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

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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 design stage become essential for the companies to maintain their competitiveness in the market. The present work, is focused on extend the Material Flow Cost Accounting application scope and in its incorporation in the Life Cycle Engineering for products and processes design, to promote the design of ecological and cost-effective products and support decision-making.

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

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 (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 [4]. From the fact that the MFCA provides detailed information about the environmental variables and the production costs, arises the hypothesis of extending the MFCA scope to a life cycle perspective and integrate it in the LCE of a product.

Therefore, on a first approach the present work 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.

2 State of the art

MFCA 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 [5][6]. It allows the recognition of the primary waste sources, simplifying the identification of the problem and thereby, the solution [3].

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][2]. 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. 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].

2.1 MFCA principals and implementation methodology

The MFCA methodology divides the process in quantity centres [5]. 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, which provides an overview of the entire process.

Moreover, considers the production of goods as a system of flows that can be divided into desired material flows (products) and undesired material flows, which are movements of unintended material outputs or material losses (waste) [2].

The implementation of MFCA method in a company can be based on the following steps:

1. Target products and processes selection;
2. Boundaries and analysis period definition;
3. Determination of the quantity centres:
4. Quantification of the flows in physical units;
5. Quantification of the flows in monetary units;
6. Development of the calculation model;
7. Communication of MFCA results;
8. MFCA summary and interpretation opportunities;
9. Identification and assessment of improvement opportunities.
10. Identification of inputs and outputs;

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. Thus, it identifies four types of costs: material, system, waste management and energy. To maximise the accuracy of the analysis, the costs should be calculated individually for each quantity centre and individual flows. However, some costs are often available only for the entire process. Therefore, is necessary to define allocation rules in a two-step procedure [5]: allocate the process-wide costs to different quantity centres and then, to products and material losses.

The calculation model should be developed by the company based on the requirements, fundamentals and principles of the MFCA methodology. It may follow 3 steps: calculation of material costs; calculation and allocation of energy, system and waste management costs and finally, integrated presentation and analysis of cost data.

2.2 Application of the MFCA to a supply chain

MFCA methodology was primarily designed for a single facility or 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], [5]. It 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 [6]. To overcome the implementation difficulties related to confidentiality issue and sharing technical and accounting information, as well as to serves as a guide, a new standard ISO 1452 is being developed since May 2014 [6].

2.3 Life Cycle Engineering

The concept of Life Cycle Engineering 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 [7]. It is a decision support methodology which assesses technical, economic and environmental performance, considering all the life cycle stages of the product [8], [7]. 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 [9].

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 of different alternatives [9]. It assesses the total costs associated with the product's useful life in a cradle-to-grave perspective [8].

The LCA is an environmental management technique, which enables the evaluation of potential environmental impacts of a product throughout its life cycle [10], [11]. It aims at the recognition of the life cycle related environmental burdens of a product and identifies and quantifies the ecological impacts of the processes and resources used throughout the entire life cycle. The Standard ISO 1040 describes the principles and framework for LCA [10], and ISO 1044 specifies the requirements and guidelines for executing the LCA [11].

2.4 MFCA and LCE integration

The underlying intentions of the LCC and LCA evaluation are different; thus, even when are used as appraisal tools of the same object within the LCE assessment, they are applied in parallel, or with little integrations. However, the integration of the LCC and LCA approaches may lead to several advantages: support the identification of trade-offs between the main purposes of both dimensions and reduce the efforts of modelling and data collection, once the modelled systems and the necessary data are similar [9]. Furthermore, a product is often inserted in a complex production system and shares many of the resources with other products. 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 [9].

The MFCA it is suggested as a potential link between LCC and LCA analysis due to its focus on the improvement of the economic and environmental performance of a company [9]**Erro! A origem da referência não foi encontrada.**. The M FCA flow models, structure and data have already been pointed as a starting base for LCA assess since it requires similar primary data [4], [9]. Furthermore, the MFCA concept of separate the value of products and losses may add a new dimension to the results [12]. Hence, the life cycle economic and ecological performance can also be evaluated concerning losses, providing a deeper comprehension about resources efficiency [9]. 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 [9].

3 Case-study and Approach

The present work has 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 tools and analysis potentialities. Once understood the main benefits and limitations of the method, aims at the extension of its applicability to appraise different design configurations. Finally, and as the ultimate goal, the enlargement of the MFCA methodology scope to be incorporated in the LCE for products and processes design.

To achieve the three goals, a manufacturing unit with a Plastic Injection Moulding process was used as a case-study. Therefore, the present work was partially developed in an industrial environment to perform the MFCA analysis and collect the necessary data. Due to a confidential agreement, the name of the company is not mentioned, and the real product cannot be described. The Product used as a case-study is composed of two parts, Part A and Part B. Both parts, are produced separately through the plastic injection moulding process.

The injection moulding process is one of the most common techniques for manufacturing plastic parts [13]. It is used for mass production through moulds and the application of heat and pressure. The material injected to produce the parts is polypropylene (PP).

Figure 1 illustrate two parts similar to the case-study real parts and describes their general dimensions.

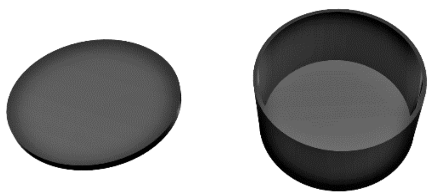

Figure 1: Left: Part similar to Part A; Right: Part similar to Part B

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

	Maximum thickness [mm]	Projected Area [mm^2]	Volume $[mm^3]$	Weight [g]
Part A	1.50	1140	2275	2.35
Part B	1.25	1206	4012	4.20

The following Figure 3 describes the approach followed in the present work to achieve the proposed goals.

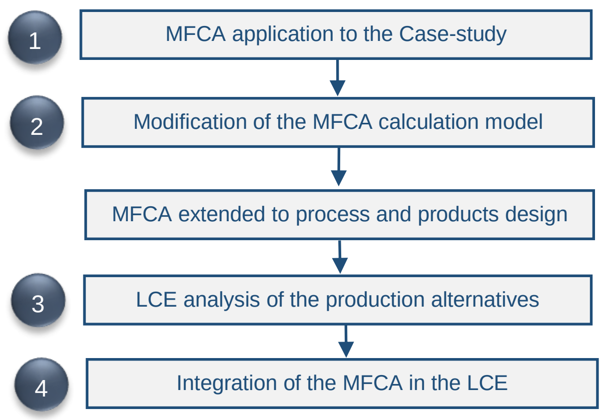

Figure 3: Approach followed in the present work

The first phase consists in the application of the MFCA to the Product's production process. 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 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. This corresponds to the second stage of this work. To analyse the practicability of the new model, several production alternatives are compared through the MFCA methodology.

In the third phase, the economic and the environmental impacts of the different alternatives are analysed in a life cycle perspective, through the MFCA methodology or using the information extracted from it. From the obtained results, the applicability of the MFCA as a tool of the LCE is discussed.

Finally, a methodology to incorporate the MFCA in the LCE for process and products design is proposed.

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.

4.1 Case-study characterisation

The first step consists in the system characterisation. Thence the boundary conditions, the analysis and data collection period and the quantity centres must be determined. Since the product is entirely produced by the company, the boundaries of the analysis are defined at the limits of the manufacturing process of the Product, including all the operations and departments involved in it. The period selected to compile meaningful information is one month.

The quantity centres should divide the production system in process or parts to further calculate and analyse their inputs and outputs. 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 within the boundaries of the analysis. Thus, can be determined based on the operations identified in each zone and the analysis of the materials movements through the entire manufacturing process. Figure 2 illustrates a material flow map where all the quantity centres are identified, as well as the material movements.

4.2 Material Flows quantification

Once defined the MFCA quantity centres, their inputs and outputs should be quantified in physical and monetary units. 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.

The overall system has only one input material, polypropylene, used by the injection moulding process to produce both parts of the product. The identified different

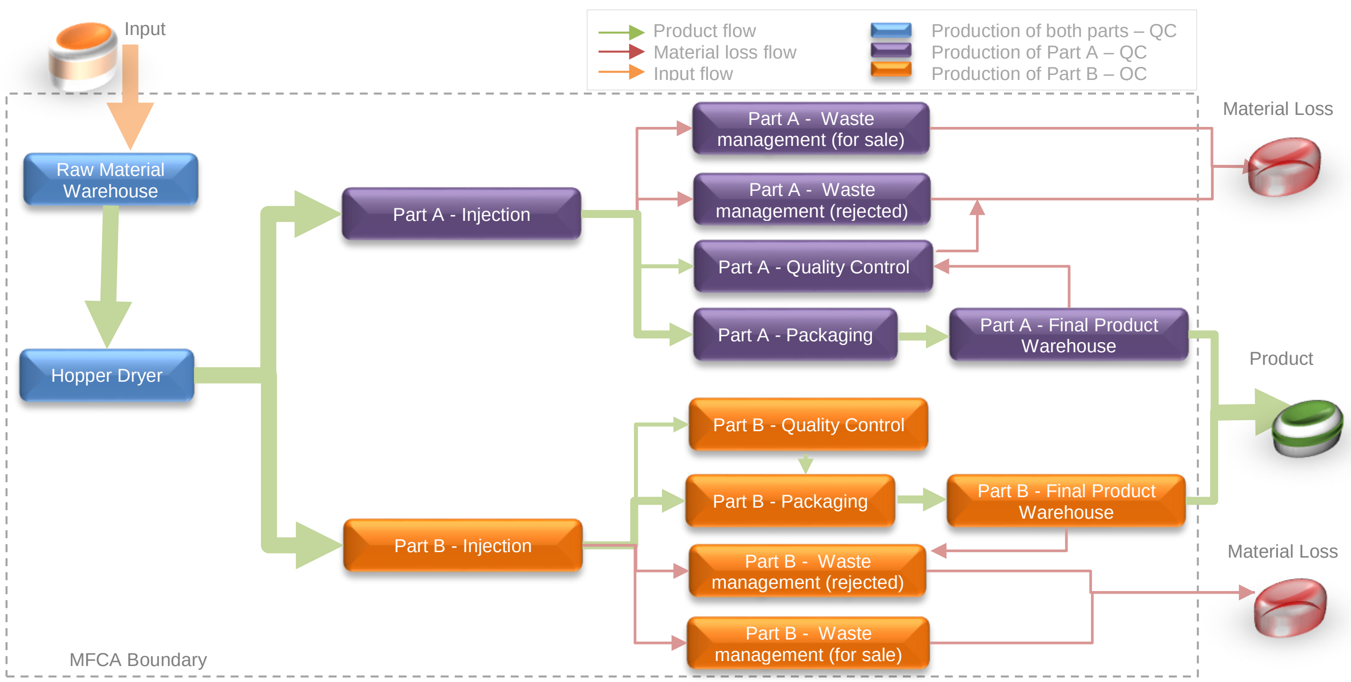

Figure 2: Material Flow Map and quantity centres of the analysis

operating materials are respectively allocated to the quantity centre where are consumed and to the output flow they are related to. 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. The Calculation Model estimates the production volume and the material consumed to produce the Product. It is based on the gathered data about material losses, the quality control records and the downtime and cycle time of each injection machine, provided by the software programme that controls the production system.

In the end of the collection period, results must be compared against the overall production records of the company. The compatibility of the results allows the validation of the calculation model and the material flows quantification in the respective quantity centres. Then, 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, quantification of material flows 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.

The material costs for each input and output flow are quantified using Equation (1) over the time chosen for the analysis.

$$Material_{costs} = physical_{amount} \times Cost/unit \qquad (1)$$

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.

The system costs are the costs incurred during in-house handling of material regardless material, energy and waste management costs [5]. 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. Often are only available for the entire organisation, therefore allocation criterions must be defined. Prior to the allocation procedure the system costs must be categorized in dedicated or non-dedicated items. 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.

4.3 MFCA calculation model

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

4.4 Analysis of the results

The material losses through the manufacture 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; and sludge from supplementary materials used for the injection machines maintenance.

Table 2 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, thereby identifying the primary sources of costs and highlighting the material losses points and drivers.

Table 2: Contribution of the outputs per quantity centre to the total production costs

	Part A		Part B	
	Product	Material loss	Product	Material loss
RM 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 %	-
FP warehouse	0,5 %	0,2 %	0,6%	0,1 %
WM (rejected)	-	0,1 %	-	0,1%
WM (for sale)	-	-0,003 %	-	-0,003 %
Total	40 %	2,2 %	56,6 %	1,2 %

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.

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 irregular distribution of the costs between Part A and Part B is related to the material required to produce each part, Part B weights 4,2 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. 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. The expenses incurred in the Raw Material Warehouse RW warehouse) quantity centre are primarily due to the Material costs. Therefore, the material used to produce both the components 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. 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.

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. From the obtained results, different improvements and suggestions were proposed related to material losses, technical problems of the equipment and to increase the overall productivity of the system through the improvement of identified inefficient activities.

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, it is important to note that 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.

5 MFCA extended to process and products design

The nature of the MFCA focus on material flows and short-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]. To extend the scope of MFCA for processes and products design, 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.

5.1 Process Based Model developed

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. Figure 4 illustrates the its macro flow chart.

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 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.

The clamping force is calculated by the Equation (2) [15], 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, SF.

$$F_{Clamping} = P_{inside} \times A_{Projected} \times n \times (1 + SF) \quad (2)$$

The cycle time is one of the most important parameters in the injection moulding process and influences the entire production system. It depends on the parts geometry, the material, the number of cavities of the mould and injection machine properties. It can be understood as the sum of three stages: injection, packing and cooling, and reset (Equation 3) [16].

$$t_{cycle} = t_{fill} + t_{cool} + t_{reset} \quad (3)$$

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.

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 This calculation is based on two requirements: per injection machine are required 0,8 employees; and every eight hours of production is added a new shift.

In parallel, the necessary raw material to manufacture the Product is calculated using Equation (4). 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, respectively.

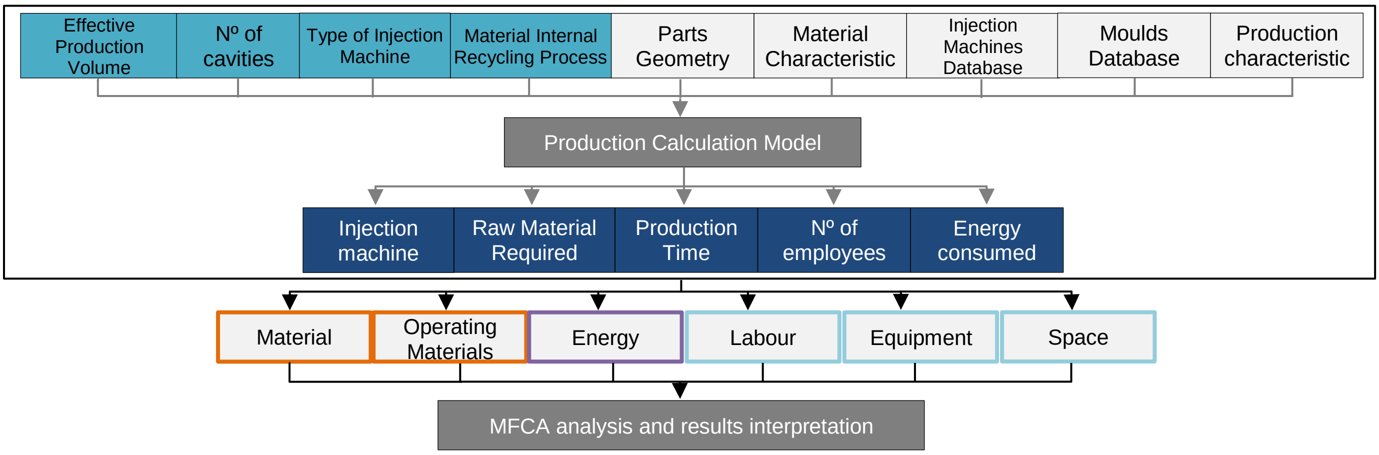

Figure 4: Macro flow chart of Process Based Model

$n_{productiovolume}$ is the effective production volume and m_{part} is the components' weight.

$$M_{rawmaterial} = m_{maintenace} + m_{QC} + m_{start} + n_{productionvolume} \times m_{part} \quad (4)$$

Finally, the energy consumed by each injection machines can be estimated through the energy necessary to melt the material and to fill the mould cavities and the energy that the machine requires for the injection process (Equation 5) [17]. Their associated parameters are calculated through the model developed by [17] and [18].

$$E = E_{thermo} + E_{machine} \quad (5)$$

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 previous case-study. 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.

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.

5.2 Analysis of results

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 product lifetime are five years; the specific daily production volume are 1 000 000 components and the company operates 360 days per year. 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.

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 is the one derived from the rejected components. The material discharges are sold. 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 as suggested by [2]. Consequently, the results from these design alternatives are evaluated considering three output flows: Product, Material losses and Material loop.

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.

For all the alternatives evaluated, the internal material recycling process allows a slight reduction of costs, when compared against the same option without internal recycling. Therefore, Table 3 presents the production costs obtained for each production alternative with internal recycling, where P is the Product, MLp and MLs the Material Loop and the Material Losses respectively, and N represents the normalisation of the results regarding the best design.

Table 3:Costs analysis for each production alternative with internal recycling

	16ER	16HR	32ER	32HR	48ER	48HR	64HR
P	4 647	4 706	4 312	4 370	4 148	4 208	4 242
MLp	122	130	85	94	71	81	85
MLs	18	18	5	5	3	3	2
Total	4 787	4 854	4 402	4 469	4 222	4 292	4 329
N	0,88	0,87	0,96	0,94	1	0,98	0,98

The analysis, regarding the number of cavities, leads to the conclusions that the use of hydraulic machines instead of electric cause higher costs. 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. Although the 48 and 64 cavities mould need the same number of equipment, the moulds of 64 cavities are more expensive and require a machine with higher power; consequently, also more expensive. Furthermore, the number of rejected components per shot is higher, leading to more associated material losses and injected material.

The alternative with the lowest costs is the one that uses electric machines, moulds with 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, is due to the small amount of wasteful material. Regarding the material injected to produce the parts, the best scenario remains the same, followed by the remaining alternatives that partially reuse the material losses through the internal recycling process.

Nevertheless, to obtain a deeper knowledge about the range of the best scenario and its sensitivity to variations in the manufacturing process a sensitivity analysis is performed to the specific daily production volume.

5.3 Sensitivity analysis

The present analysis pretends to determine the influence of the production volume in the selection of the best manufacturing alternative. The appraisal is based on the production costs per unit. Figure 6 and Figure 5 presents the results obtained and only illustrate the best solutions found for each particular production volume to facilitate the reading.

From results provided by the graphic 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 3 million.

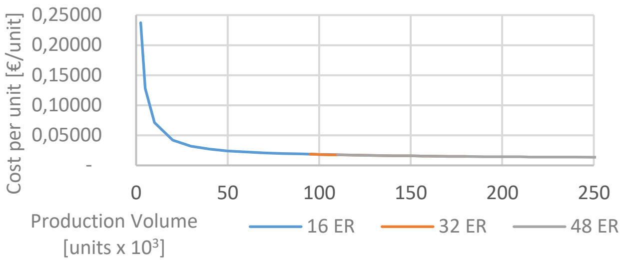

Figure 6: Sensitivity analysis to the product's production volume. (From 0 to 250 000 components produced per day)

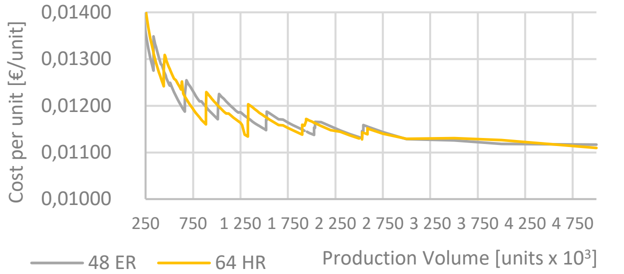

Figure 5: Sensitivity analysis to the product's production volume. (From 250 000 to 5 000 000 components produced per day)

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 6.

The best solution obtained in the differentiated second area, illustrated in Figure 5, 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 graph 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. 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.

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 life cycle analysis is performed from the moulds' perspective. The methodology applied is the LCE, including economic and environmental aspects in the global evaluation. The functional assessment is not included as both moulds and the parts produced by the different alternative have the same technical performance.

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, 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.

Figure 7 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 stage 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.

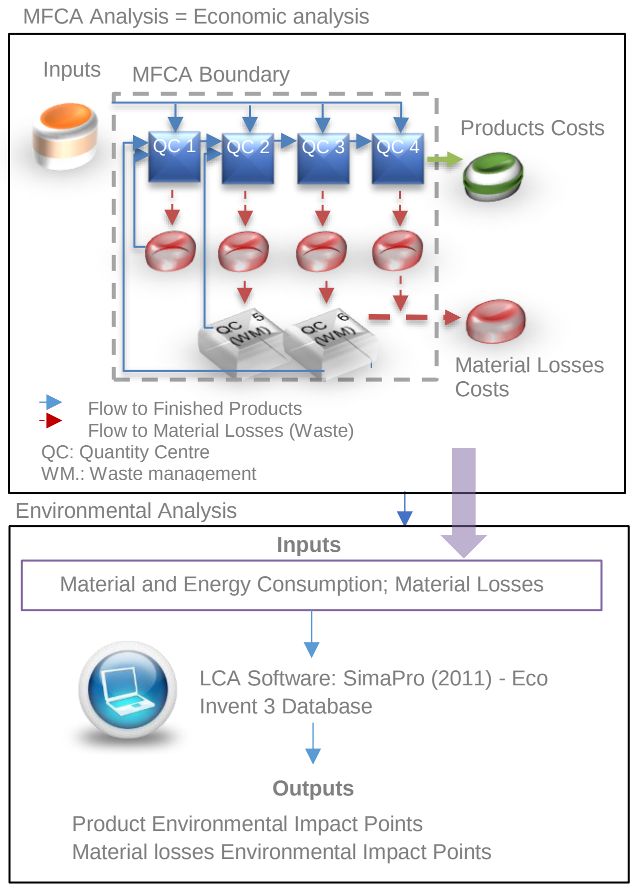

Figure 7: Approach followed to perform the economic and environmental analysis of each lifecycle phase

6.1 Life Cycle Phases characterisation

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. 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 work. 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 use phase of the mould corresponds to the Injection Moulding Process. Consequently, the results obtained in the previous section represent the economic analysis of the different alternatives for this lifecycle phase.

The end of life assessment includes the economic and the environmental disposal impacts of the moulds and the produced parts. In the present work, it is assumed that the materials of the moulds are entirely recycled. 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 stage is not performed through the direct application of the MFCA methodology. Instead of that, 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.

The functional unit of the present analysis, is one plastic part produced in the Use phase.

6.2 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 [9]. The results obtained in each phase are represented in Figure 9.

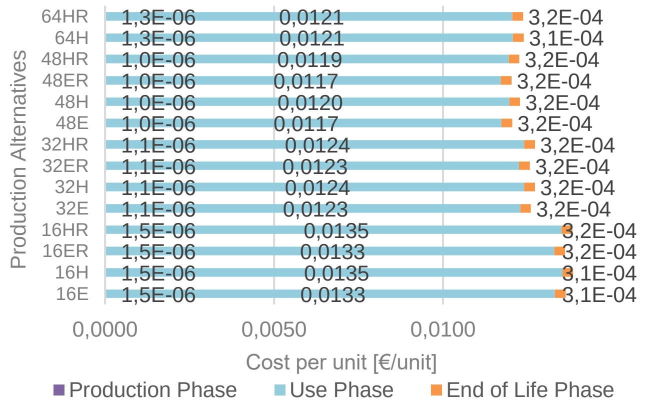

Figure 9: Costs break down by lifecycle phase per plastic part produced

The alternative that presents lower costs is the 48 cavities, using electric machines with internal recycling of the material in the injection moulding process. Due to the number of required moulds, this design 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 option that uses hydraulic machines.

The economic performance of the other production 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, worst results, i.e. the higher lifecycle costs per unit, 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.

Figure 9 also 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.

6.3 LCA Analysis and results

The LCA analysis enables the evaluation of potential environmental impacts of a product throughout its life cycle [10], [11].Figure 8 illustrates the contributions of each phase to the entire environmental impact of the product.

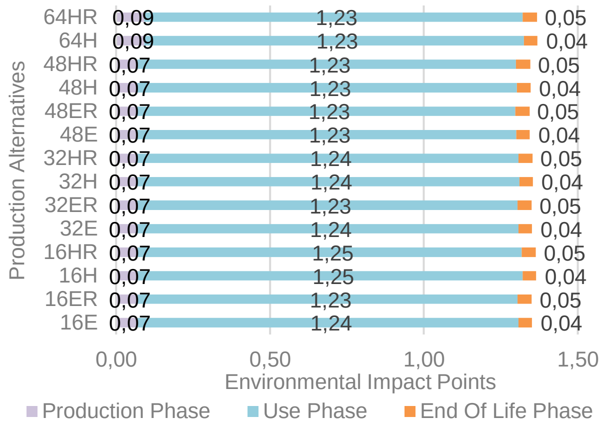

Figure 8: EI down by lifecycle phase per plastic part produced

The 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 8 is also 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.

As referred, the application of the MFCA methodology allows the evaluation of the results regarding the product (P) and the material losses (ML) separately, or together (T), as presented in Table 4: Use phase - EI per unit produced (electric machines)Table 4. It illustrates the environmental impact of the Use phase, for the alternatives that use electric machines. The results are presented in Points per plastic part produced.

Table 4: Use phase - EI per unit produced (electric machines)

	16	16R	32	32R	48	48R
P	1,23	1,23	1,23	1,23	1,23	1,23
N	0,995	0,995	0,995	0,994	1,0	1
ML	0,005	0,001	0,004	0,001	0,004	$4{\times}10^{-4}$
N	0,08	0,33	0,09	0,66	0,1	1
Total	1,24	1,24	1,24	1,24	1,23	1,23
N	0,99	0,99	0,99	0,99	0,99	1

From the previous Table is possible to conclude that the EI is primary caused by the Product due to the low amount of material losses related to this manufacturing process. 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.

The alternatives that causes the lowest EI in the three categories 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 and has lower associated losses. The worst alternative is the 16 cavities mould, using hydraulic machines based on the same reasons, for the three categories as well. This is the option that requires more material, consumes more energy and has higher material losses.

A similar analysis can be performed to all the phases of the life cycle and regarding the environmental and the economic aspects.

6.4 LCE analysis

After the evaluation of the economic and environmental dimensions separately, the presented results should be 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 [19]. 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 since the best alternative is the same for all the cases.

7 Proposed methodology for MFCA integration in LCE analysis

The proposed methodology follows the approach described in Figure 10 aiming at the comparison of the lifecycle performance of different design alternatives.

First, the Product specifications and the different 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. Once characterized the Product and the alternatives, the lifecycle phases considered for the analysis must be determined, as well as the boundaries conditions of each system.

Then, the MFCA methodology is applied to each lifecycle phase with the aim of develop a Process Base Model. The developed model is also validated by the MFCA methodology, through the comparison of the results. The primary objectives 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. Together with the MFCA methodology, provides, not only a deeper knowledge about the production context but also actual data of the existent production for the refinement and model validation. It supports the economic assessment and provided the necessary information for the evaluation of the system's environmental impacts. Additionally, it is important to note that the Process Base 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.

The information provided about the costs for each individual lifecycle phase should be integrated in a singles 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. 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 [7].

Finally, the results obtained from the economic, environmental and functional assessment 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

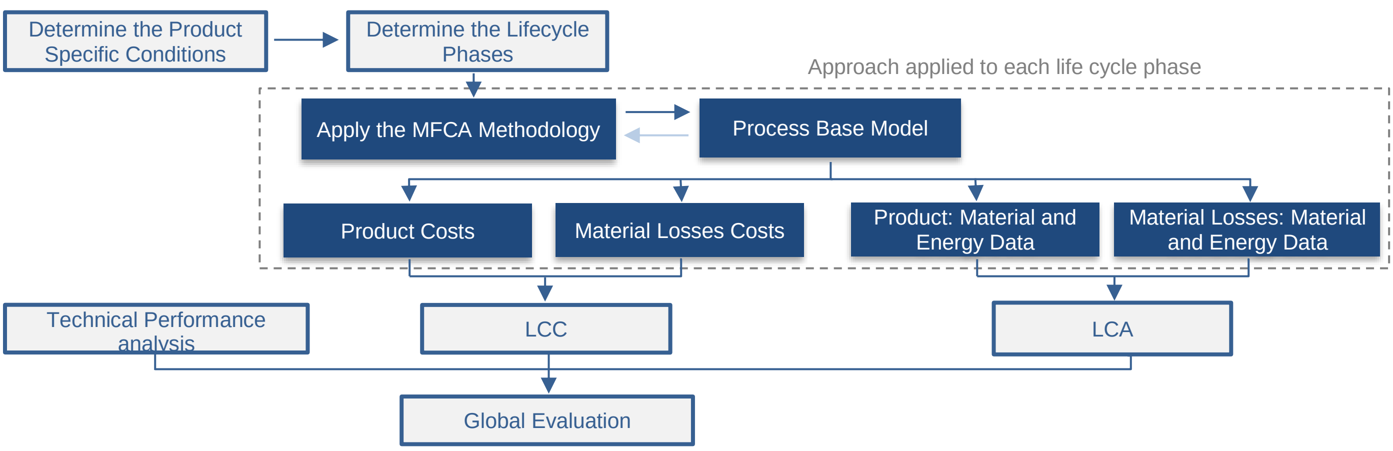

Figure 10: Overview of the Life Cycle Engineering framework

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 [7]; the development of a ternary diagram [8]; and the application of the CLUBE method to compare the economic and environmental dimensions [19].

8 Conclusions and Future Work

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. 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 to increase the productivity of the company. The improvement actions, after the MFCA application, 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. To validate the model, several processes designs were considered and compared in terms of resources consumed and costs. This analysis lead 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. 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.

Finally, the design alternatives were evaluated from a lifecycle perspective applying the MFCA methodology to each lifecycle phase. The approach followed was developed based on the similarities found between LCC and LCA models, and the extension of the MFCA original scope through the incorporation of a Process Based Model. The obtained results allowed and supported the development of the methodology proposed to integrate the MFCA methodology in the LCE model. On the one hand, 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.

Nevertheless, one of the major challenges still, 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. However, 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. Furthermore, the inclusion of the profits contribution in the Process Base Model and a deeper analysis regarding the investment appraisal of different design alternatives to support the extension of the MFCA scope as an appraisal tool is also suggested. Finally, the development of a methodology or an approach to modelling the energy flows independently to the material flows may reveal potentials for costs savings and improve the environmental performance of the company.

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