* can be consulted the list of quantity centres and their correspondent inputs and outputs. The unit selected for this analysis is the mass unit. The operating materials are quantified in units of products, e.g. the number of boxes, the number of alcohol bottled, etc., instead of mass units as the raw material due to accounting facilitate reasons.

The data compilation, together with the definition of the allocation criterions, directly influences the significance and the accuracy of the MFCA results. Thus, the methodology followed, and the applied techniques should be carefully selected. It also represents one of the phases that require more effort and the collaboration of different personnel and departments. Therefore, an adequate ratio between the required accuracy and the necessary effort should be found.

In some quantity centres, the direct quantification of the input and output materials is not possible. In those cases, the amount of material that enters and leaves the quantity centre must be estimated and calculated indirectly through the Production Calculation Model developed for this purpose. It is further described in the end of this section. The Calculation Model estimates the production volume and the material consumed to produce the Product. To validate the results, the amounts obtained should be compared against the overall production records of the Company.

The input and output flows, as well as the applied compilation technique, are presented in *Annex B -*. The procedure developed to compile the necessary data to quantify the inputs and outputs is listed in Figure 4-2 and explained in more detail bellow.

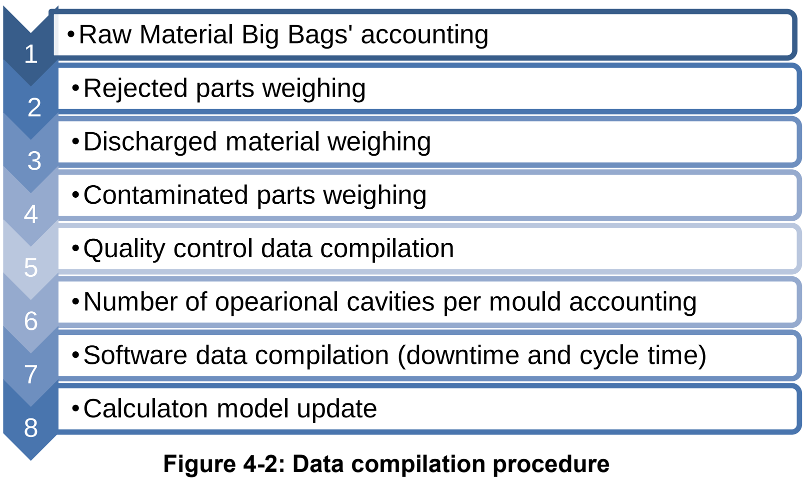


Figure 4-2: Data compilation procedure

The first step consists in the accounting of raw material Big Bags consumed per day. It is assumed that all the raw material consumed is injected in the machines to produce the parts; consequently, the material losses between the raw material warehouse and the injection machines are null.

The followed three steps are related to the quantification of the material losses associated with the injection moulding process: rejected parts, contaminated parts and material discharges after long stops. The major difficulty found to quantify these losses was due to the fact that the material losses of this particular system are storage and treated together with the wastes of other productions. Thus, to be able to quantify them, the workers stored the three types of losses separately during the compilation period. The sum of these three types of material losses represents the material loss output flow of the Injection quantity centre of Part A and Part B respectively.

The Quality Control test is performed to a sample of units equivalent to a shot of parts per hour of each injection machine. The number of tested components per day is extracted from the quality control records. The components tested of Part A are entirely assigned to the material losses flow due to the destructive character of the quality control test. In opposition, the controlled components of Part B are stored for six months and then, delivered to the customer with the other produced parts.

Since the number of operational cavities per mould was not constant, they should be accounted every day. This value is further introduced in the Production Calculation Model, together with the cycle time and the down time compiled in step 7, to estimate the number of produced components per day.

Finally, all the values must be introduced in the Production Calculation Model developed. It aims at the estimation of the daily production volume and the material consumption by each part of the product, Figure 4-3. The approach followed through its development is described below.

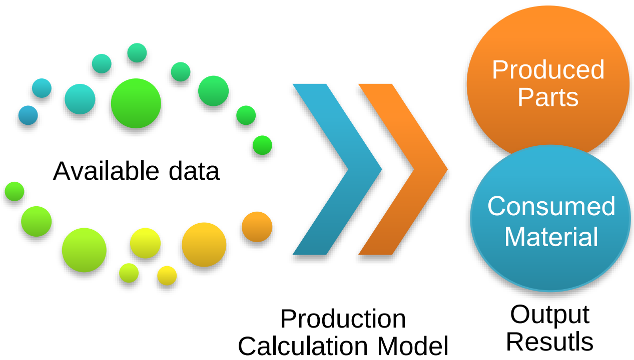


Figure 4-3: illustrative approach followed to quantify the produced parts and the material consumption

The software programme that controls the production system records the instantaneous cycle time, the machines' downtimes and consequently, the number of produced parts per injection machine. However, some cavities of the moulds are inoperable. Thus, this accounting procedure could lead to inaccuracies. Nevertheless, the knowledge of the cycle time and the downtime, together with the quality records and the different identified and quantified material losses, allowed the development of a calculation model that sought in the calculation of the number of produced parts to be delivered to the customer (Equation 4.3), and the amount of consumed material (Equation 4.4).

$$t_{production} = 24 - Downtime\ [h] \tag{4.1}$$

$$n_{produced} = \frac{t_{production}}{t_{cycle}} \times n_{cavities} \tag{4.2}$$

$$n_{goodparts} = n_{produced} - n_{rejected} - n_{contaminated} - n_{qualitycontrol} \tag{4.3}$$

$$material_{consumed} = n_{produced} \times part_{weight} + material_{discharged} \tag{4.4}$$

Where the $t_{production}$ is the production time, t_{cycle} the cycle time, $n_{cavities}$ the number of operational cavities of the mould and $n_{produced}, n_{goodpart}, n_{rejected}, n_{contaminated}, n_{qualitycontrol}$ are the number of produced, delivered to the customer, rejected, contaminated and tested parts, respectively. The $material_{consumed}$ and $m_{discharged}$ represents the amount of consumed material and the amount of discharged material, and finally, the $part_{weight}$ is the weight of each part.

The accounting of the produced parts, allows the calculation of the number of boxes, plastic bags, pallets and palletizing film consumed per day and per component of the Product, assuming that the operating materials wasted units for deterioration or misuse can be neglected.

This calculation must be performed every day during the data compilation period. At the end of the collection period, results must be compared against the raw material consumption observed and accounted, the logistic records and the stocks records. The logistic records provide information about the number of pallets delivered to the customer and consequently, about the material consumed to produce those parts and the operating materials needed to package them. In turn, the stock records provide information about the tonnes of material consumed and stored in the warehouse and the number of produced pallets that are still stored at the final product warehouse. Furthermore, it also helps to validate the operating materials consumption during the analysis period. The compatibility of the results and conclusions allows the validation of the calculation model and the material flows quantification in the respective quantity centres.

There are four types of maintenance: shiftily, weekly, monthly and annual. Each requires different times, number of workers and operating materials. The exact accounting of the operating materials consumed during the maintenance is difficult to estimate because depends on various aspects, such as the machine conditions and the operator that is performing the maintenance. Therefore, in a first approach, several shiftily maintenances performed by different team leaders were observed to estimate the materials consumption. Additionally, some interviews were conducted to understand the employees' perception of the consumed operating materials. Together with the maintenance responsible and the stock records the operating materials consumed in each type of maintenance were finally estimated.

In the end, to verify and complete this step, a material balance is performed to each quantity centre and to the overall system to confirm all the compiled information. The total amount of inputs, considering the inventory changes, must be equal to the outputs. Once confirmed the material balances, the next and final step must be performed, material flows quantification in monetary units.

4.2.3. Material flows quantification in monetary units

For each quantity centre, the production costs for inputs and outputs must be quantified. The manufacturing process costs are all monetary values of resources consumed to perform activities. Thus, any costs that are generated by or associated with the material flows should be quantified and attributed to the output flows, products and material losses. If it is possible to calculate the cost from available data for individual quantity centres and single material flows the cost must be directly assigned. Otherwise, the cost should be estimated by cost allocation procedures [7].

As it was defined in Chapter 2, there are four types of costs: material, energy, waste management costs and system costs. The only waste management costs identified in this production system are related to the waste management quantity centres.

4.2.4. Energy and Material Costs

The material costs for each input and output flow are quantified using Equation (4.5) over the time chosen for the analysis.

$$Material_{costs} = Physical_{amount} \times Cost/unit \tag{4.5}$$

The energy costs are allocated to the material costs, i.e. the energy consumed in each quantity centre should be measured and then quantified in monetary units and assign to the output flows in the proportion of the mass ratio between the products and the material losses.

First, in each quantity centre are identified the equipment that consumes energy. Then, the average power consumption by equipment is measured using a PROVA 6830 power and harmonic analyser. It allows the semi-continuous monitoring of active power, reactive power, tension and intensity for the three phases and the neutral phase, as well as the monitoring of the angle between the phases. Finally, the energy consumed and the energy costs are calculated by Equation (4.6) and Equation (4.7) respectively, where $Power_{average}$ is the averaged power measured by the equipment in kilowatts, $h_{working}$ are the hours that the machines are working, and $Price_{energy}$ is the price of the contracted electricity by the company in euros per kilowatt hour.

$$Energy_{consumed} = Power_{average} \times h_{working} \tag{4.6}$$

$$Energy_{costs} = Energy_{consumed} \times Price_{energy} \tag{4.7}$$

4.2.4.1. System costs determination and allocation criterion

The system costs, as referred previously, are the costs incurred during in-house handling of material regardless material, energy and waste management costs [8]. Often, are available only for the entire process or facility; hence, is necessary to determine appropriate allocation criterions.

In this production unit, the identified, quantified and allocated system costs can be categorised into three types: labour, equipment and space. Furthermore, two more types can be added to the analysis: semi-direct costs and structure costs. The semi-direct costs are the costs incurred by the departments related to the production system, such as the logistic and the engineering department, but that are not directly linked to the daily production; however, can be directly assigned to a quantity centre. The structure costs are the costs caused by the departments of the organisation framework, as the administration, human resources department, financial department, etc.

Figure 4-4 describes the approach followed to allocate the different types of system costs to the output flows, illustrating the procedure for a generic Quantity Centre 1. The same procedure is applied to all the quantity centres identified in the MFCA analysis.

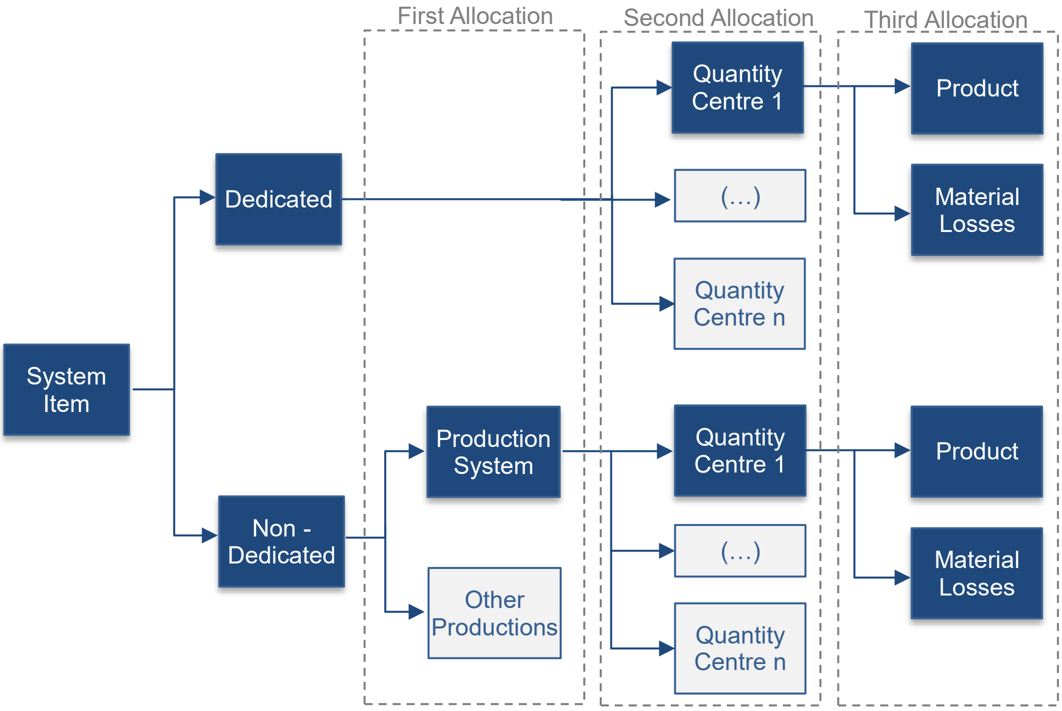


Figure 4-4: Procedure to allocate the system costs to the Output flows

Prior to the allocation procedure the system costs must be categorised in dedicated or non-dedicated items. The dedicated items are exclusively related to the processes of this production system. In opposition, the non-dedicated items are associated to other production lines. Thus, the first allocation step, consists in the allocation of the non-dedicated system costs to the production system in analysis through an appropriate criterion. Then, once all the costs are identified, should be allocated to each quantity centre. Finally, they must be assigned to every output flow.

In the present dissertation, the criterion selected to the third allocation step, assignment of the costs to the output flows, is based on the mass ratio between the product and the material loss flow of each quantity centre for all the different types of system costs. The first and second allocation criterions selected for the labour, space and equipment costs are described below.

The labour costs include the costs of all the employees that intervene in the production process. The costs of the non-dedicated employees are assigned to the present production system using a time criterion. The same rule is used to allocated the costs to each quantity centre. Therefore, the labour costs assigned to one quantity centre are calculated using Equation (4.8), where $t_{employee-n}$ is the time spent by each employee executing the activities related to that quantity centre, $cost_{employee-n}$ is the worker cost per hour and $N_{employees-n}$ is the number of employees executing that activity.

$$Labour_{costs-\,QC} = \sum_{n=1} (t_{employee-n} \times cost_{employee-n} \times N_{employees-n}) \qquad (4.8)$$

To obtain a significant and accurate time distribution, the following approach is used:

1. Identification of the main tasks performed by each type of worker;
2. Association of the identified activities to the respective quantity centre;
3. Accountment of the time required to execute each task.

A detailed description of all the employees that intervene in the manufacturing of the Product, together with their corresponded activities and allocation results can be consulted in *Annex C -.*

The space costs are allocated to each quantity centre based on their boundaries, i.e. the space required to execute all the activities related to it and the space occupied by its associated equipment. Therefore, the space costs of the facilities entire rent are allocated to one quantity centre using Equation (4.9).

$$Space_{costs-QC} = \frac{Space_{QC}}{Space_{total}} \times Rent_{facility} \tag{4.9}$$

Regarding the equipment costs, to allocate the non-dedicated equipment to the production system in analysis it is used the ratio described in Equation (4.10). $Production\ Volume_{component}$ represents the production volume of the Product, Part A or Part B depending if the quantity centre is related to the manufacture of both parts, Part A or Part B respectively. This criterion is selected because most of the support equipment, non-dedicated, are stopped part of the production time. During that period, they are not being used to support any process. Hence, they are not allocated to any production system. However, they also have an associated cost during that time. For that reason, together with the assumption that the utilisation rate of non-dedicated equipment by a manufacturing process is proportional to its production volume, an allocation rule based on the production volume is selected. Subsequently, together with the dedicated equipment costs, they are assigned to the quantity centre where they are used.

$$Aequipment_{non-dedicated} = \frac{Production\ Volume_{component}}{Production\ Volume_{total}} \tag{4.10}$$

A list of the equipment used to manufacture both components, as well as the allocation results, can be consulted in *Annex C -.*

4.3. Development of the MFCA calculation model

The evaluation of a decision in a company often involves financial considerations [7]. Therefore, the MFCA methodology points the necessity of converting the material flows physical information into monetary units to support decision-making. Thus, once all the costs associated with the manufacturing process are identified and quantified, a calculation model must be developed to appraise that information.

The calculation model should integrate the information about the costs data and material flows to assess the economic performance of the production system. It should characterise economically each quantity centre incorporating all the expenses related to previous quantity centre, material, energy and other costs incurred during inside handling of material.

The production system analysed in the present work is characterised for being constant and regular without variations during the year. Hence, the compiled information of one month of production can be extrapolated to twelve months, allowing the annual analysis of the production system performance.

Moreover, the development of the model is based on the next procedure:

1. Calculation of the input costs from previous quantity centres, following the material movements;
2. Assignment of the material and operating materials flows to the quantity centre and then, to the output flows;
3. Calculation of the materials and operating materials costs;
4. Calculation of any stock variance in the quantity centre;
5. Assignment of the energy and system costs to the quantity centre through the defined allocation criterions;
6. Calculation of the allocation rates to assign energy and system costs to the output flows;
7. Assignment of energy and system costs to the correspondent output flow;
8. Calculation of the total expenses incurred in the quantity centre;
9. Calculation of the product and material losses costs.

The calculation model should be developed from the quantity centre where the production begins, Raw Material Warehouse and subsequently, following the material movements. The steps described above must be repeated for each quantity centre.

Table 4-2, depicts the calculation model of one quantity centre, Part A – Injection. It illustrates the three calculation sections: input, quantity centre and output costs, as well as all the variables that should be considered.

Table 4-2: Example of the calculation model developed (Part A - Injection quantity centre)

Input Costs	Cost [k€]			
Inputs from previous quantity centres	935,6	k€		
New material inputs	-	k€		
New operating material inputs	10	k€		
Quantity Centre Costs				
Stock Costs				
Initial Stock	0,04	k€		
Final Stock	0,04	k€		
Stock Costs	-	k€		
Energy Costs		k€		
Injection machines	21,8	k€		
Chiller	9,8	k€		
System Costs		k€		
Labour	47,9	k€		
Space	10,7	k€		
Equipment	214,6	k€		
Waste management	-	k€		
Output Costs	Total Costs [k€]		Product Flow	Material losses flow

Output Costs	Total Costs [k€]		Product Flow			Material losses flow		
			%	Cost [k€]		%	Cost [k€]	
Previous quantity centre	935,6	k€	98%	917,8	k€	2%	18	k€
Material	-	k€	98%	-	k€	2%	-	k€
Operating Materials	10	k€	0%	-	k€	100%	10	k€
Stock Costs	-	k€	98%	-	k€	2%	-	k€
Energy	31,6	k€	98%	31,0	k€	2%	1	k€
System (labour, equipment and space)	273,2	k€	98%	268,0	k€	2%	5	k€
System (waste management)	-	k€	0%	-	k€	100%	-	k€
Total Cost	1 250,4	k€		1 216,8	k€		33,6	k€

The primary output of the calculation model is a flow map of the entire production system including the costs information.

The calculation model is fundamental for the analysis of the overall production system and to appraise its economic performance. It provides information about the costs distribution along the manufacturing process and identifies the operations with greater economic impact and higher expenses related to material losses. This can lead managers and engineers of the company to focus their efforts on the more critical points, from the economic or environmental point of view.

The results obtained from the MFCA application are present in the next section.

4.4. Analysis of the results

After the MFCA application, the results should be organised and communicated to the stakeholders. This information can be used to support different types of decisions aiming at the improvement of both, environmental and financial performance [7].

The output flow map obtained from the calculation model is represented in Figure 4-5. It describes the costs of each quantity centre by input and quantity centre expenses, including energy and system costs, as well as, by output, distinguishing the costs allocated to products and to material losses.

The material losses through the production of the analysed Product include the following:

- Off-specification components produced after maintenance step-up and non-programmed stops;
- Destroyed parts due to the destructive quality control test performed to Part A;
- Contaminated parts;
- Discharges of material after step-up maintenance and non-programmed stops;
- Returned components from the customer;
- Sludge from supplementary materials used for the injection machines maintenance;

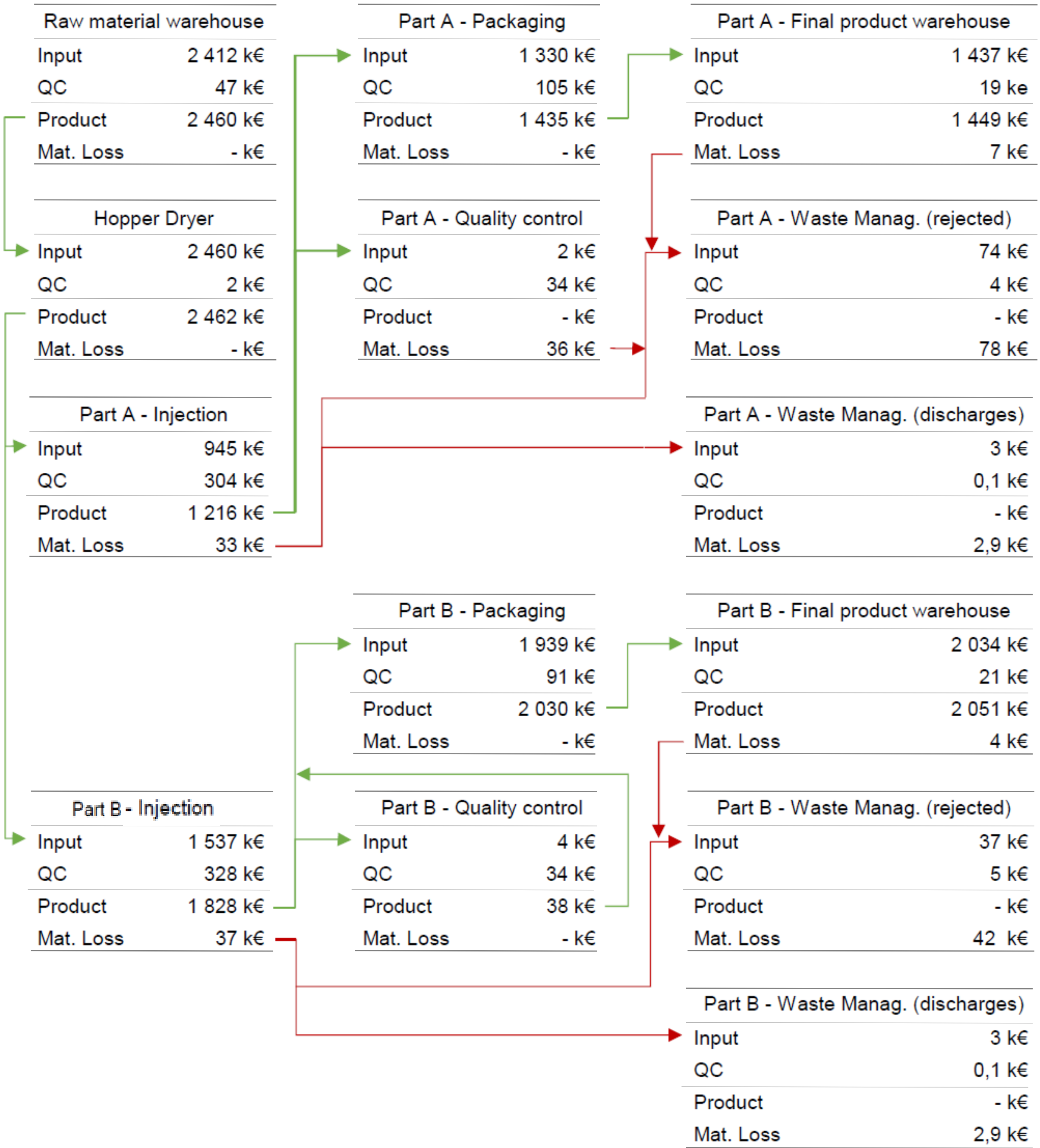


Figure 4-5: Costs flow map obtained from the calculation model

Before the application of MFCA, the company believed that the existing process for manufacturing the Product had a percentage of material losses per material inputs inferior to 1%. This result derives from the fact that their production management is based on the final product yield data only considering the loss of material. The incorporation of the other expense incurred in the manufacturing process, through the MFCA methodology, enabled to understand that these costs are in reality more than three times higher.

In the analysis of the results, it is important to determine the contribution of each quantity centre to the total production costs, for the recognition of critical points and the study of possible improvements. Table 4-3 describes the contribution of each output, Product and Material losses per quantity centre to the total manufacturing costs of Part A and Part B separately. Additionally, the MFCA application allows the identification of the primary costs drivers through the costs breakdown, illustrated in Figure 4-6. The combination of the results obtained from Table 4-3 and Figure 4-6, on the one hand, allows the identification of the primary sources of costs and, on the other hand, highlights the material losses points and drivers.

Table 4-3: Contribution of the outputs per quantity centre to the total production costs

	Part A		Part B	
	Product	Material loss	Product	Material loss
Raw material warehouse	25,8 %	-	42,2 %	-
Hopper dryer	0,02 %	-	0,03 %	-
Injection	7,7 %	0,9 %	8,2 %	1,0 %
Quality control	-	1,0 %	0,9 %	- %
Packaging	6,0 %	-	4,7 %	-
Final product warehouse	0,5 %	0,2 %	0,6%	0,1 %
Waste management (rejected)	-	0,1 %	-	0,1%
Waste management (sale)	-	-0,003 %	-	-0,003 %
Total	40,0 %	2,2 %	56,6 %	1,2 %

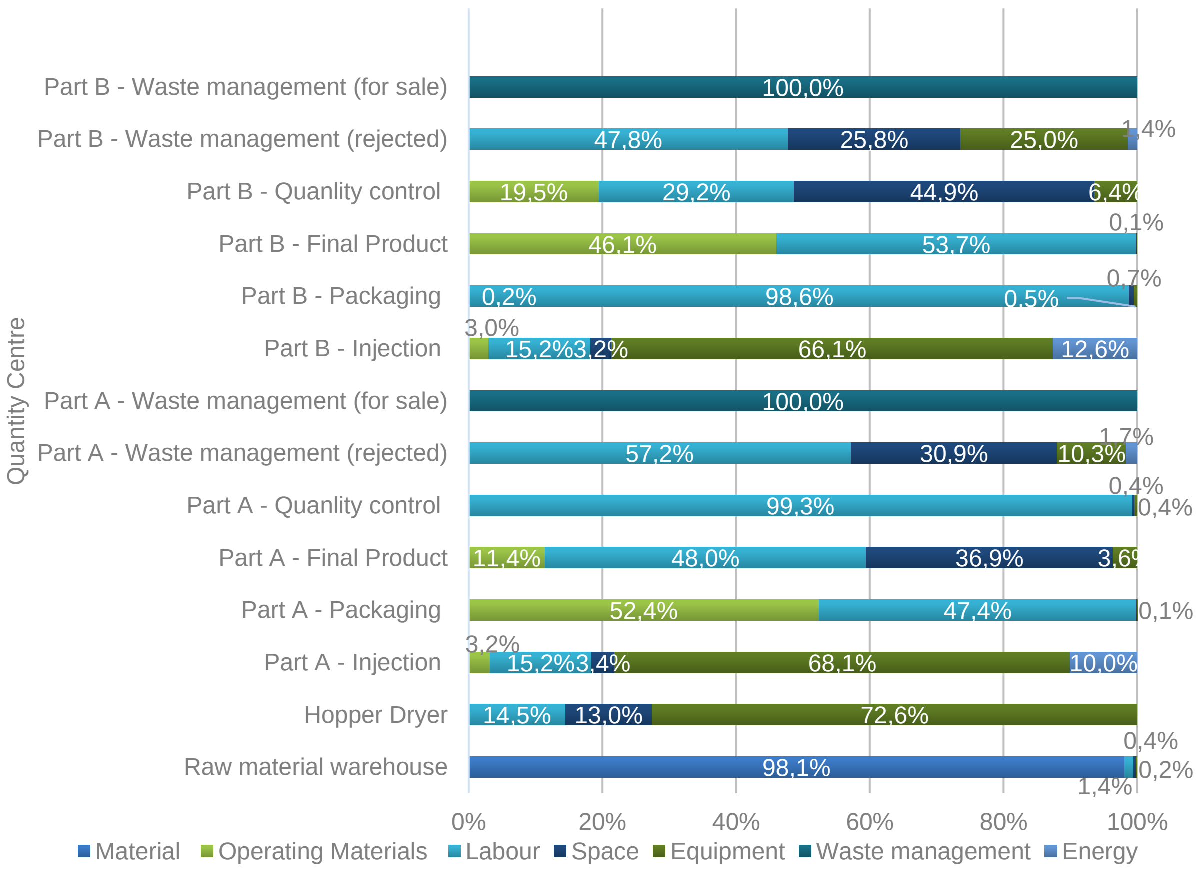


Figure 4-6: Costs breakdown per quantity centre

The evaluation of the overall results shows that 3,4% of the costs are related to material losses and 96,6% to products delivered to the customer. The manufacture of Part A represents 42,2% of the Product's production costs, and Part B represents 68,8%. This distribution is related to the material required to produce each part, Part B weights 4,20 g and Part A 2,35 g. It is important to note that from the 3,4% of wasteful expenses, two-thirds are allocated to Part A.

Thus, if the two components are analysed separately, it is possible to identify that 5% of the production costs to manufacture the Part A are due to material losses. In contrast, in the production of Part B theses expenses represent 2% of the total costs. This difference is primary due to the destructive characteristic of the quality control tests performed to Part A.

Furthermore, the results obtained also recognises the Raw Material Warehouse quantity centre as the section with higher associated costs, followed by the Injection and the Packaging quantity centres, in the manufacture of both components.

Table 4-3 identifies that 68% of the costs are related to the inputs and activities of the Raw material warehouse quantity centre. Figure 4-6 highlights that 98% of the expenses incurred in that quantity centre are due to the Material costs. Therefore, the material used to produce the components of the Product is the primary cost driver of the total production system. Thereby, regardless the high impact that the material efficiency has in the environmental performance of the production system, it also largely influences the overall economic performance, as expected due to the nature of this industry. For this reason, the quantity centres that present higher costs and material losses should be subsequently analysed.

After the Raw Material Warehouse quantity centre, the sections with higher associated costs are the Injection and the Packaging quantity centres, in the manufacture of both components. In the analysis of the sources of material loss, on the one hand, the Injection and the Quality control quantity centres are identified as the primary sources for Part A, and on the other hand, the Injection quantity centre for Part B.

In the manufacture of Part A, the Injection is the second quantity centres with higher costs and, together with the Quality control, represents the major source of loss. To better understand the material inefficiencies and the costs drivers, Figure 4-7 illustrates the Sankey Diagram of both quantity centres. This type of diagram allows a more detailed appraisal.

In the Injection, the material losses are 91% due to off-specification components and 9% due to contaminated parts and discharges of material after step-up maintenance and non-programmed stops. Once identified the main sources of loss, different studies can be conducted with the purpose of reducing, or even avoid, these material losses. Since the rejection of the components is related to technical characteristics of the injection machines and cannot be completely avoided, a solution to reduce the amount of wasteful material is presented in the next section together with other possible improvements.

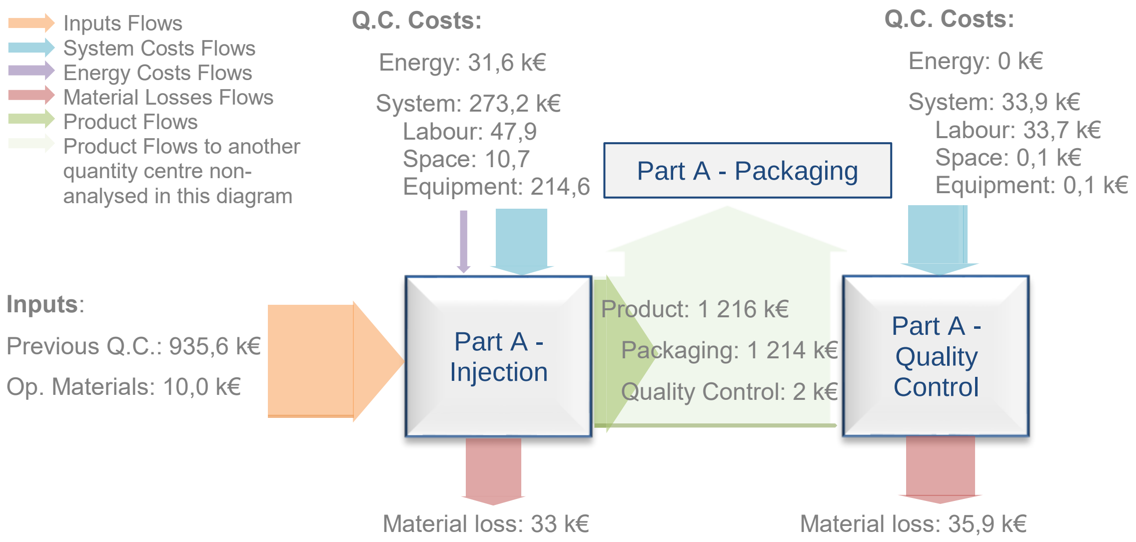


Figure 4-7: Sankey diagram of Injection and Quality control quantity centres (Part A)

In the Quality control quantity centre, the entire output flows are material losses, which are unavoidable due to the destructive nature of the performed test. The quality control of the components is a pre-condition imposed by the customer. Therefore, the quality control protocol may be reviewed by both corporations, since it leads to 1,50 tons of material wasted and 36 000 € per year.

The production system produces three pairs of Part A and Part B simultaneously, using six injection machines. The MFCA application also enables the evaluation of the environmental and economic performance of each pair of components separately. There are two pairs produced by moulds of 32 cavities, and one by moulds of 16 cavities. Table 4-4 presents the costs associated to the production of one unit. Then, the results are normalised regarding the average unitary costs of the overall production. The cost of the Product is the sum of both components' costs.

Table 4-4: Costs per unit and material losses costs analysis per injection machine

	Pair 1 (16 cavities)			Pair 2 (32 cavities)			Pair 3 (32 cavities)		
	Part A	Part B	Product	Part A	Part B	Product	Part A	Part B	Product
€ / unit	0,0058	0,0080	0,0138	0,0041	0,0069	0,0110	0,0053	0,0072	0,0125
Norm.	0,85	0,90	0,88	1,19	1,05	1,10	0,92	1,01	0,97

From this analysis, it is possible to identify the injection machines which lead to higher production costs and that have a lower efficiency. Thus, this analysis may support the company to identify inefficiencies and improve the overall performance of the production system. The injection machines with the lowest efficiency are the ones that use moulds of 16 cavities, 12% lower than the average. In opposition, the injection machines of the Pair 2 have an efficiency higher than the average, leading to lower production costs per unit produced. The identification of the reasons and drivers for the obtained results requires the performance of a deeper analysis.

An indicator that can support this evaluation is the Overall Equipment Effectiveness, OEE. The calculation of the OEE requires the knowledge of different variables that can be obtained from the MFCA methodology. Its calculation is based on three factors: availability, performance and quality, Equation (4.11) [40].

$$OEE = Availability \times Performance \times Quality \tag{4.11}$$

Each factor is calculated using Equation (4.12), (4.13) and (4.14), respectively.

$$Availability = \frac{Run\ Time}{Planned\ Production\ Time} \tag{4.12}$$

$$Performance = \frac{Ideal\ Cycle\ Time \times Total\ Count}{Run\ Time} \tag{4.13}$$

$$Quality = \frac{Good\ Count}{Total\ Count} \tag{4.14}$$

In turn, the run time is calculated by Equation (4.15), where the stop time is the sum of periods that the manufacturing process is not running due to unplanned or planned stops [40].

$$Run\ Time = Planned\ Production\ Time - Stop\ Time \tag{4.15}$$

Table 4-5 presents the OEE of each injection machine.

Table 4-5: OEE of the injection machines

	Pair 1		Pair 2		Pair 3	
	Part A	Part B	Part A	Part B	Part A	Part B
Availability	97 %	98 %	95 %	90 %	97 %	94 %
Performance	92 %	92 %	97 %	80 %	88 %	86 %
Quality	98 %	99 %	99 %	98 %	99 %	99 %
OEE	88 %	90 %	90 %	71 %	84 %	79 %

The low efficiency of an injection machine can be a consequence of technical problems of the machine itself or due to the mould malfunction. Therefore, the substitution of the equipment or its reparation can need the appraisal of financial investments that are out of the scope of original MFCA methodology.

4.5. MFCA application conclusion

The MFCA application to the Product’s manufacturing process allows to conclude that it can support the company to better understand the magnitude, consequences and drivers of material use and loss. This enables the identification of inefficiencies in the production system. After the recognition of critical points, different solutions can be developed to enhance the production line environmental and economic performance.

Improvements related to the material losses:

- Reduction of the amount rejected components after step-ups for maintenance or non-programmed stops. The employees reject twenty shots of produced parts after every stop. However, the injection parameters of the machine and the components' specifications required are stabilised at the fifth cycle. Therefore, the reduction of the number of discarded shots can increase the material use efficiency, reducing the demand for raw material and thereby, improving the environmental and economic impact of the company, without compromising the components' quality.
- The quality control performed to Part A is one of its major sources of loss. Since the tested samples often present results within the required specifications, the time between two following controls can be redefined, reducing its frequency and consequently the number of destroyed components.

Suggestions related to technical problems of the equipment based on the MFCA analysis performed per injection machine:

- Establish a standardised procedure to perform maintenance of all the injection machines in every shift, can avoid the malfunction of the equipment for lacks of maintenance.
- Analyse the possibility of replace or repair the moulds with a high number of closed cavities. In this context, the number of cavities of the moulds may be re-evaluated, to obtain higher material and energy performances according to the actual and the expected production for the following years.

Suggestions to increase the overall performance of the system through the improvement of identified inefficient activities.

- Modify the configuration of the raw material aspiration system from the warehouse to the hopper dryer. The activities related to the material suction presents several inefficiencies.
- Develop a new configuration for packaging process or a new packaging system, since the employees dedicate 65% of their working time to an activity that can be automatized.
- Change the palletizing film. The film used at present has adhesive properties on both sides, hampering and increasing the loading time of the truck.

Hence, MFCA methodology represents a significant tool for the comprehension of material uses and losses, the identification of critical points and inefficient operations, enabling, through its application, the improvement of environmental and economic performances of the manufacturing process.

During the manufacture of the components, as it was mentioned, some losses cannot be avoided due to technical and technological characteristics of the process. However, the information obtained from the MFCA application contributes to the understanding of these losses and the development of improvements. Rather than perceiving material losses as a minor issue of quality management it should be considered as an important determinant of production profits and gains.

One of the major focus of the MFCA is the reduction of the costs through the reduction of the amount of consumed material, contributing simultaneously to a positive environmental impact. The improvement of the materials utilisation decreases wasteful flows burdening the environment. Therefore, the MFCA can be a significant tool to link environmental management measures and information to financial purposes.

Nevertheless, the proposed actions should be supported by a cost-benefit analysis and the evaluation of its consequences on the overall production system. The MFCA data can support these decisions; however, some modification to the original MFCA methodology must be performed.

Additionally, the MFCA implementation creates opportunities for enhancements in the accounting and information systems of the company, providing more precise data for all future projects.

5. MFCA extended to processes and products design

The MFCA is a promising instrument regarding the identification of inefficiencies and their financial effect, the improvement of the efficiency of the resources, and thus, to promote productivity in a company. However, bears some potentials for further enhancement.

In this section, the primary limitations of the MFCA methodology to be used and an appraisal tool for process and products design are discussed. Then, some modifications to the original methodology are proposed to extending its scope to the comparison of production alternatives. Based on those limitations a Process Based Model (PBM) is developed with the aim of comparing different mould designs alternatives and production configurations.

To test the applicability of the model, different production alternatives to manufacturing the Product used as a case-study in the present dissertation are compared, applying the MFCA methodology. The results are further analysed and discussed.

In the end of this Chapter the extension of the MFCA scope to the design of products and processes is discussed.

5.1. MFCA limitations for design analysis

The nature of its focus on material flows and shot-term appraisal reveals some restrictions in the comparison of improvement alternatives configuration of the process chain and the evaluation of future states that require a dynamic investment appraisals [14]. Withal, this unique focus on losses and reporting their costs is the highest potential of the method that fosters a resource savings production policy, improving the environmental and economic performance of the company.

The comparison of different alternatives' process, configuration and technologies regarding their efficiency, may lead to different outputs that may influence the profitability of the solutions. The companies' decisions are based on the profit and not on the avoidance of costs. Therefore, MFCA analysis outputs should include different outputs and revenues to support decision-making of this character. To overcome this problem, various modelling strategies have been proposed [14]. In the present work, a virtual quantity centre is introduced to display the financial effect of the compared alternatives. This contributes to the higher transparency of results and maintains the quantity centres as the central model element of MFCA.

The MFCA aims at the identification of processes' inefficiencies and helps to identify the corresponding potentials for improvement. Often, the improvements require the adjustment of the process or the design of a new configuration and consequently investments appraisals. From the economic point of view, at least, must be considered the more important monetary consequences. Hence, the calculation model should be modified to include investment appraisal variables as depreciations, inputted interests, insurance costs, among others [14]. These new variables can be introduced under the system costs, as it is explained in the following sections. It is important to note that the inclusion of these investment costs, allows the interpretation of the MFCA calculation model as a form of investment appraisal that uses future-oriented data.

To extend the scope of MFCA to an investment appraisal tool, the database used for the calculation model must be increased to the useful life of the investment, and the future data and costs must be forecasted. Additionally, relevant monetary effects, that are not covered by the traditional model must be considered.

Despite the modification regarding economic characteristics, the calculation model should also be adapted to forecast the resources required to produce the components. Therefore, a deep knowledge of the process parameters, as well as the production particular characteristics of the production system, is necessary for the development of a Process Based Model to appraise and compare different production design alternatives. The PBM developed for the present dissertation, specifically designed for the production system in analysis, is presented in the following section.

5.2. Process Based Model developed

To study the MFCA applicability as an appraisal tool in the design phase of a product, several production alternatives to manufacturing the Product are compared, based on the data collected in the Company, using the same case-study. The alternatives include moulds with different number of cavities, two types of injection machines and the option of reintroduce the material losses in the production system to manufacture new components through an internal recycling process.

The selection of the most appropriate technological solution is a multi-disciplinary activity, which integrates different knowledge fields and professional domains. To forecast and calculate the necessary resources to manufacture the components, the amount of material losses, as well as to estimate the necessary investments related to new equipment acquisition a Process Based Model must be developed. Then, based on data provided by the model, the MFCA methodology is applied to compare and evaluate the different production alternatives. Figure 5-1 illustrates the macro flow chart for the development of the new calculation model. In *Annex D* - the detailed list of the input variables can be consulted.

Before the analysis, the production characteristics, based on the data collected for the previous case-study must be defined:

- The product lifetime are five years;
- The company operates 360 days per year;
- The specific daily production volume are 1 000 000 components;

- The number of employees per injection machine is 0,8;
- The quality control tests are performed every hour to one shot per injection machine;
- The maintenance of each injection machine must be performed every shift;
- The space required per quantity centre is based on the previous case-study data;
- After every stop, five shots of components should be rejected for off-specifications reasons;
- The amount of material discharged after any stop longer than 15 minutes should be approximately equal to 0,5kg.

Additionally, a database of injection machines and mould dimensions must be created.

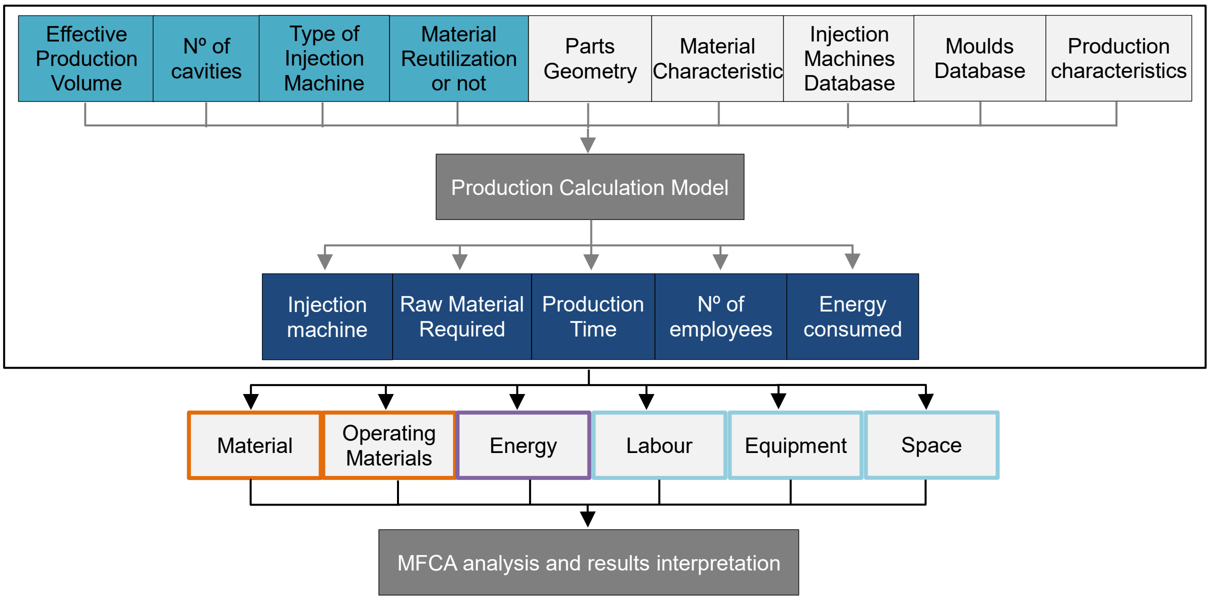


Figure 5-1: Macro flow chart of the new calculation model

The model selects the injection machine with the lowest price from the database according to the mould dimensions, the required clamping force and the type chosen, electric or hydraulic, for each component of the Product. Figure 5-2 illustrates the procedure developed to select the injection machine.

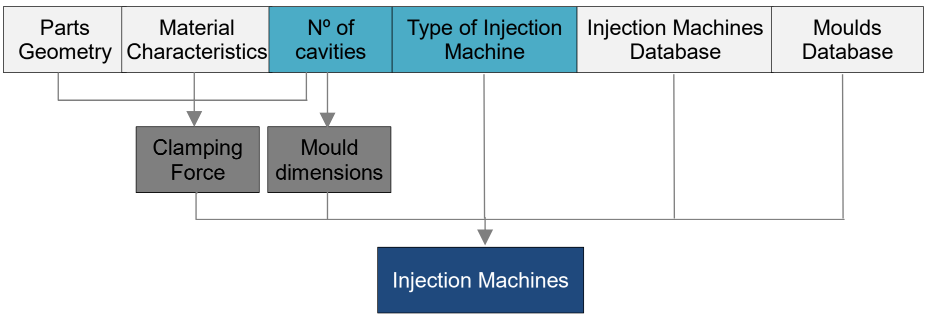


Figure 5-2: Flow chart of injection machines' selection

The clamping force is calculated by the Equation (5.1) [41], where P_{inside} is the pressure inside the mould, $A_{projected}$ represents the projected area of the part and n the number of cavities of the mould. In the present work, the value of 2,5% is assumed for the Safety Factor.

$$F_{Clamping} = P_{inside} \times A_{Projected} \times n \times (1 - SafetyFactor) \quad (5.1)$$

The cycle time is one of the most important parameters in the injection moulding process and influences the entire production system. Therefore, its accurate calculation is fundamental and required for the remaining parameters. It depends on the parts geometry, the material, the number of cavities of the mould and injection machine properties, Figure 5-3.

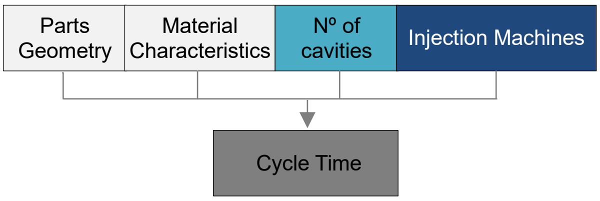


Figure 5-3: Flow chart of cycle time estimation

The cycle time can be understood as the sum of three stages: injection, packing and cooling, and reset (Equation 5.2) [42].

$$t_{cycle} = t_{fill} + t_{cool} + t_{reset} \quad (5.2)$$

The t_{fill} represents the injection time and is calculated by Equation (5.3), where V_{cavity} is the volume of the cavities, also defined as shot size, and is be obtained multiplying the number of cavities by the volume of the part. Q_{max} is the maximum flow rate of the polymer from the nozzle [42].

$$t_{fill} = \frac{2 \times V_{cavity}}{Q_{max}} \quad (5.3)$$

The t_{cool} represents the cooling and packing time, Equation (5.4), where s is the maximum thickness of the part, k is the part thickness coefficient ($k = 4/\pi$ if $s < 3\,mm$), α_{ef} is the average effective thermal diffusivity of the material and γ is obtained using the Equation (5.5). In this Equation, T_{inj}, T_{mould}, T_{ejec} represent the injection, the mould and the ejection temperatures [43].

$$t_{cool} = \frac{s^2}{\pi^2 \times \propto_{ef}} \times \ln(k\gamma) \quad (5.4)$$

$$\gamma = \frac{T_{inj} - T_{mould}}{T_{ext} - T_{mould}} \quad (5.5)$$

Finally, t_{reset} represents the reset time, when the mould is prepared for the next cycle and is calculated by the Equation (5.6). L_{stroke}^{max} is the maximum stroke length of the machine, L_{stroke} is the maximum stroke length required, t_d is the machine's dry time, which is assumed equal to 1,7 due to the lack of information about this parameter for some injection machines [42]. The maximum stroke length required is obtained by Equation (5.7) where D is the maximum depth of the part [42].

$$t_{reset} = 1 + \left(1{,}75 \times \sqrt{\frac{L_{stroke}}{L_{stroke}^{max}}}\right) \times t_d \quad (5.6)$$

$$L_{stroke} = 2D \times 5 \quad (5.7)$$

The cycle time, together with the production characteristics, enables the calculation of the number of necessary equipment for the manufacture of the defined effective production volume, and subsequently the production time, as illustrated in Figure 5-4.

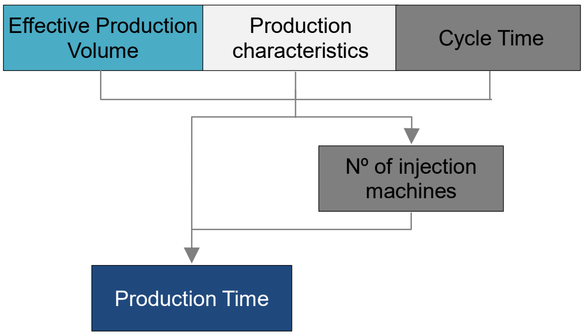


Figure 5-4: Flow chart of production time estimation

The production time is equal to the sum of the time required to produce the effective production volume and the unavoidable off-specifications parts, to perform the maintenance, to stabilise the injection machines after programmed and non-programmed stops and to perform the quality control tests.

From the production time, the number of injection machines and the defined production characteristics, the calculation model determines the necessary number of employees allocated to the production system, Figure 5-5. This calculation is based on two requirements:

- Per injection machine are required 0,8 employees;
- Every eight hours of production is added a new shift.

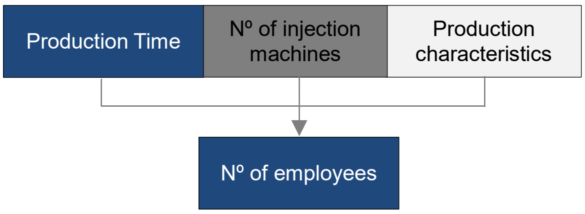


Figure 5-5: Flow chart of number of employees' calculation

In parallel, the necessary raw material to manufacture the Product is calculated as described in Figure ***5-6*** and Equation (5.8). The amount of raw material, as well as the material losses and the material internally recycled by each design alternative can be consulted in *Annex E -*

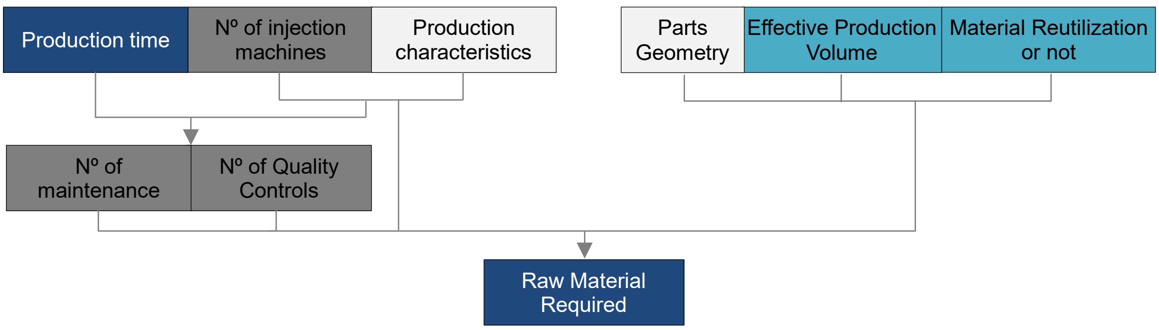


Figure 5-6: Flow chart of the necessary raw material estimation

The first three terms of the Equation represent the unavoidable material losses of the production system derived from the maintenance, the quality control tests and the machinery starting, which are obtained by Equation (5.9), (5.10) and (5.11) respectively. $n_{maintenace}$ and n_{QC} represent the number of maintenance and quality control tests per day, $n_{machines}$, $n_{cavities}$, n_{shots}, and $n_{productiovolume}$ are the number of injection machines, cavities of each mould, rejected shots after any machine stop and the effective production volume, respectively. Finally, $m_{discharged}$ represents the amount of material discharged after any long stop and m_{part} is the component weight.

$$M_{rawmaterial} = m_{maintenace} + m_{QC} + m_{start} + n_{productionvolume} \times m_{part} \tag{5.8}$$

$$m_{maintenance} = n_{maintenance} \times n_{machines} \times (m_{discharged} + n_{cavities} \times n_{shots} \times m_{part}) \tag{5.9}$$

$$m_{QC} = n_{QC} \times m_{part} \times n_{machines} \tag{5.10}$$

$$m_{start} = n_{machines} \times (m_{discharged} + n_{cavities} \times n_{shots} \times m_{part}) \tag{5.11}$$

Finally, the energy consumed, E, by each injection machine can be estimated through the energy necessary to melt the material and to fill the mould cavities; and, the energy that the injection machine requires for the injection process (Equation 5.12) [44]. Figure 5-7, illustrates the variables that influence the energy calculation.

$$E = E_{thermo} + E_{machine} \tag{5.12}$$

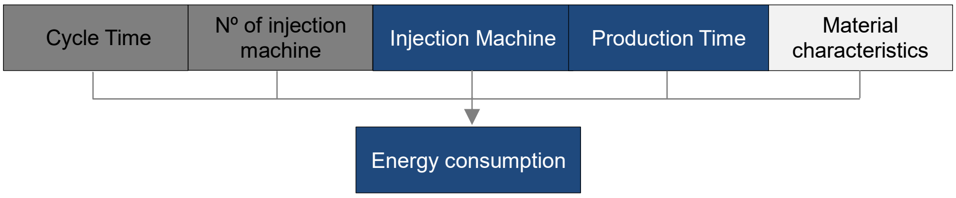


Figure 5-7: Flow chart of energy consumption estimation

The first term of the Equation (5.12), E_{thermo}, is based on thermodynamic fundamentals and depends on the part geometry and material. It is calculated by Equation (5.13) and $\varepsilon_{machine}$ is a coefficient related to the injection machine efficiency [44].

$$E_{thermo} = \frac{E_{melt} + E_{fill}}{\varepsilon_{machine}} \tag{5.13}$$

E_{melt} represents the energy required to melt the material and depends on the crystallisation degree of the polymer. It is calculated using Equation (5.14), where m is the part weight, c_p is the specific heat of the polymer, T_{melt} and T_{amb} are the melting and the ambient temperatures, respectively, λ the crystallisation degree and H_f is the heat fusion for a 100% crystalline polymer [44]. It is assumed that the ambient temperature is 20°C.

$$E_{melt} = \begin{cases} m \times c_p \times (T_{melt} - T_{amb}) + \lambda \times m \times H_f & Crystalline\ Polymers \\ m \times c_p \times (T_{melt} - T_{amb}) & Non-Crystalline\ Polymers \end{cases} \tag{5.14}$$

E_{fill} is the energy necessary to fill the cavities of the mould and is calculated by Equation (5.15). P_{inj} is the injection pressure, which depends on the material, and V_{inj} is the injected volume, which can be obtained by multiplying the volume of the part by the number of cavities of the mould [44].

$$E_{fill} = V_{inj} \times P_{inj} \tag{5.15}$$

The second term of Equation (5.12), $E_{machine}$, is the energy related to the injection machine, influenced by the type of machine and the power installed. It is calculated by the Equation (5.16), where P_{inst} is the power installed and $t_{cool/part}$ is the cooling and packing time per part, which can be obtained by dividing the cooling and packing time (Equation 5.4) by the number of cavities of the mould [45].

$$E_{machine} = CfM \times (CfP \times P_{inst}) \times t_{cool/part} \tag{5.16}$$

CfM represents the machine type coefficient. According to Ribeiro et al. is equal to 0,5 for electric machines and equal to 1 for hydraulic machines. CfP is the machine power coefficient, calculated using Equation (5.17). P_{thermo} is the thermodynamic power, calculated by Equation (5.18), where $t_{cycle/part}$ is the cycle time per part [45].

$$CfP = 0{,}432 + 1{,}465 \times \frac{P_{thermo}}{P_{inst}} \tag{5.17}$$

$$P_{thermo} = \frac{E_{thermo}}{t_{cycle/part}} \tag{5.18}$$

The parameters of the MFCA methodology and their associated costs are quantified, calculated and allocated to the quantity centres, inputs and outputs following the same methodology and criterions used in the case-study of the previous Chapter. Nevertheless, it is important to refer that the equipment acquisition costs, for the moulds and injection machines, are calculated based on investment appraisal variables, including future value evaluations, interest rates and annuities. The moulds acquisition analysis can be consulted in *Annex F -*.

It is assumed that each mould is able to perform 12 500 000 shots, then it has to be replaced by a new one. Thus, if the useful life of the moulds is inferior to the product lifetime, five years, the future costs related to the new mould acquisition must be translated to the present value. Then, is possible to calculate the annuity of the mould and input it as a system cost. The same procedure is used for the injection machines, which useful life are 10 years. The investment appraisal of new machines is necessary in the sensitive analysis to the product lifetime.

5.3. Analysis of the results

The present analysis is performed to test and validate the modifications performed to the MFCA calculation model to extend its scope to the evaluation of different production alternatives in the design phase of a product or a process. Therefore, fourteen production alternatives for manufacturing Part A and Part B are compared, varying the number of cavities of the moulds, the type of injection machines and the final use of the material losses after being properly treated. Since the analysis is performed for a particular annual production volume, the costs and the resources consumed, results are presented for the same period. The alternatives include:

- Different number of cavities per mould: 16, 32, 48 and 64;
- Two types of injection machines: electric and hydraulic, represented by an "E" or an "H" in the following tables and figures, respectively;
- Internal recycling process, represented by an "R" in the following tables and figures.

As it is referred in the previous section, the model selects the injection machine based on the clamping force, the material characteristics and the mould dimensions. Since in the database developed for the present work, there are not electric machines available with the clamping force and the size of the mould platen required to produce both parts of the Product with moulds of 64 cavities, this mould design is only analysed regarding hydraulic machines.

Additionally, is important to refer that the only material that can be internally recycled to be further reintroduced in the production system is the one derived from the rejected components. The material discharges are sold. As described in Chapter 1, the internal recycling process produces a material loop in the manufacturing process. Therefore, the costs associated with this material loop are reported separately as another output flow. Consequently, the results from these design alternatives are evaluated considering three output flows: Product, Material Losses and Material Loop.

In the following tables, used to present the results of the present analysis, the best solution obtained is underlined in green and the worst in red.

Due to the specific daily production volume, the number of moulds required depends on the number of injection machines necessary to produce the components. Table 5-1 presents the number of injection machines, as well as their estimated occupation rate for each production alternative. The internal recycling process configuration do not influence these two parameters. Moreover, it is important to note that the useful lifetime of each mould is different since the number of cavities influence the cycle time and the number of shots to produce the required components per day. Therefore, the acquisition of new moulds and the necessary investment is different for each alternative. For the 16, 32 and 48 alternatives after 3,3 years is necessary to replace both moulds, of Part A and Part B. In opposition, the moulds of 64 cavities are replaced at the 4,4 year.

Table 5-1: Production characteristics of each manufacturing alternative

Nº cavities	Part A					Part B				
	Nº IM	Electric		Hydraulic		Nº IM	Electric		Hydraulic	
		t_{cycle} [s]	Occ. Rate	t_{cycle} [s]	Occ. Rate		t_{cycle} [s]	Occ. Rate	t_{cycle} [s]	Occ. Rate
16	6	7,15	91%	7,15	91%	6	6,65	86%	6,65	86%
32	3	7,40	94%	7,40	94%	3	7,09	91%	7,09	91%
48	2	7,78	98%	7,78	98%	2	7,75	99%	7,75	98%
64	2			8,15	78%	2			8,26	80%

As expected, the number of necessary equipment, and in parallel the number of injection machines, decreases with the increase of the number of cavities, excepts for the alternative that uses moulds of 64 cavities. This option requires the same number of moulds and injection machines than the 48 cavities alternative. Consequently, the injection machine occupation rates are lower for this design.

Figure 5-8 represents the total production costs obtained for each production alternative. The analysis of this results, regarding the number of cavities, leads to two important conclusions: the selection of hydraulic machines, instead of electric, causes higher costs; and, the internal material recycling process allows a slight reduction of costs.

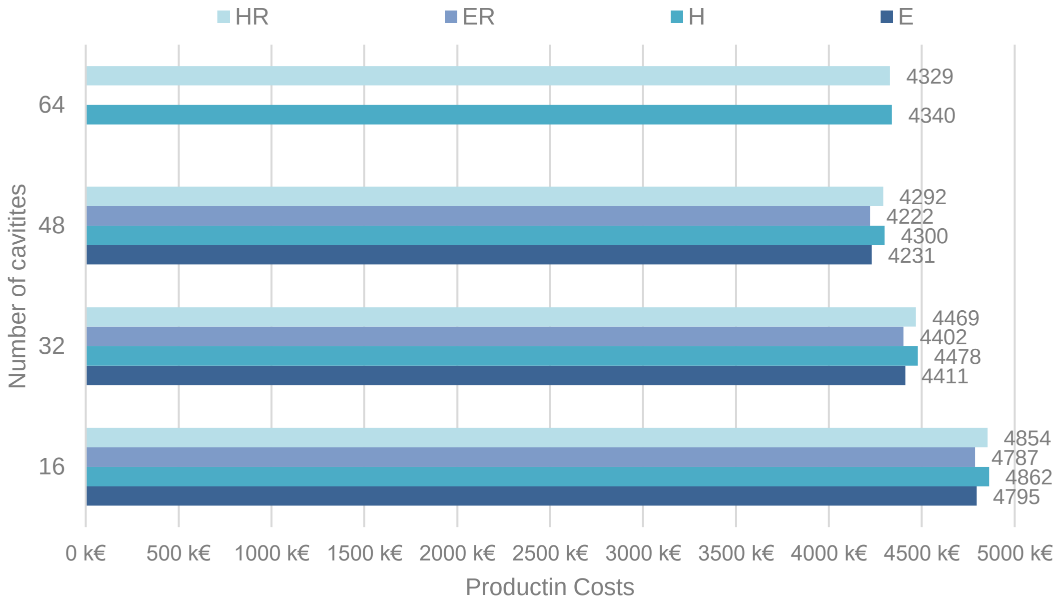


Figure 5-8: Total production costs of each design alternative

Nevertheless, the primary aim and advantage of the MFCA methodology is the monetary evaluation of material losses separately. Thus, Table 5-2 presents the results for the production configuration without internal recycling, considering the costs allocated to the Product, the Material losses and the sum of both terms for each production alternative. In turn, Table 5-3 shows the results obtained for the alternatives that internally recycle the material losses. Hence, differentiate the cost related to the Product, Material Losses and Material Loop. At the end of both tables the results are normalised regarding the best alternative. In a first approach, it is assumed that the best alternative is the one that causes lower production costs.

Table 5-2: Costs analysis for each design alternative without internal recycling process

Design alternative	16 E	16 H	32 E	32 H	48 E	48 H	64 H
Product [k€]	4 647 k€	4 706 k€	4 312 k€	4 370 k€	4 148 k€	4 208 k€	4 242 k€
Material Loss [k€]	148 k€	156 k€	99 k€	108 k€	83 k€	92 k€	98 k€
Total Costs [k€]	4 795 k€	4 862 k€	4 411 k€	4 478 k€	4 231 k€	4 300 k€	4 340 k€
Normalisation	0,88	0,87	0,96	0,94	0,99	0,98	0,97

Table 5-3: Costs analysis for each design alternative with internal recycling process

Design alternative	16 ER	16 HR	32 ER	32 HR	48 E R	48 HR	64 HR
Product [k€]	4 647 k€	4 706 k€	4 312 k€	4 370 k€	4 148 k€	4 208 k€	4 242 k€
Material Loop [k€]	122 k€	130 k€	85 k€	94 k€	71 k€	81 k€	85 k€
Material Loss [k€]	18 k€	18 k€	5 k€	5 k€	3 k€	3 k€	2 k€
Total Costs [k€]	4 787 k€	4 854 k€	4 402 k€	4 469 k€	4 222 k€	4 292 k€	4 329 k€
Normalisation	0,88	0,87	0,96	0,94	1	0,98	0,98

The production costs increase when the number of cavities decreases due to the necessity of a high number of injection machines, moulds and employees, to the meet the production requirements. However, the production alternatives that use moulds of 48 cavities present lower expenses than the ones with 64, despite needing the same number of equipment. This is due to the fact that not only the mould is more expensive, but also requires a machine with higher power; consequently, more expensive. Furthermore, the number of rejected components depends on the number of rejected shots. Although the number of rejected shots is similar, the mould of 64 cavities injects more material per shot; consequently, has more associated material losses.

When the machine costs are compared, the electric machines require higher investments than the hydraulic machines; however, consume less energy to produce the same number of components. From the previous analysis is possible to conclude that the acquisition costs of electric machines are compensated by the energy consumed for all the alternatives analysed and for this production volume. This conclusion has as exception the cases that use moulds of 64 cavities, since they are only analysed for hydraulic machines.

The alternative with the lowest costs is the one that uses electric machines, moulds of 48 cavities and internally recycles part of the material losses. However, the same option without internal recycling leads to costs only 1% higher. The low impact of the recycling process in the total production costs, which can also be verified for the remaining alternatives, is due to the small amount of wasteful material that do not largely compensate the waste management costs.

In the end, the comparison against the best alternative allows to conclude that the results obtained for the moulds of 32 and 64 cavities are similar to the best scenario, leading to production costs from 2% to 6% higher. In opposition, the costs for all the production alternatives with the mould of 16 cavities are much greater. These alternatives present 87% of the best alternatives efficiency. This is primary due to the requirement of three time more injection machines, moulds and resources.

Figure 5-9 illustrates the costs break down by type of output, Product, Material Loss and Material Loop, for the production alternatives. The alternatives are organised by percentage of costs allocated to the Product output. At the right of the Figure, there is a magnification of the graph to provide a better description of costs distribution.

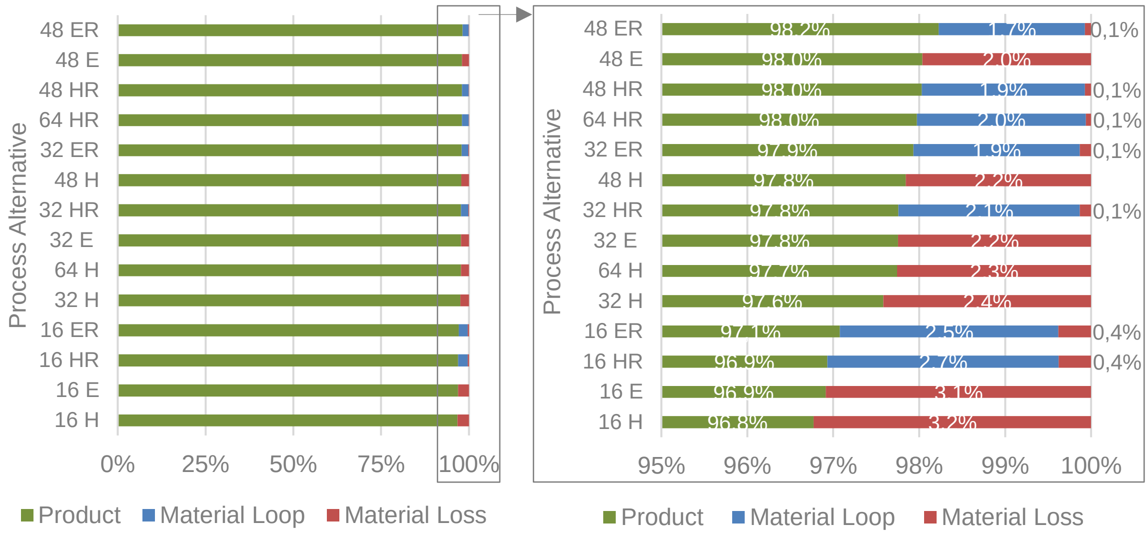


Figure 5-9: Costs break down of the design alternatives

The material losses represent between 3,2% and 2% of the total production expenses in the cases that the rejected material is not reintroduced for manufacturing new components and between 0,4% and 0,1% if the material is reused. However, in this last production cases, there is an extra type of costs associated with the Material Loop, which represents between 1,7% and 2,7% of the expenses.

Another important conclusion can be extracted from this analysis, together with the results presented in Table 5-2 and Table 5-3, for the two types of production configurations. The production alternatives that have higher costs associated to the Product are the ones that present lower production costs. Therefore, as can be expected, the improvement of the efficiency of the resources and its use leads to the better production performances, not only ecologically but also financially. Next, to better understand the consequences of material uses a similar analysis is performed to the material consumed.

The raw material consumed is equal to the material injected to produce the parts including the wasteful material. The annual production volume expected is the same for all the analysed alternatives, as well as the used material; thus, the differences in the material injected between the alternatives are due to material losses. Figure 5-10 illustrates the material injected for each production alternative.

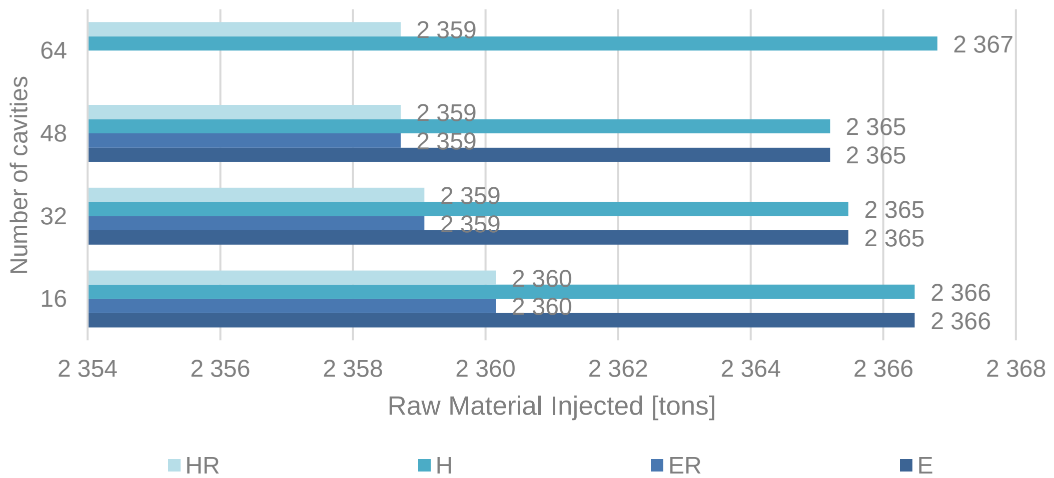


Figure 5-10: Material injected in each design alternative

To complement this information Table 5-4 presents the distribution of the material injected by the different outputs. This evaluation is independent of the injection machine type, i.e. electric or hydraulic. In the last line, the results are normalised regarding the best alternative, i.e. the one that consumes less material.

Table 5-4: Material injected analysis for each design alternative

Design alternative	16	16 R	32	32 R	48	48 R	64	64 R
Product [tons]	2 358	2 358	2 358	2 358	2 358	2 358	2 358	2 358
Material Loss [tons]	8,5	2,2	7,5	1,1	7,2	0,7	8,9	0,7
Material Loop [tons]	-	6,3	-	6,4	-	6,5	-	8,1
Total Costs [tons]	2 367	2 360	2 366	2 359	2 365	2 359	2 367	2 359
Normalisation	0,997	1,000	0,997	1,000	0,997	1	0,997	1

The material losses are related to the number of maintenance, since after every machine stop five shots of components must be rejected. Additionally, in the manufacture of Part A, the number of quality controls is also a driver for material losses, since the tested samples are destroyed. Therefore, knowing that the number of maintenance and quality controls performed per day is similar to all the alternatives, the number of components rejected strongly depends on the mould number of cavities. For this reason, the alternatives that use the mould of 64 cavities presents higher material losses, and consequently consume more raw material. Furthermore, once the two activities described above are performed individually to each injection machine, the material losses are also related to its number. Hence, the manufacturing of the parts with moulds of 16 cavities leads to elevated material losses as well.

Assuming in this case that, the best alternative is the one that requires less injected material, the best scenario remains the same, followed by the remaining alternatives that partially reuse the material losses through the internal recycling process. In opposition to the previous costs analysis, the results are independent of the type of injection machine and the options that do not recycle the material of the rejected components influences negatively the alternative performance. The worst results are obtained for the 64 cavities' moulds; however, the difference to the best scenario is lower than 1%. Therefore, regarding the material consumption, the performance of all the activities is similar due to the elevated production volume and the low percentage of inherent material losses.

Although waste recycling is one of the most important measures for efficient resources use and environmental management, the recycling process also requires substantial expenses and energy, in addition to those spent from the resource input to the waste generation [3]. The MFCA analysis allows the quantification of physical and financial effects of recycling processes. In injection moulding processes that use cold runners instead of hot runners, the consequences and benefits derived from internal recycling process may be higher than for this case, and influence more the productivity and the environmental and economic performance of the production system.

Nevertheless, to obtain a deeper knowledge about the range of the best scenario and its sensitivity to variations in the manufacturing process, two sensitive analysis are performed at the end of this section. One evaluates the best situation with the variation of the product lifetime and the other with the increase or decrease of the specific daily production volume.

5.3.1. Sensitivity analysis

The sensitivity analysis is an important tool for gaining valuable process insights and evaluate different process concepts [46]. The results obtained enable a deeper comprehension about the examined variables and a wider perspective of the system. The present work pretends to determine the influence of the production volume and the product lifetime in the selection of the best manufacturing alternative. For that, two sensitivity analysis are performed, to investigate the relative contribution of the production assumptions on the final results. To facilitate the interpretation of the results, for both cases, the appraisal is based on the production costs per unit produced, and the best alternative is the one that causes lower costs per unit.

Figure 5-11 presents the obtained results for the variation of the product's lifetime from one to twenty years. To facilitate the reading of the graphic, only the two alternatives with lower costs are illustrated, and the data labels are only presented for the best alternative. Both alternatives internally recycle the material losses, and are the following:

- Two moulds of 48 cavities for each part, Part A and Part B, electric machines;
- Two moulds of 64 cavities for each part, Part A and Part B, hydraulic machines.

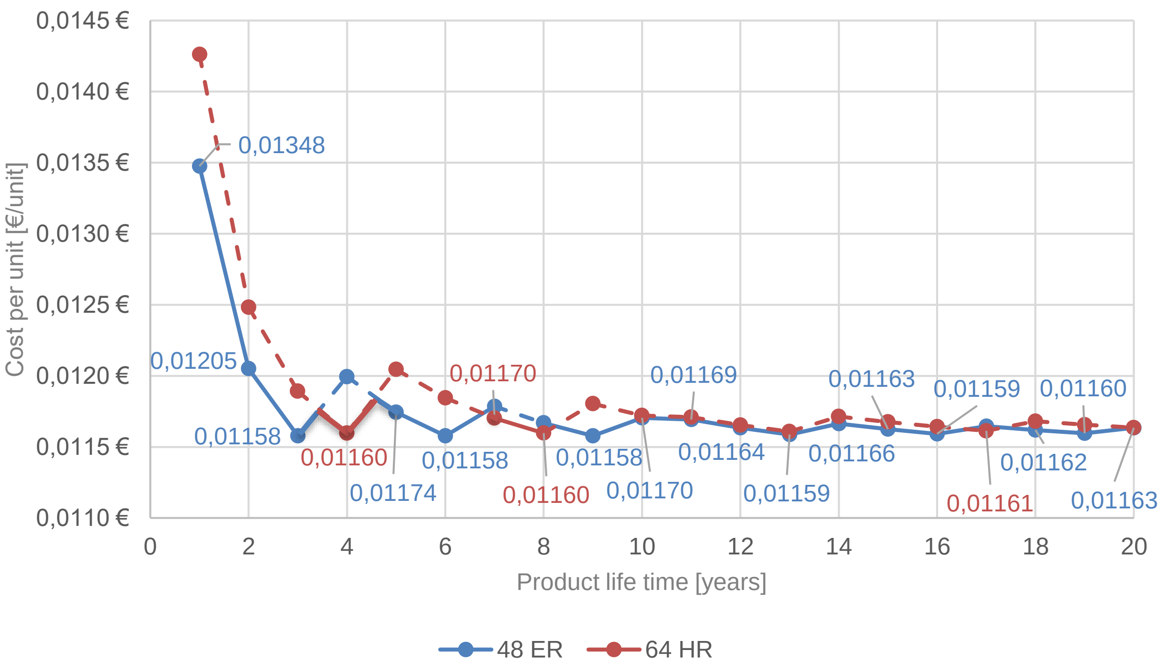


Figure 5-11: Sensitivity analysis to the product's lifetime

On the one hand, the decrease of the product's lifetime leads to higher unitary costs due to the allocation of investment costs in fewer years. On the other hand, the progressive increase of the product's lifetime tends to decrease and stabilise the unitary production costs.

As it was referred in the previous section, the useful life of the moulds depends on the number of cavities, since both are able to perform 12 500 000 shots. The moulds of 48 cavities have a useful life of 3,3 years and the moulds of 64 cavities last 4,4 years. Therefore, if the lifetime of the Product is longer, new moulds must be acquired after those periods. This leads to new investments, which correspond with the peaks of the graphic.

The moulds of 64 cavities is more expensive, requires injection machines with higher power, which are also more expensive and lead to higher material losses. For these reasons, when compared against the mould of 48 cavities presents worst performances, environmental and economic. Nevertheless, from the graphic presented above can be concluded that the 64 cavities' mould is the best alternative when, for a particular lifetime of the product, is necessary to acquire new moulds of 48 cavities and this investment is not required if are used moulds of 64 cavities.

Furthermore, the overall analysis enables to conclude that the lower costs are achieved when the lifetime of the product coincides with the moulds useful life, due to the improvement use of the moulds. If the products' lifetime is lower, the moulds utilisation is not maximised, leading to higher costs. In opposition, if it is greater, it is necessary to acquire new moulds, thereby increasing the investment and the total production costs.

Figure 5-13 and Figure 5-12 presents the results obtained from the sensitivity analysis performed to the specific daily production volume, from zero to 250 000 components produced per day and from 250 000 to 5 million, respectively. The results are presented in to separate graphics to facilitate their reading. Figure 5-13 presents only the alternative that for a particular production volume is the best solution. In turn, since for the production volumes presented in Figure 5-12 the best scenario alternates between the 48 cavities design and the 64 cavities, to better understand the variability of the best alternative, the results obtained for both designs are described.

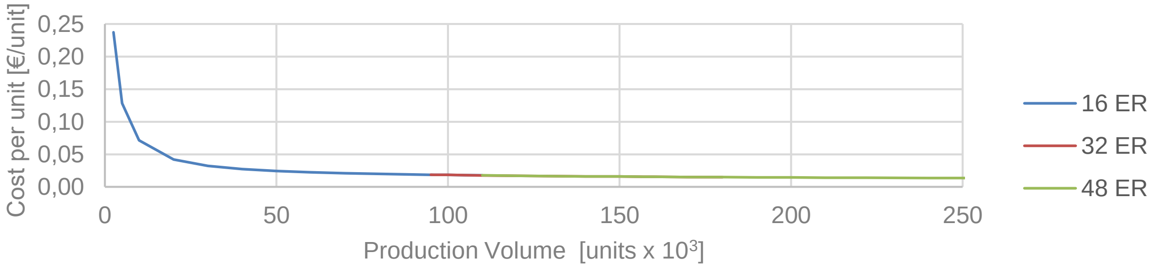


Figure 5-13: Sensitivity analysis to the product's production volume. Best alternatives for production volumes between 0 and 250 000 components produced per day

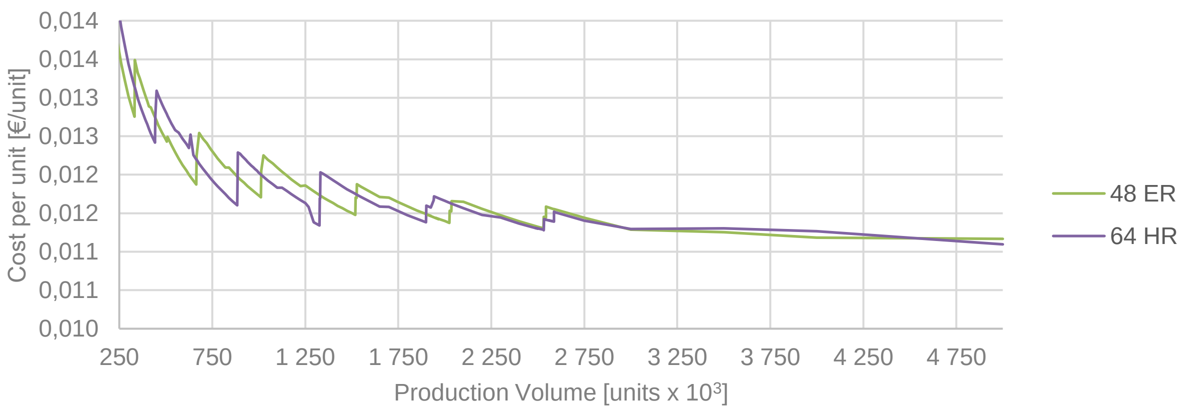


Figure 5-12: Sensitivity analysis to the product's production volume. Best alternatives for production volumes between 0 and 250 000 components produced per day

From results provided by the graphics presented above, three distinct areas can be distinguished regarding the specific production volume:

- Small production volumes;
- Production volumes between 250 000 and 3 000 000 components per day;
- Specific daily production volumes higher than three million components produced per day.

For small production volumes, the unitary cost is much higher, and the best alternatives are the ones that use moulds with the lower number of cavities, as shown in Figure 5-13.

The best solution obtained in the differentiated second area, illustrated in Figure 5-12, varies between the 48 cavities and 64 cavities alternatives. The primary variables that influence this behaviour are the number of necessary injection machines to meet the production objectives, consequently the number of moulds, the lifetime of the moulds for Part A and Part B and for each specific volume and the daily production time.

Finally, at the last part of the graphic can be appreciated that the values tend to stabilise around a unitary value of 0,0111 € per unit and the best solution alternation is smoother.

A similar analysis, following the same procedure, can be used to evaluate the environmental performance of the production alternatives. Since the primary drivers of an ecological analysis, in this context, are the material and the energy the result obtained would be similar to the economic appraisal. From the first results presented in this section, it can be concluded that the material use efficiency, in this production system, is linked to the financial performance of the company. Therefore, the alternatives with lower environmental impact coincide with the ones that lead to lower production costs. Hence, the results of the sensitivity analysis can be extended to the environmental framework.

5.4. Conclusions

The modification of the original calculation model, including investment variables, the entire useful life of the investment, and the forecast of future costs, allowed the application of the MFCA methodology to appraise different configurations for the presented production system.

Furthermore, the sensitive analysis enables the dynamic evaluation of the solutions providing a deeper comprehension about the alternatives and strong support for decision-making.

Nevertheless, it should be noted that when the different alternatives may influence the profitability of the solutions, an additional analysis should be performed. Since companies' decisions are based on the profit and not on the avoidance of costs, the best solution is not necessary the one with minimal costs, as assumed previously. Therefore, MFCA analysis outputs should include divergent outputs and revenues to support decision-making of this character. In this context, the type of appraisal and the financial consequences caused by the different outputs must be identified to select an appropriate target measure. On the one hand, if the differences are based on costs, as in the present work, the target measure are the costs and no further evaluation is required. In opposition, if the output differences imply divergent revenues the target measure should be the profit contribution. In this last case, a deeper analysis regarding the profits is required [14].

Additionally, the implementation of alternative process configuration and technologies may also lead to changes in the underlying flow system and influence the major cost items in different ways, especially the system costs. Assuming that the amount and type of outgoing desired products do not differ between the alternatives, Sygulla et al. suggest the following procedure [10]:

- Categorization of the different sub-items of the system costs;
- Identification of the cost drivers;
- Forecast the various cost sub-items by the cost drivers for every alternative.

The identification and analysis of the cost drivers can be supported by the Input-Throughput-Output-Model (ITO-Model) presented by Götze et al. This model aims at the identification of process-related drivers of ingoing and outgoing material and energy flows [10].

The refinements performed allowed the application of the MFCA methodology as a tool for comparing and evaluating different alternatives in the design phase of a product or a process. The results obtained, enable the validation of the enhancements to the original model and conclude that the MFCA can successfully be applied for process and products design in a company; nevertheless, the considerations referred before should also be considered.

Manufacturing companies are facing new challenges to succeed and remain competitive. The competitiveness and the selection of the most appropriate technological solution may not rely only on the production costs, but must also include the entire life cycle of the product, from the material acquisition to disposal. Additionally, the emerged environmental management, regulation and public concern, raises the necessity of also evaluating the environmental impacts [47]. Therefore, design decision-making should integrate lifecycle approaches and include financial and ecologic considerations. In this context, the following Chapter analyses and incorporates the life cycle perspective of the production system to the presented evaluation.

6. Life Cycle Engineering Analysis

The mould design influences the global efficiency of the plastic injection process, since it determines the manufacturing time, the consumed energy and material wasted per part. Therefore, the lifecycle analysis is performed from the moulds' perspective. The methodology applied is the LCE, including economic and environmental aspects in the global evaluation, Figure 6-1.The functional assessment is not included as both moulds and the parts produced by the different alternatives have the same technical performance.

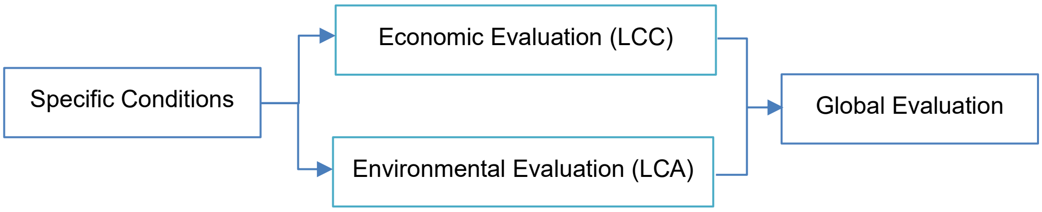


Figure 6-1: LCE methodology applied to the present work

The following section describes the lifecycle considerations and the methodology applied, describing the approach used and the required information for the development of the appraisal models. Then, the economic and environmental analysis and their respective results are presented for each phase.

Next, both dimension, economic and environmental, are assessed from the overall lifecycle perspective using the LCC and LCA methods, respectively. Finally, the results are aggregated to develop the LCE model and perform the global analysis.

The methodology applied incorporates the MFCA as an LCE tool. In the end of this Chapter the benefits derived from this integration are discussed.

6.1. Lifecycle considerations and approach

In this section is presented the lifecycle of the mould, defining all the relevant phases and the approach applied to the analysis of both dimensions. Figure 6-2 illustrates the lifecycle of a generic product, from the material acquisition to disposal. In the present work, some of the stages are not evaluated, because the results are equal for all the alternatives.

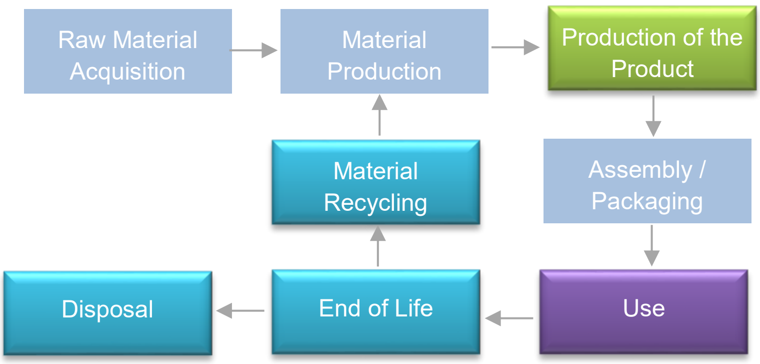


Figure 6-2: Lifecycle of a generic product

The material used to produce the moulds is the same for all the alternatives; therefore, the costs and the environmental impact per kilogram in the raw material acquisition and material production phases are equal. Thus, both impacts are considered in the Production phase of the Product, since the amount of necessary material to produce the moulds is different. The assembly and the packaging phases are not considered due to the characteristics of the product. Hence, the mould's lifecycle analysis of the present work includes the evaluation of the production, use and end of life stages.

The identification of the analysis boundaries is fundamental for the accuracy of the results [16]. The LCE approach developed integrates economic and environmental distinctive evaluation, allowing a global comparison.

Figure 6-3 illustrates the approach used to perform the economic and environmental analysis in each lifecycle phase. The MFCA methodology is used to perform the economic appraisal of each phase and to provide the necessary data to perform the environmental analysis: material consumption, material losses and energy consumption.

The incorporation of MFCA methodology adds a new perspective to the results. For each alternative and dimension of evaluation the results can be analysed regarding the product and the material losses separately, or together, as it is traditionally done. The final results of both evaluations are performed and integrated in a life cycle perspective, using LCC and LCA methods respectively.

The environmental indicator for the LCA analysis are computed through the ReCiPe Midpoint (H) V1.11 / Europe Recipe H method with the support of LCA software (SimaPro, 2011) and the Eco Invent 3 database.

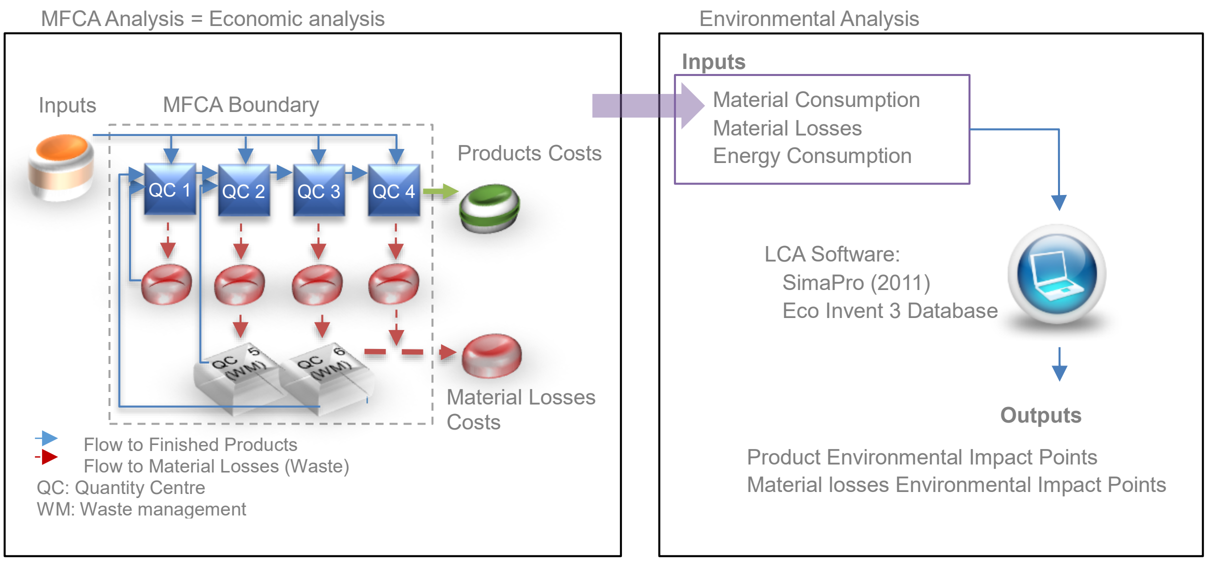


Figure 6-3: Approach followed to perform the economic and environmental analysis of each lifecycle phase

6.2. Lifecycle phases: analysis and results

The following sections describe each lifecycle phase evaluated, within the lifecycle boundaries, and the methodology followed to perform the economic and environmental appraisals. Then, the costs and environmental impacts obtained for each stage are presented.

The results are presented regarding the production of one unit of the Product, composed by Part A and Part B, for a specific daily production of 1 000 000 components and a Product’s lifetime of five years.

In the following sections the best results obtained in each performed evaluation are underlined in green and the worst in red.

6.2.1. Production phase of the mould

The moulds are produced in the Moulding Manufacturing business unit of the same Company Group that manufactures the components through the Injection Moulding Process. The application of the MFCA methodology to the moulds’ production requires the determination of the quantity centres, the identification of all the inputs and outputs and the further, quantification of material flows in physical and monetary units. However, for the present work the entire production system was considered as a single quantity centre and the input data is based on the work developed by Ribeiro [48].

The inputs of the analysis are the material and consumables used to produce the moulds. The energy consumed during the manufacturing process and its associated costs are allocated under the material costs, as in the previous analysis presented in this dissertation. The system costs include labour, equipment, tooling, space and maintenance expenses. They are allocated to the system outputs by the mass ratio between the product and the material losses. The results obtained from the MFCA application can be consulted in *Annex G* - for the different moulds’ designs.

Table 6-1 presents the manufacturing costs, assuming that each mould is able to perform 12 500 000 shots and considering the production requirements described above. The functional unit used throughout the entire lifecycle analysis is the same, one plastic Product produced; therefore, the costs presented are the allocated costs of the mould per component.

Table 6-1: Production Phase Costs per unit produced

Nº of cavities	16	32	48	64
Product [10^{-6}€/unit]	1,11	0,92	0,85	1,07
Normalisation	0,77	0,92	1	0,79
Material Loss [10^{-6}€/unit]	0,42	0,22	0,16	0,19
Normalisation	0,39	0,76	1	0,86
Total [10^{-6}€/unit]	1,53	1,13	1,01	1,26
Normalisation	0,66	0,89	1	0,8

The material is the primary cost driver in the moulds’ production. The increase of the number of cavities, increases also the dimension of the moulds and the steel consumed. Nevertheless, the number of moulds needed to meet the production requirements is lower, compensating the extra material required per mould. The alternative of 48 cavities presents the lowest costs regarding in three analysed categories: Product, Material Losses and the Total production costs. In opposition, the mould of 16 cavities presents the highest costs due to the necessity of manufacturing three times more moulds to produce the same quantity of parts.

The material losses represent between 15% and 27% of the production costs. This value is associated with inherent characteristics of the production process to shape the proper mould. Nevertheless, a deeper analysis should be performed to better understand the material losses and to identify the drivers, potential points and activities to improve the material use efficiency. In this category, the mould of 64 cavities presents better results than the one of 32 because it needs half of the moulds to produce the same quantity of components; consequently, producing half of the respective waste. Nevertheless, its global performance leads to higher costs due to the lower utilisation rate of the moulds.

The normalisation of the costs regarding the best alternative enables the identification of the 32 cavities alternative as the second-best option with 89% of the 48 cavities efficiency. The 16 cavities option presents the worst performance and has only 66% of efficiency, when compared against the best option.

The environmental analysis for the moulds' production is performed through the individual impacts caused by the material used to produce the mould itself and the material removed, together with the correspondent allocated energy consumed. This values are obtained from the MFCA analysis. The environmental results for the mould production are presented in Table 6-2. As in the previous analysis the environmental impact of each design alternative is allocated to one plastic component produced.

Table 6-2: Production Phase Environmental Impact per unit produced

Nº of cavities	16	32	48	64
Product [µpoints/unit]	50,61	55,80	57,65	77,70
Normalisation	1	0,91	0,88	0,65
Material Loss [µpoints /unit]	19,2	13,03	10,98	12,54
Normalisation	0,57	0,84	1	0,81
Total [µpoints/unit]	69,72	68,83	68,63	91,21
Normalisation	0,98	1,00	1	0,75

In contrast to the costs analysis, the impact created by the mould production is considerably influenced by the energy consumed. Nevertheless, it also depends on the number of moulds required to meet the daily and, consequently, the annual production volume. The increase of the number of cavities, increases the energy consumed during the manufacturing process. However, as it was already referred, it decreases the number of necessary moulds, compensating the energy consumption per mould.

Thus, the 48 cavities alternative also presents the lowest environmental impact (EI) per unit produced. The normalisation of the results enables the conclusion that, regarding the environmental impact, the 16 and 32 cavities design alternatives present similar performance to the best alternative, having a minor efficiency difference. Contrary, since the manufacturing process of the mould of 64 cavities requires higher energy, it alternative presents 75% of the 48 cavities design efficiency. However, as it can be observed in the Table 6-2, presented above, the mould of 16 cavities has a lower environmental impact concerning the Product. Nevertheless, the material losses associated with its production are much greater than the other alternatives and must also be considered for the EI of the mould's design.

It is important to mention that the removed material is further transformed into steel chips and sold for recycling. The recycling process has an impact lower than zero, i.e. represents an environmental benefit, since the steel returns to the steel cycle to be used again.

6.2.2. Use phase of the mould

This phase is related to the use of the mould to produce the plastic parts; thus, operational aspects such as maintenance, energy consumption and consumables must be considered. Since the ultimate aim of an injection mould is to produce plastic parts, the mould performance in this task must be included in the lifecycle analysis. Therefore, the plastic material consumed, the production time required, the energy and the parts must be also included, representing fundamental parameters to compare the mould design and the mould manufacturing alternatives [25].

Therefore, the use phase of the mould corresponds to the Injection Moulding Process. Consequently, the results obtained in the previous Chapter 5 represent the economic analysis of the different design alternatives for this lifecycle phase. Table 6-3 represents the manufacturing costs per unit for all the production alternatives without internal recycling process and Table 6-4 represents the results for the alternatives which configuration includes internal recycling process.

Table 6-3: Use Phase costs per unit produced (design alternatives that do not have internal recycling)

Design Alternative	16E	16H	32E	32H	48E	48H	64H
Product [€/unit]	0,0129	0,0131	0,0120	0,0121	0,0115	0,0117	0,0118
Normalization	0,89	0,88	0,96	0,95	1	0,99	0,98
Material Loss [€/unit]	0,00041	0,00043	0,00028	0,0003	0,00023	0,00026	0,00027
Normalization	0,02	0,02	0,03	0,03	0,04	0,03	0,03
Total Costs [€/unit]	0,0133	0,0135	0,123	0,0124	0,0118	0,119	0,00121
Normalization	0,88	0,87	0,96	0,94	0,99	0,98	0,97

Table 6-4. Use Phase Costs per unit produced (design alternatives that have internal recycling)

Design Alternative	16E	16H	32E	32H	48E	48H	64H
Product [€/unit]	0,0129	0,0131	0,0120	0,0121	0,0115	0,0117	0,0118
Normalization	0,89	0,88	0,96	0,95	1	0,99	0,98
Material Loss [€/unit]	0,00039	0,00041	0,00025	0,0003	0,00021	0,00024	0,00025
Normalization	0,53	0,51	0,82	0,76	1	0,87	0,85
Total Costs [€/unit]	0,0133	0,0135	0,122	0,0124	0,0117	0,119	0,00120
Normalization	0,88	0,87	0,96	0,94	1	0,98	0,98

The results were already discussed in the previous Chapter 5, section *5.3 Analaysis of results*.

The environmental impact is caused by the individual impact of the material injected, the moulds and the energy consumed. The energy and mould the moulds' environmental impact are allocated under the material flows. The EI results for the use phase of the mould, i.e. injection moulding process, are presented in Table 6-5 and Table 6-6.

Table 6-5: Use Phase Environmental Impact per unit produced (electric machines)

Design Alternative	16	16R	32	32R	48	48R	64	64R
Product [μpoints/unit]	1 233	1 234	1 234	1 234	1 228	1 227		
Normalisation	0,995	0,995	0,995	0,994	1,0	1		
Material Loss [μpoints/unit]	4,90	1,32	4,34	0,61	4,17	0,41		
Normalisation	0,08	0,33	0,09	0,66	0,1	1		
Total [μpoints/unit]	1 238	1 235	1 238	1 235	1 231	1 228		
Normalisation	0,99	0,99	0,99	0,99	0,99	1		

Table 6-6: Use Phase Environmental Impact per unit produced (hydraulic machines)

Design Alternative	16	16R	32	32R	48	48R	64	64R
Product [μpoints/unit]	1 247	1 247	1 237	1 237	1 229	1 230	1 229	1 230
Normalisation	0,984	0,984	0,992	0,992	0,998	0,998	0,998	0,998
Material Loss [μpoints/unit]	4,95	1,24	4,35	0,62	4,18	0,41	5,05	0,41
Normalisation	0,08	0,33	0,09	0,66	0,1	1	0,08	1
Total [μpoints/unit]	1 252	1 248	1 241	1 238	1 233	1 231	1 234	1 231
Normalisation	0,98	0,98	0,99	0,99	0,99	0,99	0,99	0,99

The material injected is the resource that creates the greater EI in the process due to the high quantity of parts produced. The energy consumed is again, in terms of EI, more critical than in costs. Finally, the moulds cause a minor EI in this phase due to the high number of components produced.

The design alternatives that causes the lowest EI is the 48 cavities mould, using electric machines and internally recycling part of the material losses, since consumes less material and energy than the others. The worst alternative is the 16 cavities mould, using hydraulic machines based on the same reasons. This is the option that requires more material and consumes more energy.

Regarding the environmental performance of the product, the alternatives that use moulds with a lower number of cavities present worst environmental performances because these moulds lead to higher material losses in the injection process, consuming more material. Nevertheless, the normalisation of the results evinces a minor difference between the impacts produced per unit by each alternative in comparison with the best scenario, approximately 1%. This is due to the fact that the plastic material is the greater impact driver in the injection moulding process. However, for this particular case, none of the alternatives have high material losses, as was also concluded in the cost analysis. In injection processes that use hot runners the results and environmental impacts may be different due to the inherent material losses produced.

The analysis of the impacts caused by the material losses highlights the benefits of internally recycling the material losses in terms of ecological performance of the production system. The alternatives that do not recycle internally the rejected parts present around 10% of the efficiency obtained by the best scenario that internally recycles the material.

Another important conclusion is that, as expected, the production alternatives that use hydraulic machines present higher environmental impacts than the ones that use electric due to higher energy consumed by the hydraulic machines.

Though, the overall environmental performance of the alternatives is very similar, due to the high production volume and the low amount of material losses over the material injected by all the designs analysed. The normalisation of the total EI shows that the worst scenario has 98% of the best alternative efficiency.

6.2.3. End of Life phase

The End of Life assessment includes the economic and the environmental disposal impacts of the moulds and the produced parts.

For the moulds, the most common alternatives are the mould material recycling and the mould components reusing in a closed loop lifecycle [25]. In the present work, is assumed that the materials are entirely recycled.

The plastic parts can follow three end of life scenarios: landfill, incineration or recycling [49]. Due to the Product characteristics, the final disposal is the landfill. Nevertheless, the material losses generated during the injection moulding process are recycled.

In opposition to the other lifecycle phases, the economic evaluation of this phase is not performed through the direct application of the MFCA methodology. Instead, the costs related to collection methods and waste treatment processes of the different disposal possibilities, as well as the revenues generated by products of recycling, are assessed, as described in Table 6-7 [50]. SUW is the acronym of Solid Urban Wastes.

Table 6-7: Specific costs for the plastic different end of life processes [50]

Collection	Undifferentiated collection of SUW	45 €/ton
	Selective collection of plastics	110 €/ton
Waste treatment	Landfill fee	30 €/ton
	Plastics recycling process	300 €/ton
Recycled products	Recycled polypropylene	600 €/ton

The information to assess the End of Life costs of the mould was provided by *Renascimento, Gestão e Reciclagem de Resíduos, Lda*. The profit obtained from the steel sale for recycling is 170 €/ton. The revenues obtained must be translated to the Present Value, since the moulds are only sold at the end of the Product’s lifetime.

The Table presented above allows the determination of the costs values related to each scenario, Equation (6.1). This calculation together with the information provided by the MFCA related to the quantity of plastic injected per part and rejected, enables the determination of the End of Life costs associated to Products and Material Losses, Equation (6.2), (6.3) and (6.4).

$$C_{EoLscenario} = C_{Collection} + C_{waste\ treatment} - Revenues \tag{6.1}$$

$$C_{EoL} = C_{EoL\_product} + C_{EoL\_materiallosses} \tag{6.2}$$

$$C_{EoL\_product} = C_{EoL\_moulds} + C_{EoL\_plasticproducts} \tag{6.3}$$

$$C_{EoL\_materiallosses} = C_{EoL\_materialdischarges} + C_{EoL\_rejectedparts} + C_{EoL\_rejectedsteel} \tag{6.4}$$

Since the End of Life results are independent of the type of injection machine, the obtained costs and EI are presented to all the design alternatives regarding the number of cavities of the moulds and the internal recycling, or not, of the rejected components. Table 6-8 presents the End of Life costs per plastic part produced. The environmental analysis follows the same approach and procedure of the different phases described previously and is caused by the parts produced and the mould. The products which End of Life is a recycling processes lead to negative EI points since the materials returns to the cycle to be used again. Table 6-9 presents the EI per produced part.

Table 6-8: End of Life phase costs per unit produced

	16	16R	32	32R	48	48R	64	64R
Product [10^{-6}€/unit]	321,82	321,82	321,87	321,87	321,88	321,28	321,51	321,51
Normalisation	0,99	0,99	0,99	0,99	0,99	0,99	1	1
Material Loss [10^{-6}€/unit]	-6,87	-2,48	-5,77	-1,33	-5,47	-0,97	-6,68	-1,06
Normalisation	1	0,36	0,84	0,19	0,80	0,14	0,97	0,15
Total [10^{-6}€/unit]	314,95	319,36	316,10	320,54	316,41	315,65	314,83	320,45
Normalisation	1	0,99	0,99	0,98	0,99	0,98	1	0,98

Table 6-9: End of Life phase EI per unit produced

	16	16R	32	32R	48	48R	64	64R
Product [µpoints/unit]	47,26	47,26	47,35	47,35	47,36	47,36	46,76	46,76
Normalisation	0,99	0,99	0,99	0,99	0,99	0,99	1	1
Material Loss [µpoints/unit]	-4,09	-1,64	-3,37	-0,90	-3,18	-0,67	-3,87	-0,74
Normalisation	1	0,4	0,82	0,22	0,78	0,16	0,95	0,18
Total [µpoints/unit]	43,17	45,62	43,98	46,46	44,18	46,69	42,88	46,02
Normalisation	0,99	0,94	0,98	0,92	0,97	0,92	1	0,93

The results of both analysis directly depend on the material; thus, the final results and conclusions are proportionally the same.

The costs and EI caused by the product are related to the disposal of the produced parts and the mould. Since the parts and their disposal is equal to all the alternatives, the differences raises from the revenues and the positive EI of the mould recycling process at its EoL. Therefore, the scenarios which moulds have a higher quantity of material allocated to the production of one part lead to higher revenues and positive EI in the recycling process.

When analysed the material losses economic and environmental performance the same logic can be applied. Since the material losses are fully recycled at the EoL, the alternatives that had greater losses lead to higher revenues and positive EI. However, it is important to note that this results only regard the End of Life phase. If the overall balance is performed including the remaining phases the results are different.

For these reasons the worst scenario, only considering the End of Life phase, is the 48 cavities mould with internal recycling in the injection moulding process and the best scenario is the 64 cavities mould without internal recycling configuration. Nevertheless, the normalisation of the results shows that the difference between the alternatives performance is small. Regarding economic performance, the 48 cavities with internal recycling presents 98% of the efficiency obtained by the 64 cavities design and concerning the environmental impact, 92%.

Once evaluated the economic and environmental performance of each phase separately, the results must be integrated to assess the overall impact on the lifecycle of the Product, through the LCC and LCA methods. Then, both lifecycle dimensions are aggregated into a single analysis, using the LCE methodology, to perform a global evaluation of the alternatives. These three analysis and their corresponded results are presented in the following Chapters.

6.3. Economical assessment – LCC analysis and results

The LCC method integrates and evaluates all the economic consequences and financial trade-offs occurring throughout the life cycle of a product [4]. Table 6-10 and Table 6-11 presents the overall lifecycle costs per plastic part produced of each alternative. The last line of the tables normalises the results regarding the design with the lowest costs. This cost analysis is complemented by Figure 6-4 which describes the contribution of each phase to the total lifecycle costs.

Table 6-10: Life Cycle Costs per produced part (alternatives that do not have internal recycling)

Design alternative	16E	16H	32E	32H	48E	48H	64H
LCC [€/unit]	0,0136	0,0138	0,0126	0,0127	0,0121	0,1220	0,0124
Normalisation	0,88	0,87	0,95	0,94	0,99	0,98	0,97

Table 6-11: Life Cycle Costs per produced part (alternatives that have internal recycling)

	16ER	16HR	32ER	32HR	48ER	48HR	64HR
LCC [€/unit]	0,0136	0,0138	0,0125	0,0126	0,0120	0,0122	0,0123
Normalisation	0,88	0,87	0,96	0,94	1	0,98	0,98

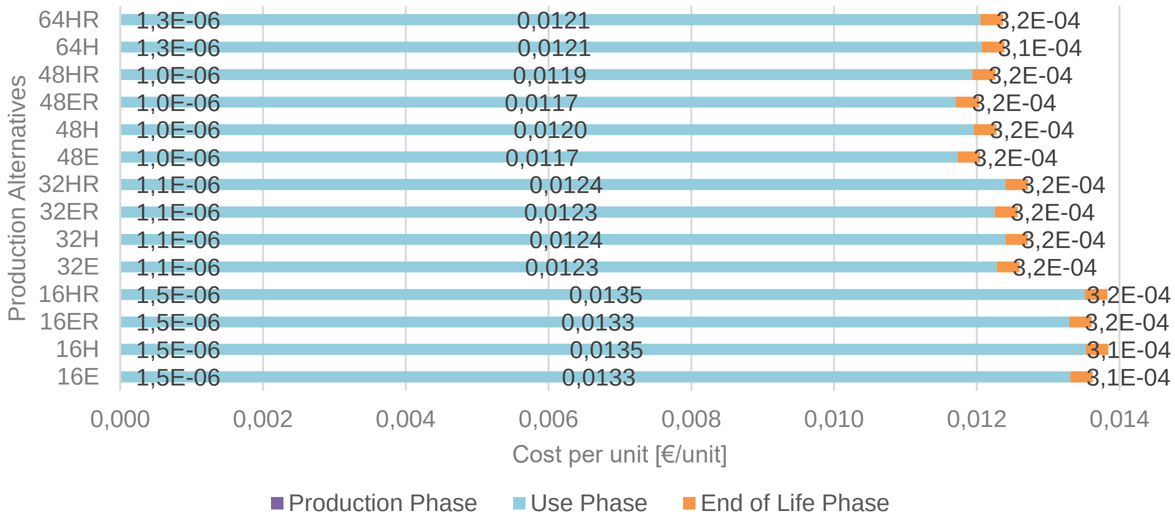


Figure 6-4: Costs break down by lifecycle phase per produced part

The alternative that presents lower costs is the 48 cavities, using electric machines with internal recycling of the material in the injection moulding process, for the reasons described previously. Summing, due to the number of required moulds, its manufacturing process consumes less material in the production phase, the number of cavities of the mould and the injection process configurations cause less material losses, consuming less material in the use phase. Finally, the electric machines consume less energy when compared against the hydraulic machines.

Based on the normalisation of the results it is possible to conclude that the economic performance of the other design alternatives that use moulds of 48 cavities and of 64 cavities is similar, presenting a financial efficiency only 2% lower. The use of moulds of 32 cavities presents, depending on the configuration, efficiencies from 94% to 96% of the best solution. Finally, lower results, i.e. higher lifecycle costs per part produced, are caused by the alternatives that use moulds of 16 cavities, leading to economic efficiencies 13% lower.

From this analysis is possible to conclude that the lifecycle costs are primary influenced by the number of cavities of the mould, followed by the internal recycling of the plastic rejected at the Use phase and then, by the use of hydraulic or electric machines.

Table 6-4 evinces that, in the present study, the influence of the Production phase is almost neglectable due to the high number of components produced per each mould. The primary cost driver is the Use phase, representing more than 95% of the costs and largely influencing the lifecycle costs associated to the manufacturing of one unit. The End of Life phase represents around 5% of the total costs for all the alternatives.

6.4. Environmental assessment – LCA analysis and results

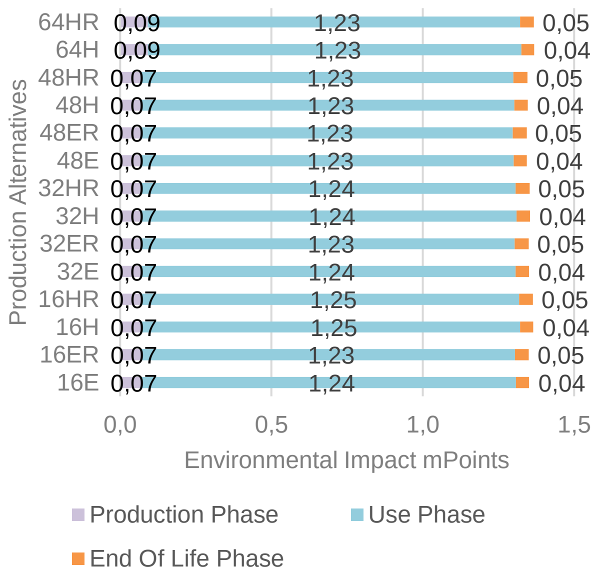
The LCA analysis enables the evaluation of potential environmental impacts of a product throughout its life cycle [19], [23]. Table 6-12 and Table 6-13 presents the potential environmental impacts per part of each alternative. Figure 6-5 (left graphic) complements the environmental analysis illustrating the contributions of each phase to the entire environmental impact of the product.

Table 6-12: Environmental Impact per produced part (alternatives that do not have internal recycling)

Design Alternative	16E	16H	32E	32H	48E	48H	64H
EI [mPoints/unit]	1,351	1,365	1,351	1,354	1,344	1,347	1,368
Normalisation	0,994	0,984	0,994	0,992	0,999	0,997	0,982

Table 6-13: Environmental impact per produced part (internal recycling alternatives)

Design Alternative	16E	16H	32E	32H	48E	48H	64H
EI [mPoints/unit]	1,350	1,364	1,350	1,353	1,343	1,346	1,367
Normalisation	0,995	0,985	0,995	0,993	1	0,998	0,982



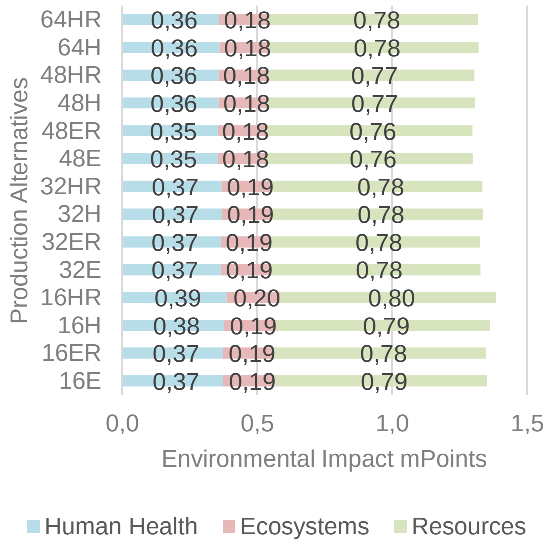


Figure 6-5: Left: EI break down by lifecycle phase per produced part; Right: EI break down by environmental category per produced part.

The design alternative that has the best environmental performance, i.e. causes the lowest environmental impact, is the 48 cavities mould, using electric machines and internally recycling the material losses in the Use phase. As in the economic appraisal, this is due to the fact that this option is the one that consumes less resources, material and energy.

In opposition to the results obtained in the LCC analysis, the environmental performance of all the alternatives is very similar. The worst scenario presents 98% of the best alternative ecological efficiency.

The same relationship between the number of cavities of the mould and the performance of the different production alternatives can be also found in the environmental analysis, since this parameter directly influences the material and the energy consumed.

Thus, the environmental impact of the alternatives depends first on the number of cavities of the mould, and then, on the internal recycling process and the type of injection machines.

From Figure 6-5 (left graphic) is possible to conclude that the environmental impacts are primarily caused by the Use phase of the mould due to the quantity of resources used, namely material and energy. Moreover, the Production phase contributes more than the End of Life phase to the potential environmental impact, representing 5% of the total impact points.

The environmental indicator used for the LCA analysis also allows the identification of the impacts in the Human Health, Ecosystems and Resources, presented above in Figure 6-5 (right graphic). The major impact is caused in the resources, 60% due to the amount of material and energy consumed.

The application of the ReCiPe Midpoint (H) V1.11 / Europe Recipe H to assess the LCA results allows the deeper categorisation of the impact indicators. Figure 6-6 illustrates the normalised impact results obtained for each production alternative in each category. The results are normalised from 0 to 10, where 10 represents the highest impact.

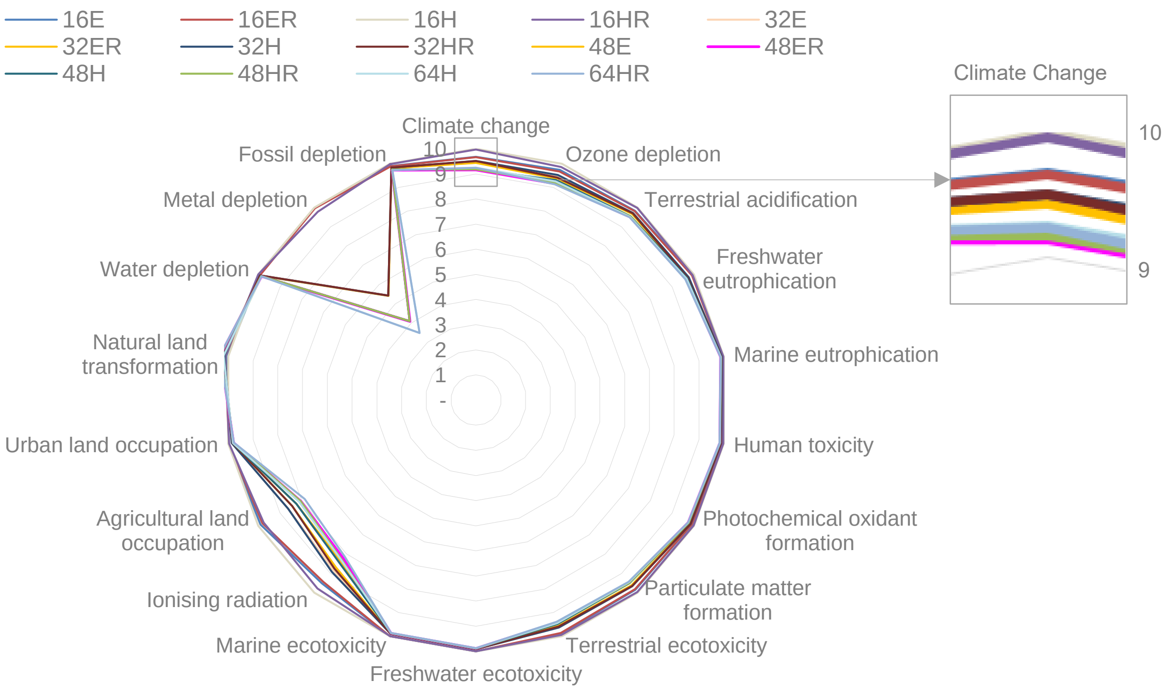


Figure 6-6: Normalised Environmental Impact in each ReCiPe Midpoint (H) V1.11 / Europe Recipe H category per produced part

Nevertheless, when it is analysed the environmental performance of a product or a process the primary indicator is the climate change, evaluated through the kilograms of CO_2 equivalents. To facilitate its reading, a magnification of the *Climate change* category area of the graphic is presented.

Thus, albeit the alternatives that use moulds of 64 cavities seems to cause lower environmental impacts in several categories, they present a lower performance regarding the climate change. Table 6-14 shows the grams of CO_2 equivalent caused by one unit of Product through its entire lifecycle per each production alternative.

Table 6-14: Grams of CO_2 equivalent per produced part

	16				32				48				64	
	E	ER	H	HR	E	ER	H	HR	E	ER	H	HR	H	HR
g CO_2 eq	16,2	16,1	16,7	16,6	15,8	15,8	15,9	15,9	15,3	15,3	15,3	15,3	15,4	15,4
Normalis.	0,95	0,95	0,92	0,92	0,97	0,97	0,96	0,96	1	1	1	1	0,99	0,99

The design alternatives that cause the lowest number of grams of CO_2 equivalent coincide with the alternatives that have a better environmental performance, which are the ones that use moulds of 48 cavities. The worst scenario is again obtained for the designs that use moulds of 16 cavities, and lead to more than one gram of CO_2 equivalent per plastic part produced. This represents more 360 tons of CO_2 equivalent per year.

6.5. LCE model and results

After the evaluation of the economic and environmental dimensions separately, the results should be aggregated to perform the global evaluation and select the best alternative regarding both dimensions. Thus, the presented results are integrated in the LCE model to assess the overall life cycle performance of the different alternatives. Since only two dimensions are compared, the best solutions can be "mapped" through the CLUBE method, regarding the performance of the design alternatives in terms of costs and environmental impact [51].

However, in the present analysis, the best alternative regarding the environmental and the economic performance, from the Producers and the Consumers perspective is always the same: moulds of 48 cavities, internally recycling the material losses in the Use phase and using electric machines. Therefore, the method is not applied and the results are not mapped on a graphic because the best alternative is the same for all the cases.

6.6. Conclusions

The integration of the MFCA in the LCE as economic appraisal tool to assess the LCC model is possible thanks to the modifications performed to the original calculated model which allows the analysis of different configurations of a production system.

The individual application of the MFCA methodology to each lifecycle phase, on the one hand, assess the economic performance of each stage and, on the other hand, provides the necessary information to perform the environmental appraisal. Therefore, not only creates as common data base for both evaluations, but also reduces the double effort of data compilation and analysis. Nevertheless, this requires the collaboration of the different companies and stakeholders involved in the lifecycle of the product. In the present work, the Production and the User companies belong to the same Company Group.

Furthermore, the application of the MFCA methodology to assess the costs and compile the information for the environmental analysis adds a new dimension to the lifecycle appraisals. It enables the evaluation of each phase regarding the products and the material losses separately, providing a deeper comprehension of the material uses and resources efficiency throughout the entire lifecycle.

The following Chapter presents and proposes a methodology to integrate the MFCA in the LCE model based on the results, and conclusions obtained from the work presented. This represents the ultimate goal of the present dissertation.

7. Proposed Methodology for MFCA incorporation in LCE analysis

In this Chapter is described the proposed methodology for the incorporation of the MFCA in the LCE model for product and process design. The methodology follows the approach described in Figure 7-1, aiming at the comparison of the lifecycle performance of different design alternatives.

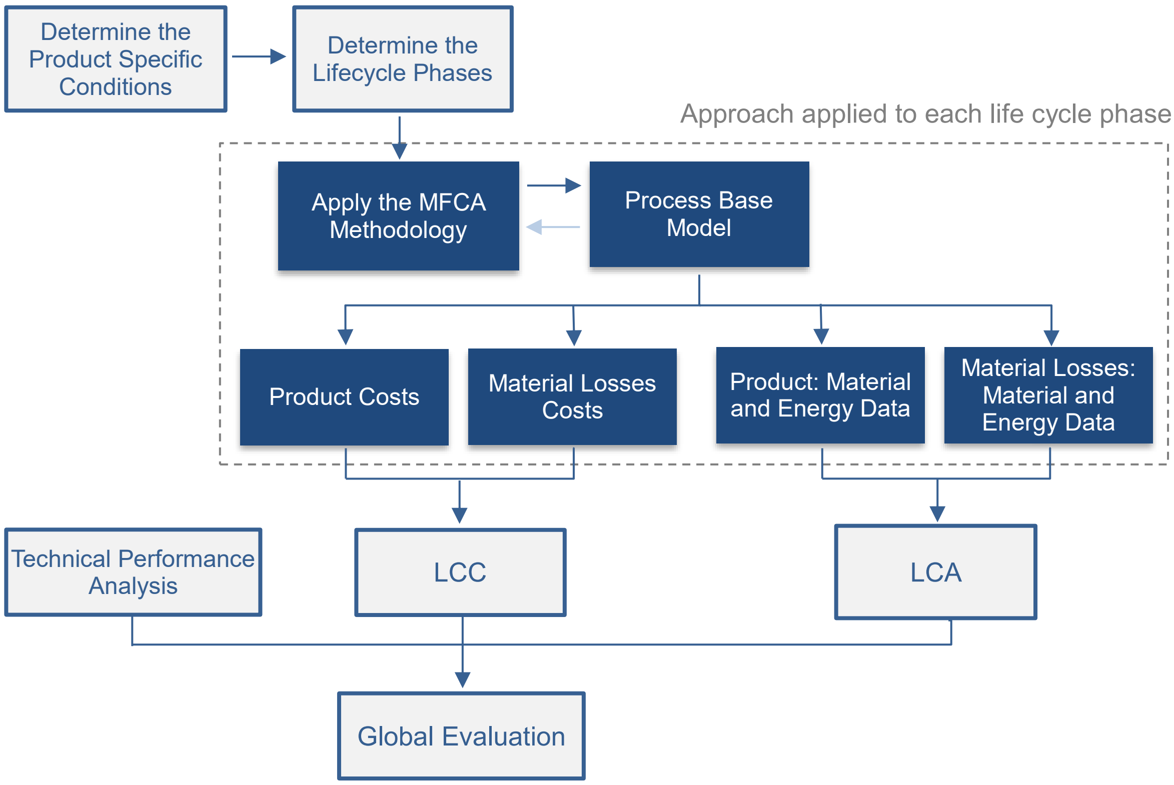


Figure 7-1: Overview of the Life Cycle Engineering framework

First, the product specifications and the different design alternatives to be compared must be defined. Thus, some parameters such as materials, production volume, product lifetime, processing requirements among other variables considered relevant for the analysis should be determined.

The LCE analysis often considers the entire lifecycle of the product, from the raw material acquisition to end of life. Hence, once characterized the product and the design alternatives, the lifecycle phases considered for the analysis must be determined, as well as the boundary conditions of each system.

Then, the MFCA methodology is applied to each lifecycle phase with the aim of developing a Process Based Model. The developed model is also validated by the MFCA methodology, through the comparison of the results.

The application of the MFCA methodology to each lifecycle phase can be performed following the procedure described in Chapter 2, section *2.3 MFCA implementation methodology*.

The primary objective of the Process Based Model is the quantification of the necessary resources in each process and quantity centre through theoretic and empirical relations. This analysis enables the evaluation of the different alternatives in the early design phase. This, together with the MFCA methodology, not only a deeper knowledge about the production context is achieved, but also actual data of the existent production for the refinement and model validation. It supports the economic assessment and provides the necessary information for the evaluation of the system's environmental impacts. Therefore, the outputs of the model are:

- Costs related to the Product and Material losses separately, to be integrated in the Life Cycle Costs analysis;
- Material and Energy data related to the Product and Material losses separately, to perform the environmental analysis.

Additionally, it is important to note that the Process Based Model is specifically designed for the system in analysis, supporting the company in further decision making. In parallel it can be used to perform sensitive analysis to study the influence of different parameters in the total costs and environmental impact, such as the production volume, the lifetime of the product or technical characteristics.

The information provided about the costs for each individual lifecycle phase should be integrated in a single analysis, applying the Life Cycle Costs method, to assess the overall economic performance of the product throughout its lifecycle.

The data provided about the material and energy flows is used to perform the environmental analysis of the Product, through the Life Cycle Assessment method. For this analysis, different environmental indicators, data bases and software can be used. The present work applied the ReCiPe Midpoint (H) V1.11 / Europe ReCiPe H method, the Eco Invent 3 database and the LCA software SimaPro, 2011.

In parallel, the functional assessment of the alternatives should be also performed. The technical evaluation must consider the relevant requirements that must be fulfilled by the different analysed scenarios [6]. This analysis is out of the scope of the present dissertation.

Finally, the results obtained from the economic, environmental and technical performance dimensions must be aggregated in a single analysis framework for the global evaluation of the alternatives. For this step, literature proposes different approaches and methodologies depending on different aspects such as the primary objectives of LCE analysis, the dimensions considered or the companies' strategies. Three possible methods are:

- Attribution of importance weights to each individual dimension [6];
- The development of a ternary diagram, where each axis represents one dimension of analysis, mapping the best solution according to a set of weights, as well as the domain of weights for each best option [16];
- Application of the CLUBE method to compare the economic and environmental dimensions and including different levels of importance that each stakeholder might give to each lifecycle stage [51].

The application of the MFCA methodology enables the evaluation of the economic and environmental performance, in terms of Products and Losses separately, highlighting the impact caused by the material and energy losses in each life cycle phase. This adds a new dimension to the LCE analysis supporting the identification of the primary sources of loss and quantifying their impact in the overall lifecycle.

Furthermore, it creates a common database for the economic and the environmental analysis; hence, linking the LCC and the LCA assessments. This leads to two important advantages. On the one hand, it increases the consistency and the significance of the results when both evaluation are compared, since both appraisals are based on the same information and assumptions, together with that fact that are performed within the same boundaries. On the other hand, it reduces the effort of data compilation and analysis, which often represent the most time-consuming activities.

8. Conclusions and Future work

The present dissertation had three primary objectives. In a first approach, the application of the MFCA methodology to a production line and the evaluation of its benefits as a diagnosis tool and analysis potentialities. Once understood the main advantages and limitations of the method, aims at the extension of its applicability to appraise different design configurations. Finally, and as the ultimate goal of the present dissertation, the enlargement of the MFCA methodology scope to be incorporated in the Life Cycle Engineering for products and processes design. To achieve these three goals, a manufacturing unit with a Plastic Injection Moulding process was used as a case-study.

The application of the original MFCA methodology to a particular component production system, supported the company to better understand the magnitude, consequences and drivers of material use and losses. It allowed the perception of material losses as a determinant target of production profits and gains instead of a minor issue of quality management. Hence, its application enabled the identification of critical points and the development of solutions to enhance the environmental and economic performance of the production unit.

Therefore, the MFCA proved to be a significant tool for the comprehension of resources use and efficiency, as well as a promising instrument regarding the identification of inefficiencies and their financial effect. Its focus on the reduction of costs through the improvement of resources' efficiency, fosters the productivity of the company. Simultaneously decreases the wasteful flows; thus, contributing to a positive environmental impact.

Nevertheless, the proposed improvement actions should be supported by a cost-benefit analysis and the evaluation of the consequences on the entire production system. In this context, the MFCA original calculation model was extended into a Process Based Model for the appraisal and comparison of different design alternatives. It is important to note that the MFCA methodology and the data collected from the production shop-floor allowed the development of a PBM contextualised for that particular production system and to obtain results more close to the reality.

To validate the model, several processes designs were considered and compared regarding the resources consumed and costs. This analysis leads to the conclusion that to extend the MFCA applicability to evaluate different design configurations a specific Process Based Model must be developed for the system in analysis. For its development, a deep knowledge of the process and systems is fundamental, to identify and accurately estimate the more relevant parameters which may influence the alternatives performance. The model must consider the entire investment useful life, include investment appraisal variables, and evaluate future states. Hence, it must be able to forecast future data, future costs and the necessary resources required for each design alternative.

Subsequently, from the successfully obtained results, it was possible to conclude that the MFCA scope can be extended to appraise different design and configurations of a product production system, which represents the second objective of this work.

Furthermore, one of the inherent limitation of MFCA methodology to be applied for design decision-making, pointed by literature, was mainly related to the fact that it evaluates the process as-is state. The refinement performed, incorporating the development of a Process Based Model as the primary calculation tool, allowed to overcome this issue.

Additionally, the sensitivity analysis enabled the dynamic evaluation of the solutions for different design alternatives. The obtained results allow a deeper comprehension of the examined variables and a wider perspective of the system itself, evincing the MFCA potentialities as a dynamic appraisal tool and as a strong support instrument for decision-making.

Finally, the ultimate aim of the present work is to incorporate the MFCA in the LCE model for design decision-making. To achieve that purpose the different design alternatives were evaluated from a lifecycle perspective applying the MFCA methodology to each lifecycle phase. Since the technical performance of the Product was not influenced by the different compared configurations, the LCE analysis only included environmental and economic dimensions analysed through the LCC and LCA models respectively.

The approach followed was developed based on the similarities found between LCC and LCA models, discussed in the first Chapter of this dissertation, and the extension of the MFCA original scope through the incorporation of a Process Based Model. Literature had already pointed the MFCA as a potential link between LCC and LCA models, due to its simultaneous goal of improving economic and environmental performances of a company. Furthermore, the extension of the MFCA applicability to the supply chain inherently addresses both enhancements for the entire lifecycle of the product.

Thus, the MFCA extended methodology was applied to each lifecycle relevant phase for the assessment of the economic performance. The data provided by the Process Based Model about the material and energy uses supported the assessment of the environmental impact of each phase. Then, the obtained results for each phase were integrated in the LCC and LCA models for the overall assessment of the economic and environmental impacts respectively. For the global evaluation, none of the suggested methods in the methodology was applied, since the best alternative was the same for all the dimensions in analysis and regarding the Producer and the User perspectives.

The applied methodology allowed to identify the best alternative regarding both dimensions, economic and environmental from the different stakeholders' perspective and considering the entire lifecycle of the Product. The obtained results allowed and supported the development of the methodology proposed in the previous Chapter to integrate the MFCA methodology in the LCE model.

On the one hand, the incorporation of the MFCA as an LCE tool links the LCC and LCA assessments, increasing the consistency and the significance of the results when both dimensions are compared. The creation of a common database contributes to the harmonisation of both models, establishing the same boundaries and assumptions. Additionally, reduces the double effort of data compilation and analysis.

On the other hand, adds a new dimension to the lifecycle analysis, enabling the evaluation of the economic and environmental performances, in terms of Products and Losses separately. It can support the identification of the primary sources of loss and quantify their impact in the overall lifecycle. Moreover, provides a deeper comprehension of the importance of resources efficiency and its consequences throughout the entire lifecycle.

8.1. Future Work

In this Chapter, a few suggestions for future work are presented.

First it is suggested the application of the proposed methodology to an entire supply chain. One of the major challenges is the sharing of technical details and costs information between different companies. The incorporation of the MFCA in the LCE can potentially contribute for the enhancement of the resources efficiency throughout the lifecycle of product. The identification of the material losses and the quantification of its real economic and environmental impact in the entire supply chain can potentially lead to the improvement of both performances. Nevertheless, the reduction of losses may lead to unequal distributions of the costs and advantages among the partners. Thus, a broader study may be necessary to overcome the difficulties related with confidentiality reasons and the implementation of an enhanced solution.

It is also suggested the inclusion of the profits contribution in the Process Based Model, as well as a deeper analysis regarding the investment appraisal of different design alternatives to support the extension of the MFCA scope as an appraisal tool. For that, it is suggested the application of the proposed methodology to evaluate different design alternatives to a case-study, which design configuration imply divergent revenues for the company. Another interesting analysis may be the comparison of the optimal solution, including all the necessary investments to be implemented, against the actual production system and evaluate its viability and if it is economical advantageous.

Finally, it is also suggested the development of a methodology or an approach to modelling the energy flows independently to the material flows. The allocation of the energy flows under the material flows neglects information about the consequences and drives of energy losses, as well as the appraisal of wasted energy in form of heat and vibrations. The identification of energy inefficiencies may reveal potentials for costs savings and improve the environmental performance of the company.

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Annexes

Annex A - MFCA application – Operating Materials

Injection Operating Materials for both components:

- Alcohol 96% (used in the shiftily maintenance);
- Cleaning Cloths (used in all the maintenance);
- Tribol 4020/220-2 (used in the weekly and monthly maintenance);
- Petraqua and Salt (used in the monthly maintenance);
- Tribol 800/460 (used in the annual maintenance);
- Tribol 800/220 (used in the annual maintenance);
- Tribol 3020/100 (used in the annual maintenance);
- Mass for moulds maintenance (used in the annual maintenance).

Packaging Operating Materials for both components:

- Tags (one per 2500 components);
- Adhesive tape (one portion per 2500 components);
- Boxes (one per 2500 components);
- Plastic bags (one per 2500 components);
- Pallets (one per 48 boxes of Part A and per 16 boxes of Part B);
- Foam paper (one per pallet).

Final Product Warehouse Operating Materials for both components:

- Palletizing film (one portion per pallet).

Annex B - MFCA application – Quantity centres determination and characterisation

Table B-1 Main identified activities in each zone of the production system

Area	Activities
Raw Material Warehouse	• Reception and storage of the raw material in the raw material warehouse; • Suction of the raw material from the big bag to the hopper dryer; • Distribution to the injection machines from the hopper dryer.
Injection and adjacent areas	• Injection moulding process • Packaging of the produced parts in carton boxes; • Organization of the boxes in pallets and transportation to the final product warehouse; • Quality control of one shot per hour per injection machine; • Transportation of the rejected parts to the shredding area; • Transportation of the material discharged after set-ups and the contaminated parts to the Plastics' collection area.
Fina Product warehouse	• Palletizing the parts' pallets; • Truck loading and delivered to the customer;
Shredding area	• Rejected parts shredding; • Storage of the shredded materials.
Plastic collection area	• Sale of material discharges and contaminated parts.

Table B-2: Inputs and outputs of each quantity centre, together with the compilation technique applied

Raw Material Warehouse

- Input: Raw material – observation and accounting;
- Output (product flow): Raw material consumed – accounting and production calculation model.

Hopper Dryer

- Input: Material sucked by the vacuum pump – production calculation model:
- Output (product flow): Material distributed to the injection machines – production calculation model.

Injection (Part A and Part B)

- Input: amount of material injected – production calculation model;
- Input (operating materials): materials and products used in the maintenance of the machines –stocks records, observation and interviews;
- Output (product flow): Produced parts – production calculation model;
- Output (material loss flow): Material discharged after set-ups, rejected and contaminated parts and operating materials – weighing and stocks records, respectively.

Part A – Quality control

- Input: samples to be tested – observation and quality records;
- Output (material loss flow): tested samples – quality records.

Part B – Quality control

- Input: samples to be tested – observation and quality records;
- Output (product flow): tested samples – quality records.

Part A – Packaging

- Input: produced part to be packaged – production calculation model;
- Input (operating materials): carton boxes, plastic bags, pallets – Production Calculation Model, stock records and logistic records;
- Output (product flow): parts properly packaged, carton boxes, plastic bags and pallets – production calculation model, stock records, logistic records, observation.

Part B – Packaging

- Input: produced part to be packaged and tested parts after being stored for six months – production calculation model and quality records, respectively;
- Input (operating materials): carton boxes, plastic bags, pallets – Production Calculation Model, stock records;
- Output (product flow): parts properly packaged, carton boxes, plastic bags and pallets – production calculation model, stock records, logistics records and observation.

Final product warehouse (Part A and Part B)

- Input: boxes containing the produced parts to be delivered to the client – production calculation model and logistic records;
- Input (operating materials): palletizing film – production calculation model, stock records, observation and interviews;
- Output (product flow): parts palletized and palletizing film – production calculation model, logistic records, stock records, observation and interviews;

- Output (material loss flow) parts returned by the customer – quality records.

Part A – Waste management (rejected)

- Input: rejected parts and tested parts after the quality control destructive test – weighing and quality records;
- Output (material loss flow): shredded material – estimated.

Part B – Waste management (rejected)

- Input: rejected parts – weighing;
- Output (material loss flow): shredded material – estimated.

Waste management (discharges and contaminated) – (Part A and Part B)

- Input: discharged material after set-ups and contaminated parts – weighing;
- Output (material loss flow): sold material – estimated.

Annex C - MFCA application - System Costs Data

Dedicated Employees:

The dedicated employees are organised in three shifts. Each shift has one team leader and four dedicated employees. On the one hand the team leader is responsible for the team and shift change coordination, control and solve problems, perform the maintenance of the injection machines each sift and change the Big Bags of raw material. On the other hand, the employees must perform the quality control tests, check the Big Bags of raw material, package the components and check the cycle time and the size of the pillow of the injection machines. Based on the activities performed by each type of worker and the time required to execute them, their labour costs are distributed for the quantity centres presented in Table C-1.

Table C-1: Dedicated employees' labour costs allocation results.

	Raw Material Warehouse	Part A Injection	Part A Quality Control	Part A Packaging	Part B Injection	Part B Quality Control	Part B Packaging
Team Leader	25%	35%	-	-	40%	-	-
Employee	5%	5%	10%	35%	5%	10%	30%

Raw Material Warehouse Employee:

It is one employee responsible for receiving the raw material for the production and store it in the raw material warehouse and for receiving and store the operating materials, such as boxes and pallets, used to pack the final product. Therefore, his work and consequently his labour costs are to the following quantity centres in the percentage indicated:

- Raw Material Warehouse – 2%;
- Part A – Packaging – 2%;
- Part B – Packaging – 2%.

Employee responsible for grinding the defective products:

The costs of this employee are 10% allocated to this production system:

- Part A - Waste management (rejected) – 5%;
- Part B - Waste management (rejected) – 5%.

Final Product Warehouse employee:

They are organised in 3 shifts with one employee per shift that is responsible for palletizing and store the pallets containing both parts of the final product, and for loading them into the customers' trucks, which is the last activity within the defined frontiers of the analysis. Therefore, their costs are only allocated to the Final Product Warehouse quantity centres in the following proportions:

- Part A – Final Product Warehouse – 13%;
- Part B – Final Product Warehouse – 13%.

Table C-2: Production system equipment - classification and allocation results per quantity centre

Quantity Centre	Equipment	Type	% cost allocated
Raw Material Warehouse	Fork Lift	Non-dedicated	43%
	Electric Stacker	Non-dedicated	43%
	Manual Stacker (two)	Non-dedicated	43%
Hopper Dryer	Vacuum pumps (two)	Dedicated	100%
	Hopper Dryer	Dedicated	100%
Part A – Injection	Injection Machines, moulds and accessories (three)	Dedicated	100%
	Chillers (two)	Dedicated	50%
Part B – Injection	Injection Machines, moulds and accessories (three)	Dedicated	100%
	Chillers (two)	Dedicated	50%
Part A – Quality Control	Easy – Open machine	Dedicated	100%
Part B – Quality Control	Poka-yoke	Dedicated	100%
Part A – Packaging	Weight scale	Dedicated	52%
	Manual Stacker	Non-dedicated	22%
Part B – Packaging	Weight scale	Dedicated	48%
	Manual Stacker	Non-dedicated	22%
Part A – Final Product Warehouse	Stretch wrapper	Non-dedicated	11%
	Electric Stacker	Non-dedicated	11%

	Manual Stacker (two)	Non-dedicated	11%
	Electric Fork-lift (two)	Non-dedicated	11%
Part A – Final Product Warehouse	Stretch wrapper	Non-dedicated	32%
	Electric Stacker	Non-dedicated	32%
	Manual Stacker (two)	Non-dedicated	32%
	Electric Fork-lift (two)	Non-dedicated	32%
Part A – Waste management (rejected)	Shredding machine	Non-dedicated	22%
Part B – Waste management (rejected)	Shredding machine	Non-dedicated	22%

Annex D - Input variables for the Process Based Model

Material Data
• Unit Cost [€/ton] • Density [kg/m^3] • Thermal Diffusivity [m^3/s] • Injection Temperature [ºC] • Ejection Temperature [ºC] • Mould Temperature [ºC] • Thermal Conductivity [W/mK] • Specific Heat [J/kgK] • Melt Temperature [ºC] • Degree of crystallinity [%] • Typical injection pressure [Pa] • Heat of fusion for 100% crystalline polymers [J/kg]
Operating Materials Data
• Tags [€/unit] and [units/day] • Adhesive tape [€/unit] and [units/day] • Part A – Boxes [€/unit] and [units/day] • Part B – Boxes [€/unit] and [units/day] • Part A – Plastic Bags [€/unit] and [units/day] • Part B – Plastic Bags [€/unit] and [units/day] • Pallets [€/unit] and [units/day] • Foam paper [€/unit] and [units/day] • Palletizing film [€/unit] and [units/day] • Materials used to perform the maintenance [€/unit] and [units/day]
Part Data
• Volume [mm^3] • Thickness [mm] • Projected Area [mm^2] • Part Lifetime [years]
Mould Data
• Number of cavities • Plates Dimensions [mm^2] • Acquisition Costs [€/unit] • Lifetime [shots]
Injection Machine Data
• Acquisition Costs [€] • Type of injection machine • Clamping force [kN] • Installed Power [kW] • Plate dimensions [m^2] • Dimensions [m^2] • Lifetime [years]
Injection Moulding Process Data

- Daily Production Volume [units]
- Working days [days/year]
- Number of moulds and injection machines required
- Number of shifts [shifts/day]
- Number of quality control tests [tests/day]
- Number of maintenances [maintenance/day]
- Stabilization time after programmed and non-programmed stops [h/day]
- Quality control tests time [h/day]
- Maintenance time [h/day]
- Production time [h/day]
- Rejection Rate [%]
- Recyclability Rate [%]

Energy Data

- Injection Machine Data
- Production time [h/day]
- Cycle time [s/cycle]
- Number of cavities
- Material Data
- Part Data
- Energy model coefficients
- Energy unit cost [€/kWh]

System Costs – Labour Data

- Number of workers per machine
- Number of employees per shift
- Number of Injection machines
- Number of shifts
- Production Time [h/day]
- Dedicated employees' unit cost [€/h]
- Non-dedicated employees' unit cost [€/h]
- Dedicated employees time assigned to each quantity centre [h/quantity centre]
- Non-dedicated employees time assigned to each quantity centre [h/quantity centre]

System Costs – Space Data

- Boundaries of each quantity centre [m^2]
- Building unit cost [€/m^2]

System Costs – Equipment Data

- Number of moulds
- Moulds acquisition costs [€/unit]
- Number of injection machines
- Injection machines acquisition costs [€/unit]
- Interest rate [%]
- Parts lifetime
- Number of chillers
- Chiller acquisition costs [€/unit]
- Hopper dryer acquisition cost [€/unit]
- Vacuum pumps acquisition cost [€/unit]
- Easy-open equipment acquisition cost [€/unit]
- Poka-yoke acquisition cost [€/unit]
- Weight scale [€/unit]
- Support non-dedicated equipment allocation costs [€/day]

Annex E - Material consumed by each design alternative

Table E-1: Material consumed by each design alternative to produce 1 000 000 components of Part A

	Raw Material Required [kg]	Material Wasted [kg]	Material internally recycled [kg]
16 E	2 362,48	12,48	-
16 ER	2 362,48	3,00	9,48
16 H	2 362,48	12,48	-
16 HR	2 362,48	3,00	9,48
32 E	2 361,20	11,2	-
32 ER	2 361,20	1,50	9,70
32 H	2 361,20	11,2	-
32 HR	2 361,20	1,50	9,70
48 E	2 359,93	10,93	-
48 ER	2 359,93	1,00	9,93
48 H	2 359,93	10,93	-
48 HR	2 359,93	1,00	9,93
64 H	2 362,73	12,73	-
64 HR	2 362,73	1,00	11,73

Table E-2: Material consumed by each design alternative to produce 1 000 000 components of Part B

	Raw Material Required [kg]	Material Wasted [kg]	Material internally recycled [kg]
16 E	4 211,06	11,06	-
16 ER	4 211,06	3,00	8,06
16 H	4 211,06	11,06	-
16 HR	4 211,06	3,00	8,06
32 E	4 209,56	9,56	-
32 ER	4 209,56	1,50	8,06
32 H	4 209,56	9,56	-
32 HR	4 209,56	1,50	8,06
48 E	4 209,06	9,06	-
48 ER	4 209,06	1,00	8,06
48 H	4 209,06	9,06	-
48 HR	4 209,06	1,00	8,06
64 H	4 211,75	11,75	-
64 HR	4 211,75	1,00	10,75

Annex F - Moulds acquisition analysis

Table F-1: Lifetime of the moulds

	Mould to produce Part A	Mould to produce Part B
Nº of cavities	Mould Life Time	Mould Life Time
16	3,32	3,33
32	3,32	3,33
48	3,32	3,33
64	4,42	4,43

Table F-2: Numbers of moulds and years of acquisition throughout the Product's lifetime analysis

Nº of cavities	Nº of moulds required	Years				
		0	1	2	3	4
Moulds acquisition analysis to Produce Part A						
16	6	6	0	0	6	0
32	3	3	0	0	3	0
48	2	2	0	0	2	0
64	2	2	0	0	0	2
Moulds acquisition analysis to Produce Part B						
16	6	6	0	0	6	0
32	3	3	0	0	3	0
48	2	2	0	0	2	0
64	2	2	0	0	0	2

The overall costs related to the moulds acquisition throughout the entire lifetime of the product is translated to the Present Value using Equation (E.1), where r is the interests rate.

$$Present\ Value = \sum_{i=0}^{4} \frac{Future\ Costs}{(1+r)^i} \tag{E.1}$$

The system costs related to the moulds acquisition costs is equal to the correspondent annuity calculated based on the interest rate, the number of payments and the present value.

Annex G - MFCA methodology applied to the Production Phase (Moulds' production)

Table F-1: Material required for the moulds production depending on the number of cavities

	Mould A				Mould B			
Nº of cavities	16	32	48	64	16	32	48	64
Raw Material required [kg]	1275	2175	3193	4088	1121	1932	2742	3489
Product (Mould) [kg]	925	1767	2700	3509	814	1563	2288	2949
Material Losses [kg]	350	408	493	579	307	369	454	540

Table F-2: MFCA costs of the Production of Mould A (results per mould produced)

Nº of cavities	**16**	**32**	**48**	**64**
Inputs Costs				
Raw Material	96,61 k€	139,41 k€	185,66 k€	231,05 k€
Operating materials	0,13 k€	0,25 k€	0,38 k€	0,51 k€
Energy Costs				
Energy Consumed	0,34 k€	0,59 k€	0,84 k€	1,10 k€
System Costs				
Labour	8,83 k€	13,33 k€	17,84 k€	22,34 k€
Equipment	7,18 k€	11,65 k€	16,12 k€	20,59 k€
Tooling	1,50 k€	2,46 k€	3,42 k€	4,37 k€
Space	0,10 k€	0,17 k€	0,24 k€	0,30 k€
Maintenance	0,18 k€	0,29 k€	0,4 k€	0,51 k€
Outputs				
Product	83,24 k€	136,40 k€	189,85 k€	240,57 k€
Material Losses	31,63 k€	31,75 k€	35,05 k€	40,20 k€

Table F-3: MFCA costs of the Production of Mould B (results per mould produced)

Nº of cavities	16	32	48	64
Inputs Costs				
Raw Material	94,33 k€	140,65 k€	187,24 k€	232,99 k€
Operating materials	0,19 k€	0,39 k€	0,58 k€	0,77 k€
Energy Costs				
Energy Consumed	0,45 k€	0,76 k€	1,06 k€	1,37 k€
System Costs				
Labour	8,99 k€	13,42 k€	17,85 k€	22,28 k€
Equipment	7,95 k€	13,33 k€	18,70 k€	24,08 k€
Tooling	1,78 k€	2,91 k€	4,03 k€	5,15 k€
Space	0,12 k€	0,20 k€	0,28 k€	0,36 k€
Maintenance	0,20 k€	0,33 k€	0,46 k€	0,59 k€
Outputs				
Product	82,65 k€	138,83 k€	191,60 k€	242,43 k€
Material Losses	31,36 k€	33,16 k€	38,60 k€	45,16 k€