UNIVERSIDADE TÉCNICA DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

Comprehensive Life Cycle Framework Integrating Part and Tool Design

Inês Esteves Ribeiro

Supervisor: Doctor Paulo Miguel Nogueira Peças

Co-Supervisor: Doctor Elsa Maria Pires Henriques

Thesis approved in public session to obtain the PhD Degree in
Leaders for Technical Industries
Jury Final Classification: Pass with Merit

Jury

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Resumo

O desempenho da maioria dos processos produtivos depende grandemente da engenharia das ferramentas. Apesar da importância das ferramentas dedicadas ser reconhecida pela indústria, a quantificação do seu impacto é limitada. Isto é devido principalmente à natureza única deste tipo de ferramentas, sendo a quantificação especialmente crítica em fases avançadas no seu ciclo de vida. O enquadramento Abrangente de Ciclo de Vida proposto integra os ciclos de vida da peça e da ferramenta e combina modelos baseados nos processos envolvidos em todas as fases do ciclo de vida, introduzindo relações entre estas, tanto ao nível de custos como de impactos ambientais. Este enquadramento é depois explorado no caso de moldes de injecção de plásticos, tendo sido desenvolvidos modelos específicos para analisar o impacto da concepção de peças e ferramentas no ciclo de vida integrado. São apresentados casos de estudo de peças produzidas por moldação por injecção, ilustrando a metodologia e explorando as suas vantagens em decisões de concepção. Esta abordagem é especialmente útil em novas tecnologias e tipologias de ferramentas, pois a modelação dos processos permite estimar os seus custos futuros e outros impactos sem grandes investimentos, apoiando assim decisões mais conscientes na fase de concepção.

Keywords: Concepção de Ciclo de Vida, Ciclo de Vida Abrangente, Custo de Ciclo de Vida, Análise de Ciclo de Vida, Modelos Baseados em Processos, Moldação por Injecção, Ferramentas Dedicadas

Abstract

The performance of most manufacturing processes is highly determined by the tooling engineering. However, despite being acknowledged by the industry, the explicit quantification of the impact of tooling design decisions is still lacking mainly due to the "one-of-a-kind" nature of these tools. This is especially critical when moving forward through the tool life cycle. The proposed Comprehensive Life Cycle (CLC) framework integrates the part and the tool life cycles and combines process-based models of all life cycle phases involved, introducing relations of dependencies and impacts between them. The impacts regard not only cost, but also environmental impacts. This framework is then explored in the case of plastic injection moulds, developing specific models to capture part and mould design impact in the integrated life cycle. Case studies are presented regarding plastic parts produced by injection moulding, illustrating the CLC framework and exploring its advantages when dealing with design decisions. This approach is especially useful when dealing with new technologies and tool features, as the modelling of the processes allows estimating their future costs and other impacts without major investments. Hence, it can be used to support more informed decisions in the tooling and part design phase.

Keywords: Life Cycle Design, Comprehensive Life Cycle, Life Cycle Cost, Life Cycle Assessment, Process-Based Models, Injection Moulding, Dedicated Tooling

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1 INTRODUCTION

The design and production of dedicated tailored tools is a topic of major concern in nowadays industry. Not only to tool makers but also to new products developers and producers. Any mass production or customized mass production product relies on dedicated tools lead time and performance. However, their one of a kind nature has limited comprehensive and quantitative analysis of their impact on the parts and products produced with them. While a wide range of analysis have been developed to support new product design, dedicated tools design and production is still a qualitative field dependent on the expertise of mould producers. Being Life Cycle Design concepts methodologies and tools commonly stated in most product development studies as the best practice to achieve sustainable and successful products, it has not been applied by other researchers or industries to the area of dedicated tools. A tool can not only be perceived as a product, and therefore with a specific life cycle, but is also intrinsically connected with the life cycle of products or parts produced with the tool. Despite the obvious relation between dedicated tools and products, the life cycle analyses usually developed nowadays disregard this fact. This thesis proposes the integration of both life cycles, of the tool and part/product, in an analysis framework, named Comprehensive Life Cycle (CLC). This framework addresses life cycles involving products or parts and dedicated tools, and needs to be "filled" with models correlating design decisions with the life cycle impacts. The impacts regard not only costs but also environmental impacts, following the Life Cycle Cost and Life Cycle Assessment methodologies, correspondingly. At this point, one question arises; are the impacts of the tools design decisions relevant in the proposed integrated life cycle? To answer this question, the research was focused mainly in one kind of dedicated tools and products – plastic injection moulds and plastic parts. Through case studies developed in both mould making industry and plastic parts producers, the relations between design decisions and the subsequent life cycle stages were investigated, developing theoretical and empirical models based on process-based models concept, filling the proposed framework. In some cases only tool alternative designs were evaluated, other only part design and other both, aiming to understand which models are critical in different design problems. Results have shown that the use of the developed models can be determinant in

assessing the “best” design decision economically or environmentally, with some relevant differences between design alternatives. Notice that the best choice in the economic dimension can be different from the best environmentally. Another possible difficulty is the different value of money in different time frames when dealing with life cycle approaches. These issues led to develop an output of “best” design alternatives map when different sets of weights regarding environmental impacts and downstream costs are chosen. Ultimately, this framework does not aim to translate current design decisions or to be a decision making “tool”, but aims to capture and present in a comprehensive way the impact in different dimensions of a design decisions, being therefore a tool to support an informed decision making process by the designers.

On the course of the research, the suitability of the framework to other type of dedicated tools and products was questioned. Moving to other type of processes, two case studies involving other two main families of dedicated tools were addressed; die casting and stamping cases. Revising case studies from past projects, the models developed for the specific production processes were used to fulfil the CLC framework. Despite occasional lack of data, it was possible to develop the proposed framework with interesting results, proving to be possible to expand this comprehensive analysis approach to a wider range of dedicated tools.

This thesis contributes to the dedicated tools design area not only by developing quantitative knowledge regarding tool design impacts, but also by establishing a comprehensive framework to apply life cycle design principles to dedicated tool design. It also contributes to Life Cycle Design knowledge field by proposing the inclusion of dedicated tools life cycle in the life cycle of products or parts. It promotes a concurrent process in new product development, encompassing both design decisions and life cycle impacts in the same framework.

Starting with the state of the art in Life Cycle Design (chapter 2), methods and tools developed nowadays are investigated, along with the areas of application. The applications regarding product and tools design are further explored, finding a gap in literature regarding the connection between products and dedicated tools. Following the role of dedicated tools in sustainable design is reviewed, as well as the links found in literature between tools and products, and nowadays challenges in dedicated tools industry. Although there are no comprehensive studies linking both life cycles, several

authors propose concurrent engineering methods to support tools and parts design. In chapter 3 is explained the research path followed, from the internships that first allowed understanding the need to integrate the both life cycles and after gave me the tools and knowledge to develop the models, to the conferences with academia that gave me feedback that fostered new ideas. The CLC framework is presented in chapter 4, open to be applied to any kind of dedicated tools. It is then applied to injection moulding in chapter 5, in which the specific models required to “fill” the model are presented. Aiming both to understand the relevance of such approach and the determinant models in each design decision type, several case studies are developed and presented following the CLC framework applied to injection moulding (chapter 6). The applicability of CLC to other dedicated tools and processes is addressed in chapter 7, with case studies from past projects. Finally, conclusions are presented in chapter 8 and future work in chapter 9.

2 STATE OF THE ART

This chapter is structured in different sections; the first address to the state of the art in Design for Life Cycle, focusing on Life Cycle Engineering (LCE) methodology and its tools, namely Life Cycle Cost (LCC) and Life Cycle Assessment (LCA). Following are investigated the applications to the date of LCE to products and dedicated tools, along with the role of dedicated tools in sustainable product design. That is, relations between dedicated tools and impacts on product life cycle are analysed through review of studies developed so far. Also design challenges and current developments in tooling industry are dealt with in this section. In the last section the main findings and lacks found in literature are summarized.

2.1 Design for Life Cycle

In an increasingly competitive environment, the traditional manufacturing business focused on physical products has been shifting to embrace an integrated product-service approach. Companies are no longer just responsible for the physical product, but also for the entire product's life cycle. Moreover, it is a well known fact that most impacts in a product life cycle, either economic or environmental [Asiedu and Gu, 1998; Jeswiet and Hauschild 2005], are defined in early design phases. This has also fostered the need to expand the limited scope of manufacturing costs as the main decision factor, triggering the development of several life cycle approaches to product design.

In this context, life cycle approaches appeared in the mid sixties on an economic point of view, with the life cycle cost (LCC) methodology [Woodward 1997, Dahlén and Bolmsjö 1996, Barringer 1995] and the life cycle assessment (LCA) methodology regarding the environmental impacts [Roy et al. 2009]. Both methodologies can be acknowledged as the starting point of the current life cycle thinking. However, despite both concepts were defined in the sixties, the LCA concept, unlike the LCC concept, only became popular in the nineties. The climate change and other environmental threats have come more into focus in that decade, fostering the first scientific publications in the area [eg. Guinée et al. 1993 a,b]. In fact, in the beginning of the 90's an EPA report on life cycle design [EPA Life Cycle Design Guide 1992] claimed that

environmental criteria often were not considered at the beginning of design when it is easiest to avoid adverse impacts. Therefore, only the rising public concern with environmental problems in the nineties fostered the use of LCA in the design phase of products and services by European firms, in the vanguard of adopting and applying life cycle approaches [Berkhout and Howes 1997]. In fact, improvement potentials throughout a product life cycle are strictly linked with changes in product concept, structure and/or components [Alting 1995].

Following nowadays trend, to design better products for their entire life Design-for-X (DfX) strategies, supported by the corresponding DfX tools, have been increasingly and successfully applied. These strategies drive the design team in the creation of products and services that achieve a specific target or that maximize the performance in a wide range of engineering fields (cost, environment, assembly, etc.). Despite the wide spectrum of design accomplishments, the DfX strategies restrict the analysis to trade off among several specific alternatives in each engineering field. In fact, the general objective of design for cost is to minimize the production cost; design for assembly aims the definition of the product's features to minimize the effort of the assembly tasks; and design for environment targets a lower environmental impact focusing essentially on product material issues. The integration of the decisions considering multiple design objectives and perspectives is difficult and sometimes impossible. In addition most individual DfX strategies are focused on a product life window and do not tackle conveniently the overall impact of a design decision. The consideration of the all life cycle stages of a product in the early design phase allows a more complete perception of the product's importance and differentiation in the market and in the society. This way of design and develop a product can be called as Design for the Life Cycle. To differentiate it from the regular DfX strategies, several authors prefer the denomination: Life Cycle Engineering (LCE), which is defined as a decision-making methodology that considers technical performance, environmental, and cost dimensions throughout the duration of a product, guiding design engineers towards informed decisions [Wanyama et al. 2003; Betz 1998].

2.2 Life Cycle Engineering/Design

Lundquist et al. [2000] claimed that economic processes at the time were resource intensive, being only 5% of the resources consumed actually transferred to the final product. This situation started shifting the companies' strategies to integrate environmentally conscious technologies and products in their business chain. In fact, Fiksel [1993] followed in the beginning of the 90's some progressive U.S. manufacturing companies that started implementing environmental quality programs. His observations and cooperation revealed that design for the environment practices provided competitive advantage by reducing the costs of production and waste management, encouraging innovation in product simplification, and attracting new customers. This trend continued until nowadays, having been developed several life cycle design approaches to support sustainable design, both economic and environmentally.

The concept of life cycle design/engineering was first introduced by Alting and Legarth [1995] as "the art of designing the product life cycle through choices about product concept, structure, materials and processes". Going beyond the traditional decision based on technological and economic performances, this concept introduces the decision in a life cycle perspective also regarding the environmental performance of a design. In fact, LCE emerged in response to the need to develop life cycles causing the lowest possible environmental impacts, while still offering economic viability. LCE stands for the need to consider from the early product concept its complete projected life, including market research, design phases, manufacturing processes, qualification, reliability aspects and customer service-maintainability-supportability issues [Wanyama et al. 2003; Keys 1990; Alting and Legarth 1995]. To develop increasingly sophisticated products (systems or facilities) in shorter timeframes is a tough challenge that can be better achieved by a holistic understanding of products and processes life cycle [Alting and Legarth 1995; Ishii 1995].

Additionally, a change in the whole concept of industrial production and in the behaviour of the consumer society has been mandated by profound demographic and economic evolutions, and by a growing awareness of environmental issues [Alting and Legarth 1995; Fava et al. 2000]. So, to support LCE philosophy in early design phases, LCE principles were defined and implementation guidelines were published,

considering LCE an ongoing process to develop specifications to meet a set of requirements and goals that span the product life cycle [Cooper and Vigon 2001, Vezzoli and Sciama 2006].

Most authors agree that the main LCE principles are:

- The extension of the design horizon, that is, the scope from product design to the design of all product life cycle stages in a systemic way;
- A new design reference: from product design to product function design.

The first principle is quite straightforward; it is necessary to consider all activities related to the product, from the production of materials to its distribution, to its use and finally its disposal, as a single unit. This fosters a shift from the design of the product to the design of the product-system, considering the whole of processes characterizing its life cycle [Jeswiet, 2003]. The second principle claims a shift in the focus from the physical product itself to the function delivered by the product. According to the products function, it is then assessed whether the environmental impact have been reduced and how [Vezzoli and Sciama 2006].

Following these principles, guidelines have been developed to support the application of LCE to the development of sustainable products and processes. Cooper and Vignon [2001] developed the first LCE guidelines for the implementation of its concepts, information, and techniques in engineering products, systems, processes, and facilities. Furthermore, an LCE framework was presented and generic types of engineering decisions candidate to include environmental implications in conjunction with cost and performance requirements were classified in a scheme. These were divided into products, systems, processes and facilities - new (original or improvement), upgrade of existent ones, maintenance (routine or unanticipated) and decommissioning.

In addition to those guidelines, tools and methodologies have be developed to foster the implementation of the LCE approach to product design as "engineering activities involving the application of technological and scientific principles to the design and manufacture of products with the goal of environment protection and resources conserving, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimizing the product life cycle and minimizing

pollution and waste" [Keys 1990; Jeswiet 2003]. A LCE tool integrates in a single decision framework all the relevant information that must be available within the design phase, regarding the technical, economical and environmental dimensions, and considers all the life cycle stages of the product to avoid tradeoffs [Tseng et al. 2008; Aurich et al. 2006]. The tools and methodologies found in literature are presented in the following section.

Ultimately, there is no precise definition for LCE, as different approaches exist. However, Jeswiet [2003] developed a widely known image to define LCE through its keywords (fig. 2.1).

Figure 2.1. - Keywords of Life Cycle Engineering [Jeswiet, 2003]

2.2.1. Challenges in Life Cycle Engineering/Design – Current Methods and Tools

As mentioned by Keys [1990], the research in LCE challenges the academic world because it is based on a multidisciplinary approach in dealing with a problem solving framework. In fact the development of LCE tools and its implementation in product design and development requires the collaboration of different expertises during several phases of such project. Therefore, the incorporation of concurrent engineering practices is recommended if not mandatory [Bento et al. 2008; Ribeiro et al. 2008].

Although it is convenient to develop the LCE approach in the early design phase, it can involve a large set of alternative materials and other design options which means an enormous effort in terms of life cycle analyses [e.g. Life Cycle Cost and Life Cycle

Assessment). Providentially, there are several factors that limit the number of alternatives to study on the LCE approach. In fact, the company technological and strategic framework restricts the number of alternatives to the ones possible to handle, to have access, to process, among others. Additionally, the product logic and specific requirements limit the alternatives domain to a few options [Peças et al. 2009; Pousa et al. 2009]. Despite this focus on specific alternatives range, the spectrum of possible design variables is still large. So, to efficiently and effectively apply the LCE approach, the design problem must be well established based on the definition of a few set of design alternatives for further analysis and comparison. This allows focusing the LCE analysis on the most promising design alternatives.

The analysis of the technical, economic and environmental performance provides a solid foundation for designers to understand the trade-offs and implications of product design alternatives [Wanyama et al. 2003; Fava et al. 2000]. The reduction to three dimensions can be considered as a drawback as compared with DfX, which foster the consideration of a wide spectrum of disciplines. The answer to this relies in the way the three dimensions are analyzed. For the economic performance the use of methodologies like Life Cycle Cost is recommended. The estimation of all the costs associated with a product throughout the product's life, from "cradle" to "grave" integrates the analysis of the impact of design for cost, design for maintainability, design for assembly, etc. Accordingly, the use of methodologies like Life Cycle Assessment to estimate the environmental performance includes the disciplines of design for environment, design for recycling, design for standards, etc. Finally the designs for reliability, for service, for use, among others are surely integrated in the technical performance assessment (if not already integrated in cost if there are available prediction models). For the integrated analysis of the three dimensions comparison methods can be used, e.g. graphic theory and matrix approach (GTMA) and fuzzy multiple attribute decision making methods (MADM). The technological assessment can be seen as the most sensitive part of the LCE analysis, as the technical performance is often related with both costs and environmental impacts. In fact, most technical impacts can be translated directly into these dimensions. This may induce an excessive assessment of the impacts of a certain variable by overlapping the variable in the three dimensions. In fact, several authors only consider life cycle costs and environmental impacts when developing LCE models for specific situations where the technological assessment is assured or even performed

to restrict the number of candidate alternatives [Zhu and Deshmukh 2003, Züst et al 1997, Peças et al. 2013].

Regarding specific models and software tools, an early work by Tipnis [1991] proposed a product life cycle economic model for designing products and processes in a robust, competitive, and environmentally safe to operate, dispose and recycle way. For this, the model included not only the cost of materials, labour, consumables, and all support functions, but also, the potential penalty costs resulting from the environmental risks while the product is being manufactured, stored, in use, disposed or recycled.

Following Tipnis work, several methods have been proposed for modelling and/or evaluating all or part of a lifecycle system. Takata and Kimura [2003] proposed flexible means to represent technical information relevant to manufacturing facility management, especially with respect to maintenance. A simulation system was developed for life cycle design and management, including functions or modelling and controlling each life cycle process. Brissaud and Tichkiewitch [2001] proposed a comprehensive model that can be used to globally optimize the phases comprising the product lifecycle. Their product model deals with the problem of incidents happening along the life cycle of a product and is based on the capitalization of quality discrepancies in product life cycle. That is, product design is improved by organising continuous information feedback loops regarding quality problems from product usage to the designers and manufacturers. It also introduces learning procedures in a design system. Concurrently, Westkämper [2002] proposed a platform for integrating the management of assembly/disassembly and product lifecycle. According to the author, business strategies are aiming more and more towards perfecting technical systems, optimizing product usage and maximizing added value over the entire lifetime. Therefore, a life cycle management platform is proposed to address the manufacturers need to manage products, adding value to the after sales processes.

Eco-efficiency appeared in the 90's along with the LCE principles and guidelines. It was first proposed by the World Business Council for Sustainable Development (WBCSD) as an environmental analysis indicator for productive systems. [Aoe 2007]. The aim of this concept is to connect the economic performance with the environmental, stimulating the development of economically competitive products and services reducing simultaneously the environmental impact of the life cycle. It is traduced by a

ratio between the product or service value and their environmental impacts [Kharel and Charmondusit 2008]. These impacts are evaluated by the consumption of energy, material and water, and by the emissions and wastes generated. The simplicity of this concept and its practical importance allowed its acceptance and generalized use by the companies, being nowadays one of the most referred by researchers and experts [Hahn et al. 2010].

Tools to support conceptual design, development, and assessment in terms of environmental cost and impact have been proposed by several authors. Park et al. [2002] developed a predicting life cycle method using an Artificial Neural Network (ANN) model, especially focused on energy cost and maintenance cost in conceptual design stage. Kaebernick et al. [2003] proposed a simplified lifecycle assessment for the early design stages of products based on the analysis of LCA case studies. They developed the product's Environmental Performance Indicator by using two sets of energy-based and material-based Impact Drivers. A similar study by Duflou et al. [2003] presented two strategies to support LCE application in the conceptual design phase; an Ecodesign Knowledge System and Eco-Cost Estimating Relationships. The first supplies problem-specific guidance based on mapping both available knowledge and user situations on three domain models. The second allow estimating the environmental impact of design concepts based on a limited number of functional parameters. A more recent study was carried by Pousa et al. [2009] who developed simplified LCC and LCA models to foster the design of sustainable plastic injection moulds in the design phase. Focused on a more specific area, developed a predictive lie cycle model, retrieving cost and environmental results with a low number of design inputs. Zhang et al. [2004] have proposed web-based applications, such as a web-based system for reverse manufacturing and product environmental impact assessment, which takes end-of-life dispositions into consideration. All these methods and tools support the integration of life cycle design in products or tools in early design phases minimizing the cost and time typically required for this type of analysis.

The time and economic constraints in product design and projects is a limitation to the application of LCE practices. The need for software tools integrating regulations and data in user-friendly platforms has fostered the development of LCE tools. Table 2.1. presents some of them, but others exist or are being developed. Given the wide scope of LCE, the focus and subject of analysis differ between these tools. Every year new

software tools are presented in the annual CIRP Life Cycle Engineering Conference, a valuable source of information.

Table 2.1. Life Cycle Engineering Tools

Name	**Source**	**Application**
ReStar	Carnegie Mellon University, USA	Identification of optimal recovery path. Assessment of design for disassembly, recycling and repair.
Environmental Standards Processor	Carnegie Mellon University, USA	Search, selection and use of applicable standard provisions to evaluate product conformity.
Component Design Advisor	Carnegie Mellon University, USA	Assessment of potential product improvements based on design guidelines and rules of thumb.
Design for the Environment Tool	Boothroyd Dewhurst Inc., USA and TNO, Netherlands	Product analysis with respect to disassembly. Cost-benefit analysis for design optimization.
EcoDesign Tool	NEC Corporation, Japan	Environmental product assessment in relation to a reference product, life cycle assessment, assembly, disassembly evaluation.
RecyKon	University of Erlangen, Germany	Design for recyclability based on material and energy flow charts for evaluation of product solutions with assistance from external and internal databases.
COMOS	Siemens	Integrated plant asset management projects over the entire life cycle of an industrial plant or machine. Provides a continuous flow of data to meet specific needs across all project phases.
GaBi	PE International	Supports the user in modelling, management and assessment of life cycle data on the process, product and company level.
Umberto	IFU, Hamburg	Software for Life Cycle Assessment (LCA), Energy Management and Eco Efficiency

2.2.1.1. Life Cycle Cost (LCC)

Life Cycle Cost generally refers to the "assessment of all the costs associated with the life cycle of a product that are directly covered by the any one or more of the authors in the product life cycle (supplier, producer, user/consumer, EOL-actor), with complimentary inclusion of externalities that are anticipated to be internalized in the decision-relevant future" [Rebitzer et al. 2003]. Its objective is to cover the assessments of costs in all steps of the product's life cycle, including the costs that are not normally expressed in the product market price [Krozer 2006], such as costs incurred during the usage and disposal. LCC is essentially an evaluation tool in the sense that it gets on to important metrics for choosing the most cost-effective solution from a series of alternatives [Shtub et al. 2005].

As previously stated, LCC was originally developed as a formal analysis tool by the US Department of Defence in the mid-sixties and has been used since then moving to the areas of industrial and consumer products [Sherif and Kolarik 1981; Barringer and Weber 1996]. However, LCC is not a standard analysis and several approaches have been developed, depending on the context and focus of analysis [Dhillon 1989]. In fact, LCC has been developed for products, machines, infrastructures and projects, focusing on different aspects. Depending on the type of product, asset or project under analysis, LCC started to be developed on four main model types: total cost models, logistic support models, design trade models and level of repair models [Sherif and Kolarik 1981]. In fact, in the literature there is no standard method to perform a LCC analysis and there are a vast number of proposed approaches varying in their form and scope. An extensive review study of Durairaj et al [2002] on existing cost models for life cycle cost studies analysed the models developed until the date. This study was based on an earlier review study on LCC by Asiedu and Gu [1998].

The models reviewed are the Life Cycle Cost model developed by Fabrycky and Blanchard [1991], the LCC model by Woodward [1997], the LCC model of Dahlen and Bolmsjo [1996], and other LCC variation models developed and used by several researchers; the Activity Based Costing (ABC) or Process-based model, the Economic Input-Output LCA model, the Design to Cost model, the PLCC to Manufacturing System and the Total Cost Assessment (TCA) model. These models are summarized in table 2.1., adapted from Fabrycky and Blanchard [1991].

Analysing the differences between the more traditional LCC models, these are relatively similar, allowing the identification of alternatives, cost break down structures (CBS), cost profiles and sensitivity and risk analysis. The holistic Fabrycky and Blanchard model [1991] model differs from the others LCC models for its effectiveness in assessing the capability of an existing system by identifying high-cost contributors and costly problem areas. The Woodward [1997] model focus on optimizing the trade-off between the cost factors relating to the assets during their operational life in order to minimize its life cycle cost. Finally, the Dahlen and Bolmsjo LCCA model [1996] widen the field of application, and carry out an analysis of investments considering the production factor namely, labour. It covers the cost of an employee over the whole employment cycle, from recruitment until retirement.

Moving to more different approaches to the traditional life cycle cost, Bras and Emblemsvag [1996] proposed the use of ABS to address life cycle design. This approach is also called by other authors as process-based modelling [e.g. Field et al. 1997, Fuchs et al. 2008] and was also applied to life cycle design by Ribeiro et al. [2008] and Peças et al. [2013]. This approach to life cycle costing is very useful and efficiently compares alternative designs, allows analysing the CBS, generation of cost estimates, cost profiles and cost contributors. Moreover, it is extremely suitable when dealing with product design as its focus is on correlating cost with design changes. This allows performing without re calculations sensitivity analysis to design and process parameters, allowing also risk analysis to be incorporated.

The Economic Input Output–LCA (EIO-LCA) Model was first introduced in an IEEE on electronics and environment conference by Cobas et al. [1995]. EIO-LCA is a tool that complements conventional LCA with conventional economic input-output tables with appropriate sectored environmental impacts indices, which are then used to analyze economy-wide, direct and indirect environmental impacts of changes in the output of selected industries. Moreover, this model incorporates the supplier relationships in a feasible, rapid and inexpensive way.

The Design to Cost (DTC) model was developed by Eversheim et al. [1998] for production systems. Its generic methodology combines cost modelling and Quality Function Deployment (QFD) in order to assess the potential trade-offs between the cost and performance of competing product alternatives at the early stage of the production

system design. Being its aim the selection of a system design, first derives the system performance, then evaluates the system costs and finally presents the results for decision-making (Performance, Cost, and Conclusion modules).

A Product Life Cycle Costing (PLCC) model [Westkämper and Osten-Sacken 1998] was developed based on the life cycle costs of capital goods such as machines and manufacturing systems in order to anticipate life cycle costs. In this method the products life cycle are connected to single processes with the aim of redesigning current product structures. It considers as the main product life cycle production, usage and disposal or de-production. Cost reductions in the different life cycle stages are achieved through a product conception focused on the needs of the use and disposal phases.

The development of the Total Cost Assessment (TCA) was fostered by the need to provide a practical and useful tool to small manufacturers. It is a simple approach to identify and quantify the costs of pollution prevention investments, expanding the scope of capital budget to include indirect benefits. Its aim is to increase the amount of savings from pollution prevention investments in a simple way, easy to implement [Pacific NW Pollution Prevention Resource Center 1997].

The above models, which functions are summarized in table 2.2., have in common the attempt to apply the LCC methodology to products, projects or equipments. Some perform cost estimations, that is, prior to product production, project execution or equipment acquisition, others integrate LCA and LCC in the same framework, and others outstand in some specific aspects further explored in the models, namely supply chain integration and employment cycles. When choosing the most adequate model, there is no “best one”, being the decision on the kind of model to apply or develop dependent on the goal of the analysis and desirable results to obtain.

Table 2.2. – Comparison between life cycle cost approaches and models. (✓- available; NA - not available)

Features	LCC [Fabrycky and Blanchard 1991]	LCC [Woodward 1997]	LCC [Dahlen and Bolmsjo 1996]	ABC or Process-based [Bras and Emblemsvag 1996]	EIO-LCA [Cobas et al. 1995]	DOC [Eversheim et al. 1998]	PLCCA [Westkämper and Osten-Sacken 1998]	TCA [Pacific NW Pollution Prevention Resource Center 1997]
Identification of alternatives	✓	✓	✓	✓	NA	✓	NA	NA
Development of CBS & CBRs	✓	✓	✓	✓	✓	✓	✓	✓
Identification of suitable cost model	✓	✓	✓	✓	✓	✓	✓	✓
Generation of cost estimates	✓	✓	✓	✓	NA	✓	NA	✓
Availability of cost profiles	✓	✓	✓	✓	NA	✓	NA	NA
Break Even Analysis	✓	✓	✓	✓	NA	NA	NA	NA
Determination of High Cost contributors	✓	NA	NA	✓	✓	NA	NA	NA
Total Cost Determination	✓	✓	✓	✓	✓	✓	✓	✓
Incorporation of Eco-costs	NA	NA	NA	NA	NA	NA	✓	NA
Correlation with Design changes	NA	NA	NA	✓	NA	✓	✓	NA
Implementation of a Design solution	NA	NA	NA	✓	NA	✓	✓	NA
Quality Aspects	NA	NA	NA	NA	NA	✓	✓	NA
Inclusion of Supplier Relationships	NA	NA	NA	NA	✓	NA	NA	✓
Trade – offs	NA	✓	NA	✓	✓	✓	✓	✓
Employment cycles	NA	NA	✓	NA	✓	NA	NA	✓
Sensitivity Analysis	✓	✓	✓	✓	NA	NA	NA	NA
Risk Analysis	✓	✓	✓	✓	NA	✓	✓	NA
De-manufacture concept	NA	NA	NA	✓	NA	✓	✓	NA

- ***LCC Applications***

Regarding product design, LCC analysis has been widely used due to the increasing demand for greater responsibility of the manufacturers for their products in the entire life cycle. In fact, the traditional industrial perspective on the physical product has evolved towards an integrated product-service focus [Datta and Roy 2010]. In this context LCC is a suitable method for assessing the costs of a product throughout its life cycle, especially if one consider that product life cycle cost is mainly committed by early design stages [Park et al. 2002, Asiedu and Gu 1998]. The area of product design

has fostered the development and integration of several aspects in LCC: product reliability, quality and warranties [Dunk 2004, Chien 2010], design impact on manufacturing costs [Westkämper and Osten-Sacken 1998, Lee et al. 2002, Ribeiro et al. 2008, Peças et al. 2010], eco-design and translation of environmental burdens into costs [Senthil et al. 2003, Vogtländer et al. 2002], utility of a product to consumers [Hannsgen 2008, Nam et al. 2011].

Machines and tools have also been subjected to LCC analysis. To counter the tendency to make decisions based only on the initial purchase cost [Woodward 1997, Tysseland 2008], there have been significant studies shifting this paradigm by evaluating a fixed asset purchase decision integrating its performance throughout its operating life [Chen and Keys 2009, Jambulingam and Jardine 1986, Dhillon 1996, Lanza and Rühl 2009, Peças et al. 2009, Folgado et al. 2010]. The Life Cycle Cost of this kind of assets is generally evaluated with Net Present Value method [Barringer et al. 1998], exploring mainly their operational performance, namely reliability and maintainability aspects [Dhillon 1996, Lanza and Rühl 2009, Wu and Longhurst 2011]. Reliability has also been further investigated in the LCC context in the infrastructures area, having been developed several probabilistic failure models and maintainability models integrated in the operating costs [Kim et al. 2010, Cho et al. 2007, Lee et al. 2004, Frangopol and Maute 2003].

Investment projects are becoming more and more an area where decisions need to be taken favouring solutions that yield the lowest possible cost of the project-product life cycle, even if this means that the initial investment cost becomes higher. So, LCC is here a suitable approach to keep a strategic view on the final project-product (managing its the functionality and operability) during the project implementation together with the more conventional project management objectives of completion within time, cost and scope [Artto et al. 2001]. The research interest in the areas of performance/earned value management has increased significantly after the year 2000 [Ahsan 2010, Tysseland 2008, Kwak and Anbari 2009]. Developments have been published in the area mainly regarding the integration of simulation models in the projects' LCC [Artto et al. 2001, Chou 2011, Yu and Tao 2009] and risk [Tummala and Burchett 1999, Dey 2010].

In fact, several authors have approached differently the LCC methodology and applied them to a vast number of products, projects and machines, in different forms and extent.

Despite the wide range of developed models found in literature, there is a common aspect regarding most product LCC analysis: the scope is on either on the product design and on the impacts of design changes or on design alternatives throughout its life cycle [Asiedu and Gu 1998, Park et al. 2002].

Moreover, the LCC method by itself, without additional assessments, is not sufficient as an indicator for sustainable practice [Rebitzer et al. 2003]. Thus, it is also advised to evaluate the product on an environmental basis also with a life cycle approach, namely with LCA.

2.2.1.2. Life Cycle Assessment - LCA

LCA can be defined as a tool to assess potential environmental impacts and resources consumed throughout the product's life cycle, that is, from raw material acquisition to waste management [Finnveden et al. 2009, Jeswiet and Hauschild 2005]. Other authors have broadened the scope of LCA to projects and activities [Jeswani et al. 2010, Andersson et al. 1998], being the area of buiding and construction projects prolific in LCA studies and developments [Bribiàn et al. 2009, Ramesh et al. 2010]. The LCA concept appeared in the 1960s and has been subject of several developments since then, until an overall LCA framework and well-defined inventory methodology was settled in the 1990s [Roy et al 2009]. Two main organizations fostered the international consensus regarding LCA – The Society of Environmental Toxicology and Chemistry (SETAC), the host of meetings with the global community of LCA researchers, and the International Standards Organization (ISO), which initiated a global standardisation process for LCA [Hauschild et al 2005]. These standards define the framework for LCA as shown in Figure 2.2. Due to the large amount of data required to perform an LCA, several software applications (see table 2.3) have been developed making the studies much more efficient [Bribiàn et al. 2009].

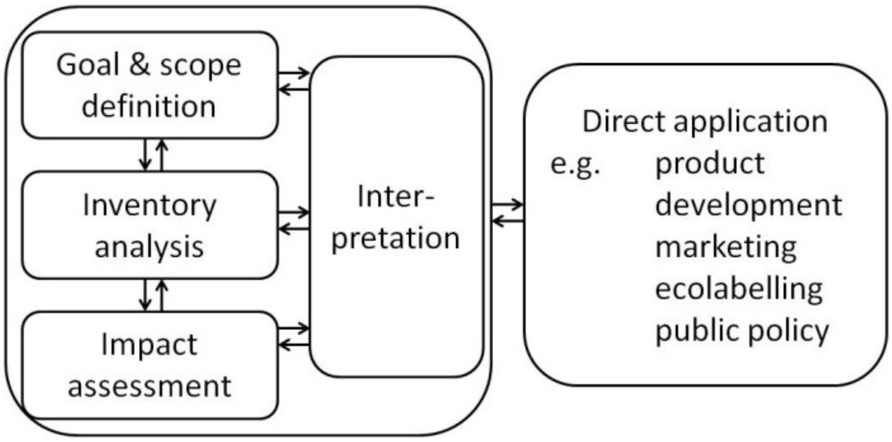


Figure 2.2. – LCA framework according to ISO 14040 standard [Hauschild et al 2005]

Table 2.3 – General LCA tools [Bribiàn et al. 2009]

Boustead	www.boustead-consulting.co.uk
Eco-it	www.pre.nl
Ecopro	www.sinum.com
Ecoscan	www.ind.tno.nl
Euklid	www.ivv.fhg.de
KCL Eco	www.kcl.fi/eco
GaBi	www.gabi-software.com
LCAit	www.ekologik.cit.chalmers.se
Miet	www.leidenuniv.nl/cml/ssp/software
Pems	www.piranet.com/pack/lca_software.htm
SimaPro	www.pre.nl
Team	www.ecobilan.com
Wisard	www.pwcglobal.com
Umberto	www.umberto.de

Hence, the LCA methodology is nowadays a structured method to quantify potential environmental impacts of products or services over their full life cycle [Johansson et al. 2007, Udo de Haes and Heijungs 2007], being therefore a valuable tool to provide designers with information on inputs, outputs and associated environmental impacts of a defined system [Warren and Weitz 1994.]. Presently, LCA consists of four steps: definition of the goal and scope of the study, construction of the product life cycle model with all environmental inflows and outflows (Life Cycle Inventory stage - LCI),

evaluation of the environmental relevance of all the inflows and outflows (Life Cycle Impacts Assessment stage - LCIA) and, finally, the interpretation of the results [Goedkoop et al. 2007]. There are several methods for LCIA stage compatible with ISO requirements and therefore most experts prefer to select a published method instead of developing a new one [Goedkoop et al. 2007].

Notice that LCA is not a method for environmental accounting [Rebitzer and Hunkeler 2003], as it typically lacks information on costs. In terms of the utility of the LCA results, companies have used them internally to support management decisions, externally for marketing purposes and to support product claims, and the government agencies use LCA results to support technical and regulatory decisions [Warren and Weitz 1994].

- *Goal and Scope Definition*

The definition of the goal and scope of specific study is probably the most important step in LCA, as it defines its purpose, expected outcome, , functional units and assumptions [Roy et al. 2009]. According to the purpose of the study, different types of LCA can be developed. Finnveden at al. [2009] differentiated two types of LCA: attributional and consequential LCA. The first, as the name suggests, has its focus on describing relevant physical flows to and from a life cycle and its subsystems. Consequential LCA is defined by its aim to describe how environmentally relevant flows will change in response to possible decisions.

- *Life Cycle Inventory (LCI)*

This part of the LCA method regards the system boundaries, generally illustrated by a general input and output flow diagram. These boundaries comprehend the inputs and outputs to the environment system and the boundaries between the product system and other product systems [Guinée et al. 1993a]. Within life cycle inventory three main elements can be defined:

- The specification of the processes within the product system;
- The specification of all processes and data;
- The compilation of the inventory tables.

The compilation of the inventory tables is the most work intensive and time consuming compared to other phases in an LCA, mainly because of data collection. However, if good databases and collaboration with customers and suppliers are available, this phase can be more time-effective [Roy et al. 2009]. Moreover, in order to overcome the time-consuming critical aspect of LCA, facilitating the LCI and avoiding duplication in data compilation, many databases have been developed in the last decades. These include public national or regional databases, industry databases, and consultants' databases that are often offered in combination with LCA software tools [Finnveden et al. 2009]. In table 2.4 are presented the most well known databases developed so far.

Despite the importance of the inventory stage of the LCA, it provides the amounts of emissions and extractions, having no meaning by themselves [Guinée et al. 1993b]. The problems caused by them are then addressed in the LCIA stage, following described.

Table 2.4 – National, Regional and International LCI databases [adapted from Finnveden et al. 2009]

Type of Database	Origin	Name and website
National or Regional, Public	Sweden	SPINE@CPM (http://cpmdatabase.cpm.chalmers.se/AboutDatabase.htm)
	Germany	PROBAS (http://www.probas.umweltbundesamt.de/php/index.php)
	Japan	JEMAI (http://www.jemai.or.jp/english/index.cfm)
	United States of America	NREL (http://www.nrel.gov/lci/)
	Australia	LCI (http://www.auslci.com/)
	Switzerland	Ecoinvent (http://www.ecoinvent.org)
	Europe	European Reference Life Cycle Database (ELCD) (http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm)
International, from Industry	Aluminium industry	(http://www.eaa.net/eaa/index.jsp)
	Copper industry	(http://www.kupfer-institut.de)
	Iron and steel industry	(http://www.worldstainless.org/About+stainless/Ss+and+he/LCI/)
	Plastic industry	(http://www.plasticseurope.org/plastics-sustainability/eco-profiles.aspx)
	Paper and board industry	(http://www.fefco.org/)

- *Life Cycle Impact Assessment (LCIA)*

LCIA is the stage where the results from the LCI are connected with the corresponding environmental impacts [Van den Heede and De Belie 2012]. Impacts considered in a LCIA include climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related) respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion. The emissions and resources are assigned to each of these impact categories, being then converted into indicators using impact assessment models [IES, 2010].

Two main phases comprehend LCIA, the classification and characterization. In classification, the environmental life cycle inventory results are assigned to appropriate impact categories. In the characterization phase, the quantity of each output of the inventory is multiplied by the characterization factor assigned to that specific output, in each impact category. Characterization factors refer to weighting factors assigned to environmental inputs/outputs to aggregate their associated life cycle impacts into scores for human health damage and environmental damage [Azari-N and Kim 2012].

According to Van den Heede and De Belie [2012], there are two main types of methods followed by LCIA experts; the first one is the classical impact assessment approach, considered problem oriented (mid points). The mid point methods (e.g. CML 2002) restrict quantitative modelling to relatively early stages in the cause-effect chain to limit uncertainties and group LCI results related to a certain environmental problem. Resuming, these methods model the impacts at a midpoint somewhere in the environmental mechanism between emissions and damages. The second type of LCIA methods focuses much more on the actual effect. The damage oriented impact methods, end points methods (e.g. Eco-indicator 99), try to model the cause effect chain up to the endpoint, or the actual environmental damage within protection areas. A study by Benetto et al. [2004] claims that the problem oriented approach provides more reliable results, although sometimes difficult to be compared. The second one, the damage oriented approach, provides results with higher uncertainty but with much easier interpretation.

A joint work developed by the Institute for Environment and Sustainability [2010] with the major LCIA developers analysed the existent environmental impact assessment

methods and developed an overview table with each one. Table 2.5, adapted from the stated report and completed with a more recent method, presents the current available methods.

Table 2.5. – Overview of the current life cycle impact assessment methods [Adapted from IES, 2010]

LCIA Methods	Type	Developer	Website Access Point
CML 2002 (baseline; spreadsheet)	Mid point	Institute of Environmental Sciences, University of Leiden, Nederlands	http://www.cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html
Eco-indicator 99	End point	PRé Consultants, Nederlands	http://www.pre-sustainability.com/
EDIP97	Mid point	Institute for Product Development (IPU) at the Technical University of Denmark.	http://www.ipu.dk/English.aspx
EDIP 2003	Mid point	Institute for Product Development (IPU) at the Technical University of Denmark.	http://www.ipu.dk/English.aspx
EPS 2000d	End point	ENVIRONMENTAL SYSTEMS ANALYSIS (ESA), Chalmers University of Technology, Gothenburg, Sweden	http://www.chalmers.se/ee/EN/research/research-divisions/environmental-systems
IMPACT 2002(+)	End point	Risk Science Center, University of Michigan, USA	http://www.sph.umich.edu/riskcenter/jolliet/impact2002+.htm
LIME	End point	Japan Environmental Management Association for Industry	http://www.jemai.or.jp/english/index.cfm
LUCAS	Mid point	CIRAIG, Interuniversity Research Centre for the Life Cycle Products, Processes and Services, Polytechnique Montréal, Canada.	http://www.ciraig.org/fr
ReCipe	End point	The National Institute for Public Health (RIVM), Institute of Environmental Sciences, University of Leiden, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft, Nederlands	http://www.lcia-recipe.net/

- Interpretation

In the Interpretation phase the results from the previous phases are evaluated in relation to the goal and scope in order to reach conclusions and recommendations [ISO 2006a]. In this stage, depending on the study goal, conclusions are drawn in order to support a decision or to provide an understandable result of an LCA. The outputs are the discussions of the results, together with the significant environmental issues. These are identified for conclusions and recommendations [Finnveden et al. 2009]. The discussion fosters measures for improvements in product, process and activity design; raw material use, industrial processing, consumer use and waste management.

- ***LCA Applications***

Traditionally, environmental problems have been most focused at large point sources, namely industrial plants, power plants and mining areas. However, the rapid growing interest in LCA during the 1990s [Finnveden 2009] fostered a shift in focus towards product design in more dispersed sources, like agriculture, transport, service activities and households. This shift is related to a preventive strategy for improving environmental performances along the whole product chain, from raw material acquisition and production, to distribution, consumption and final waste treatment [Hanssen 1998].

Nowadays, LCA plays an important role in product design as a tool for eco-design. The increasing trend in developing sustainable products drives companies to consider environmental assessment during product development [Sousa and Wallace 2006]. The major limitations for the integration of LCA in product development are cost and time. The concept phase, widely believed to have the most influence in defining environmental aspects of products [Alting 1995, Duflou et al. 2003], also creates particular challenges for environmental assessment. Competing product concepts are several and have numerous differences, detailed information is sometimes not available and multi-attribute trade-off and decisions must be made quickly [Sousa and Wallace 2006]

A research work regarding the significance of decision making for LCA claims that two main categories of LCA should be established; one retrospective and therefore an accounting perspective, and one prospective, focused on modelling the effects of changes [Tillman 2000]. The last perspective is clearly focused on achieving the lowest hazardous products in the design phase, by estimating in early design stages the environmental impacts of design changes regarding throughout the product life. An early work by Keoleian [1993] explores the application of life cycle assessment to product system development, integrating LCA methodology in each stage of the product development process.

Regarding environmental studies of machines and tools, it is usually focused on energy and material efficiency of production processes. In fact, energy efficiency is acknowledged as the great challenge of the XXI century and several authors have developed studies estimating the energetic consumption of several production processes and machines [Dahmus and Gutowski 2004, Gutowski, et al. 2006, Jeswiet and Kara 2008]. Regarding material consumption, several studies have been dealing with the influences of material removal, cooling and lubrification strategies [Fratila 2010, Bay et al 2010, Pusavec et al. 2010a, Pusavec et al. 2010b].

Finally it is clear that like LCC analysis, LCA has been applied both to products and tools, although lacking in connecting both life cycles. Following is analysed the LCE application to products and tools, reviewing past applications and relations between them studied by other authors.

2.3. Life Cycle Engineering of Products and Tools

Literature review on life cycle engineering/design, LCC and LCA showed that the typical scope of life cycle studies is either on the product design and impacts of design changes or on design alternatives throughout its life cycle [Asiedu and Gu 1998, Park et al. 2002]. Some authors have focused LCC and LCA analysis on the manufacturing phase mainly to evaluate equipment disregarding the product design, being the product specifications only a static input to the model that evaluates only the manufacturing equipment able to produce it [Westkämper and Osten-Sacken 1998, Chen and Keys 2009, Jambulingam and Jardine. 2009]. Nonetheless, a product is made of parts and

almost every part requires dedicated tools in the manufacturing phase. Tools are often disregarded or included in product LCC studies as a cost input, despite the fact that the tool design, along with the product design, highly affects the manufacturing phase [Peças et al. 2009, Ribeiro et al. 2011]. These designs are not independent, as the product design also constrains tooling engineering solutions albeit leaving open several tool design alternatives to produce the same product. In summary, the tool life cycle enters the production phase of the product life cycle and affects part production regarding material waste, energy consumption and productiveness, among others, much beyond the mere tool investment. This leads to the need to fill a gap in Life Cycle models developed so far.

In parallel, the tool also affects the environmental impacts by affecting energy consumption and material waste. Having in mind the goal of developing a model that captures the most relevant impacts of these design decisions, it is also necessary to assess the environmental burdens of the product and tool life cycle in an early design stage. This is increasingly important given the fact that 70% of the final cost/impact of a product is determined at its design phase [Jeswiet and Hauschild 2005].

The vast and strong links between the tool design and the product design in addition with their effects on the performance of manufacturing processes bring out the fact that the integration of the two life cycles cannot be a simple sum of the tool life cycle cost and environmental impacts to the product's LCC and LCA. Moreover, a dedicated tool is a one of a kind device, being difficult to quantify its influence in the part production phase, as there is a lack of data regarding a specific tool. It is relatively easy to estimate its production cost, but it's increasingly harder to estimate impacts going forward in the tool and product's life cycle. This is extendable to the environmental impacts, as many of the required information, in some extension, is identical for both analyses.

One major limitation for the implementation of Life Cycle Approaches to the tooling industry is the pressure felt in the last decades to reduce lead time. The importance of dedicated tools in product life cycle and the challenges faced by this industry are further described in the following section.

2.4. Role of dedicated tools in sustainable product design and challenges

Tooling design and manufacturing sector is critical in innovation processes. It is in the critical path of any new product development, determining largely the time to market. Product innovation, technological development and the optimization of the whole manufacturing system strongly depends on innovations and developments on Tooling. This is particularly true in the dedicated tools case as its design is determinant in the productivity of the final product manufacturing process and in the product quality [Li and Li 2008].Their cost and time to market as well as their quality and reliability are key competitive factors which, directly or indirectly, have a structural and horizontal strategic effect in the sustainability of the European industrial competitiveness.

Tooling companies have a strong technological base and a medium/high qualified work force, moving themselves away from an intensive unqualified and low wage labour industry. Moreover, as an industry they have a strong multiplier effect on the local economy in light of the variety of links and interface activities with other industrial sectors, both in the acquisitions of materials, components and services with a high technological content, and in the design phase, in the manufacturing and assembly of final goods. This strength gives to the tooling industry a significant position in the dissemination chain of technological innovations, playing simultaneously roles as receivers, promoters or disseminators of innovation [Peças and Henriques 2011].

Concurrent engineering in the development of tool design has been the central focus of several studies on mould and dies design and are based mainly on design for manufacturing principles. That is, in the cooperation between the product and tool designers in order to minimize the tool lead time and to optimize the part manufacturing quality, therefore minimizing cost and time. Following are further investigated the current challenges and developments in the integration of tool design in the part design process.

Notice that for sake of simplicity, the term tool is from now on referring only to dedicated tools.

- **Design challenges and current developments in tooling industry**

Tools are complex and one-of-a-kind systems, materializing intensive knowledge on engineering and production, which overcomes the strict frontiers of the sector. The tools design and manufacturing represent a significant link in the entire production chain because nearly all mass produced discrete parts are formed using production processes that employ dies and moulds. In fact, tools are present in the design and manufacturing of almost all industrial products from aeronautics and automotive, to electronics, household, equipment goods and micro-devices. Having interfaces to the final parts (products and components) and production equipment (such as, machine-tools), the tooling sector is in the core of the production system of these products, determining its efficiency, robustness and wealth. Tool design plays therefore a key role in the final product development [Lee et al. 1997].

Conventionally, tool design is performed separately from product design and in some cases, from tool manufacturing process planning. The lack of communication between the actors in these activities result in long mould lead times and even incompatibility problems in the part manufacturing phase [Lee et al. 1997].

An extensive study regarding moulds and dies production [Altan et al. 2001] pointed out the importance of these tools in production chains of nowadays products through several observations found in academia and industry; first, dies and moulds, despite their importance in determining the products' lead time, quality and costs, represent a small investment in an overall mass production program; second, manufacturing and try-out of new dies and moulds determine both the feasibility and lead time of an entire production program; third, the quality of the parts are directly influenced by the quality of the dies and moulds. Furthermore, the authors also observed the wide range of activities covered by this industry: manufacturing of new dies and fixtures, maintenance and modifications, and technical assistance and prototype manufacturing for the customer. These last activities are particularly important as they are tied up to expensive equipment and directly affect lead times.

Reducing tool lead time is therefore a main issue found in literature regarding mould design. Several approaches where found, from design methods and software tools to concurrent engineering principles [e.g. Nakao et al. 2002, Lee et al. 1997, Huang et al.

2009]. Nakao et al. [2002] introduced a "Decision-based process design" for reducing the process time of the design and production of moulds. This method reviews the human processes of making decisions for setting unknown parameters, and reduces their process time by actively reducing the operations with such decisions by standardizing some. This requires developing analytical models and capturing knowledge from experts. Several authors have developed efforts in this area with similar approaches. Regarding the application of concurrent engineering principles, also several authors proposed several approaches and methods to its application in tooling design, always with the aim of reducing lead time. One example is the work by Lee et al. [1997], who proposed a systematic approach to the development of a computer-aided concurrent mould development system. Their results include both the process for the development of a mould based on concurrent engineering principles and a computer-aided concurrent mould development framework. Still, it focuses mainly on the integration of the mould design and mould manufacturing activities, although incorporating also product requirements. Software tools to aid tooling design have also been developed, namely through World-Wide-Web collaborative operations. Huang et al. [2009] developed a web-based parametric model to mould base design using a function modelling method (IDEF0). Information and data from the company and suppliers are analysed, expanded and are finely structured into design procedure and databases. The system interface uses parametric and feature-based database to simplify the design process and enables viewing results, namely cost.

Quality of mass production parts is also dependent on proper tool design, being several factors required to take into consideration in the tool design process; mould size, number of cavity, cavity layouts, runner systems, gating systems, shrinkage and ejection system. In fact, the design and manufacture of injection moulded polymeric parts with desired properties is a costly process dominated by empiricism, including the repeated modification of actual tooling. Some studies found develop new materials or cooling systems to decrease process time without compromising part quality e.g. [Tang et al. 2006]. However, most focus on the process parameters rather than in the mould design. The impact of mould design in part quality is still a mostly empiric field with mould testing as a crucial step.

Along with the impact of tool design and manufacturing in the part production lead time and quality, another aspect is also decisive in the performance of part manufacturing

process – tool reliability. If tool design influences the performance of the part manufacturing process, then tool reliability is a crucial aspect to understand. Manufacturing processes highly depend on machine reliability [Lanza et al. 2009]. Whilst machines are generally standard, a great amount of data is available and reliability data is often easy to find, the same does not happen as regards dedicated tools. The reason, already explained, is that a dedicated tool is a non-standard device materializing a unique engineering solution. Literature review shows a wide number of studies regarding machine tools reliability, with several studies aiming to extend their life and decrease time between failures. Being this type of tool standard and despite the variations possible in the processes with different parameters, several relations have been developed between these parameters and tool wear and thermal fatigue, the most common causes of failure in machine tools. Some authors deal with the choice of process parameters, others develop reliability estimation tools to optimize tool change times [Rodriguez and Souza 2010, Xie et al. 2005]. Whilst machine tools, commonly standard, have been exhaustively studied to extend tool life and reliability for decades, there is no failure probability estimation method in the dedicated tools case. Some studies studied methods to prolong moulds and dies' life by repairing cracks with different solder joints, or estimated the reliability of these different joints [e.g. Song et al 2008]. However, no model, method or tool was found to address to overall dedicated tools reliability, mainly due to their one of a kind nature. Looking at these tools as complex mechanical systems, it is possible to estimate failure probability parameters of mechanical components through experts' knowledge. Some authors have developed methods to assess mechanical components reliability through the Weibull distribution [Lanza et al. 2011, Jagger and Bertsche 2004] that can be useful in evaluating dedicated tools reliability.

Regarding the product manufacturing process, tool design is a key element in cycle time, energy and material consumption. The cooling system design is determinant in reducing the cycle time, which also affects the energy consumption [Tang et al. 2006]. Accordingly, the runner systems determine the amount of material waste generated in each production cycle [Ribeiro et al. 2011]. Tool design can therefore optimize the costs and environmental impacts regarding the part material and manufacturing phases.

2.5. Main findings from literature review

In summary, the literature review on design for the life cycle strategies revealed a huge amount of principles, guidelines, methods and tools. It has been a central focus in the areas of product design, equipments and tools, construction and production systems with a vast number of case studies and applications. It is clear that life cycle approaches and methodologies are difficult to separate and define, being terms as eco-efficiency, life cycle design/engineering, life cycle cost analysis and assessment, among others, connected and sometimes virtually the same. In the last decades the term Life Cycle Engineering has been more referred by authors, possibly due to the annual CIRP conference on Life Cycle Engineering, where the main experts and precursors of life cycle approaches gather and discuss the latest sustainable strategies in different fields.

Looking deeper in the application LCE, LCC and LCA on products and dedicated tools, a vast number of studies, methods and tools were found, analysing the design and processes with different goals. Some authors focus their approach on sustainable product design, disregarding the production processes and tools. Other authors address to the product life cycle and integrate life cycle strategies in product design, but fail in incorporating the dedicated tools required to produce most products.

When analysing the existent studies on tool design and manufacturing, it is clear its strong link with the final product lead time, quality and with the manufacturing process cycle time, material consumption and reliability. Being dedicated tools used mostly in mass production products, the importance of their good performance in product manufacturing phase clearly surpasses their production cost. However, these tools are one of a kind mechanical systems and their design difficult to normalize. In fact, most studies focus on either particular tools for a particular product or on tool features improvement, namely the cooling system. Their determinant role in the part material consumption and manufacturing energy consumption, cycle time and reliability puts tool design in the path of sustainable design. Moreover, the intrinsic relations between tool and part design are patent in all tool design and manufacturing studies, being clear its impacts on products and processes.

The production processes are also an important subject in LCE approaches, but the analysis are often limit to either energetic optimization of processes, lubrication

strategies and process reliability. In fact, there is a void in the vast research field of sustainable design in developing a truly integrating approach to address product life cycle. Despite the importance of dedicated tools design in the product life cycle performance, these are disregarded in the traditional product life cycle framework.

3 RESEARCH METHOD, MEANS AND MATERIALS

The framework proposed in the following chapter results from the need to adopt a comprehensive approach to the life cycle design of products composed of parts produced by dedicated tools. This framework is the result of four years of active research in the area of dedicated tools, with several visits to companies and internships in the areas of injection moulding die casting and stamping – the main three processes using dedicated tools. Having in mind the goal of assessing the impacts throughout the life cycle of the part and tool in early design phases, several case studies were analysed and alternative designs studied regarding the part and/or tool. In each case study process based models were developed modelling each process in the tool and part life cycle. The wide scope of this research field, comprising different processes and materials, makes inadequate the development of a process based model suitable for all classes of dedicated tools. However, the life cycle of a dedicated tool is always connected with the life cycle of the part produced by the tool. This asks for a structured and comprehensive framework to address the problem. The diversity of tools, parts, materials, processes and end-of-life scenarios enhance the need to follow an approach that guides to the development of specific models that allows the designer to acknowledge the impacts of design decisions. Despite the proposed framework has been developed throughout the thesis years to fill the lack of structured methods to address life cycle design in this area, this thesis presents the work backwards. The framework is first presented, followed by its deep exploration in parts produced by plastic injection moulds. Several case studies are then presented using the process based models and specific models developed for the injection moulds and injected parts life cycle. Finally other case studies are addressed regarding the other classes of dedicated tools – stamping and die casting tools, in order to further demonstrate and validate the proposed approach.

3.1.Research means

The following picture (figure 3.1.) illustrates the research path during the development of the framework proposed in this thesis. The final outcome was fostered by the initial motivation to assess the impacts of design decisions of parts and dedicated tools throughout their life cycle, exploring the interactions between them. Bibliographic research in the area revealed several approaches to life cycle design, mainly in the area of part design, assessing cost, environmental impacts or quality throughout the part life

cycle, independently or integrated in the same framework (Life Cycle Engineering). Tools life cycle design related studies have been mainly focused on either extended their manufacturing life cycle or in improving tool reliability. Most of the approaches of other researchers are methodological and there is no settled method to deal with life cycle design. Regarding environmental analysis, Life Cycle Assessment and eco-indicators can be found and have been widely developed and applied to case studies, but are usually either product oriented or process oriented, the last one usually related with eco-efficiency. Concerning the cost approaches, Life Cycle Cost has been the main method to address the cost impacts of products and equipments throughout the life cycle. Again, no settled method to perform an LCC exists and most of the studies in the area focus on investment decisions rather than being design oriented. The research was therefore focused on developing LCA and LCC analysis that would capture cost and environmental impacts of design decisions in a life cycle perspective, liking the part and tool life cycles.

Process based models were then investigated and further explored in an internship in a research group in Massachusetts Institute of Technology (MIT), as they revealed to be very suitable to assess in early design stages the impact of design decisions. Usually developed to support design and strategic decisions and oriented to the production cost, these models are process oriented and capture the cost of a design alternative, either regarding material or geometry, by modelling the process to produce it. By applying this type of models to each process of a tool and/or part life cycle stage, the cost and environmental performance of a design alternative can be assessed throughout the life cycle. When applying to case studies developed during internships in companies and research projects (see figure 3.2.), the entrenched relation between the life cycle of dedicated tools and parts was made clearer. Moreover, the tool reliability proved to be a crucial aspect in tooling design, in particular in companies in the area of electronics and automobile part high volumes production. Part quality within tool design alternatives was disregarded, as only tools capable of producing acceptable parts were considered to be a real alternative. Being the classical approach to life cycle engineering the assessment of three dimensions of analysis, cost, environment and quality, the third was proved to be controversial and in tools case related with tool reliability. In order to approach the problem, a bibliographic research on tool reliability studies allowed the integration of dedicated tools reliability in the cost dimension, enabling to focus the

study in cost and environmental impacts. The case studies and methods to deal with those impacts have been presented in international conferences, both to validate and to receive feedback. Finally, all the case studies and developed models allowed to build the framework proposed in this thesis, named comprehensive life cycle design. This framework is further explained in chapter 4.

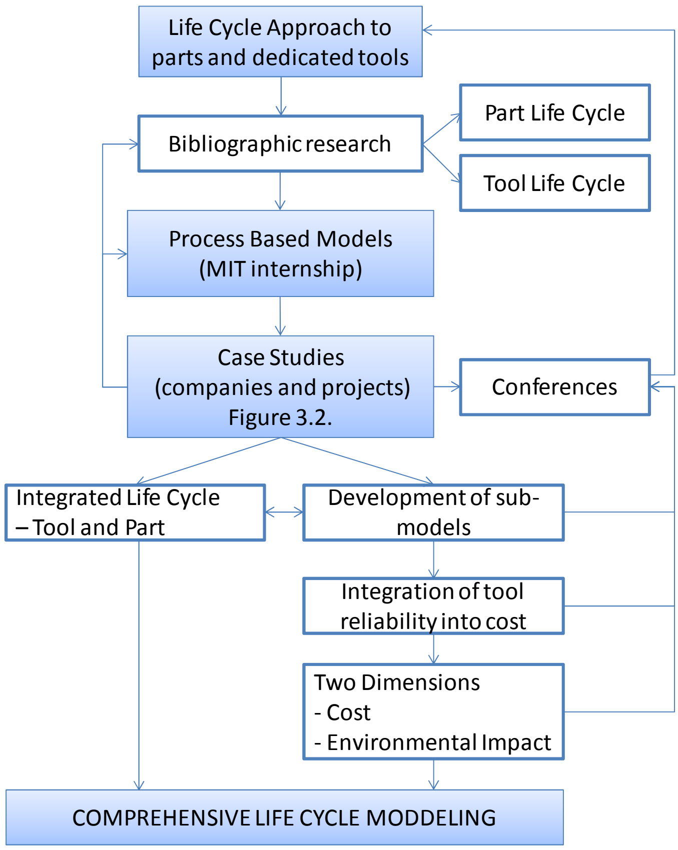


Figure 3.1. – Research development

The case studies developed in the area of life cycle design, companies involved and conferences attended are presented in figure 3.2. The injection moulding cases were developed during two internships in Celoplás and Famolde, two companies producing high technological moulds and in the Celoplás case, producing also the parts. The case studies in Celoplás, assessing the impacts of mould design alternatives throughout the tool/part life cycle were presented in the 2011 International Conference on Engineering Design [Ribeiro et al. 2011]. Also the Eurotooling21, a project in moulds for very low part production levels enabled the development of a case study, presented in PMI 2008 conference and published in an international journal [Ribeiro et al. 2008, Peças et al. 2009]. Still in injection moulding process, two case studies were developed in Fapil, a

company dedicated to household goods, being one focused on part design and mould design alternatives and the second dealing with part material selection comparing fossil based polymers and biodegradable polymers from renewable sources. The case studies were presented in the CIRP Conference on Life Cycle Engineering 2009 [Ribeiro et al. 2009], in the CIRP Design Conference 2010 [Almeida et al. 2010] and in the CIRP Conference on Life Cycle Engineering 2011 [Ribeiro et al. 2011]. Regarding the stamping process, the participation in a project within MIT-Portugal cooperation allowed the development of a life cycle engineering approach to support the material selection of an automobile fender produced in Volkswagen Autoeuropa. This case study was presented in the 2008 International Conference of Manufacturing Engineering and Engineering Management (MEEM) in the World Congress of Engineering. Finally, the die casting process was analysed through a case study during an internship in GM research and development centre in Detroit, aiming to compare the use of aluminium and copper in the injection of an electric motor rotor bars. This fostered exploring the tool alternatives and expected life, as this was critical point in the decision. Moreover, the internship allowed visits to two die casting machines producers, Buhler (MI, USA) and THT (OH, USA).

Finally, it is important to add that while papers presented in conferences were useful mainly to receive feedback by the scientific community and to bring new ideas, some papers were published in international journal [Ribeiro et al. 2008, Peças et al. 2009], books or chapters [Ribeiro et al. 2008, Ribeiro et al. 2009, Peças et al. 2010] with the main goal of validation of the work under development.

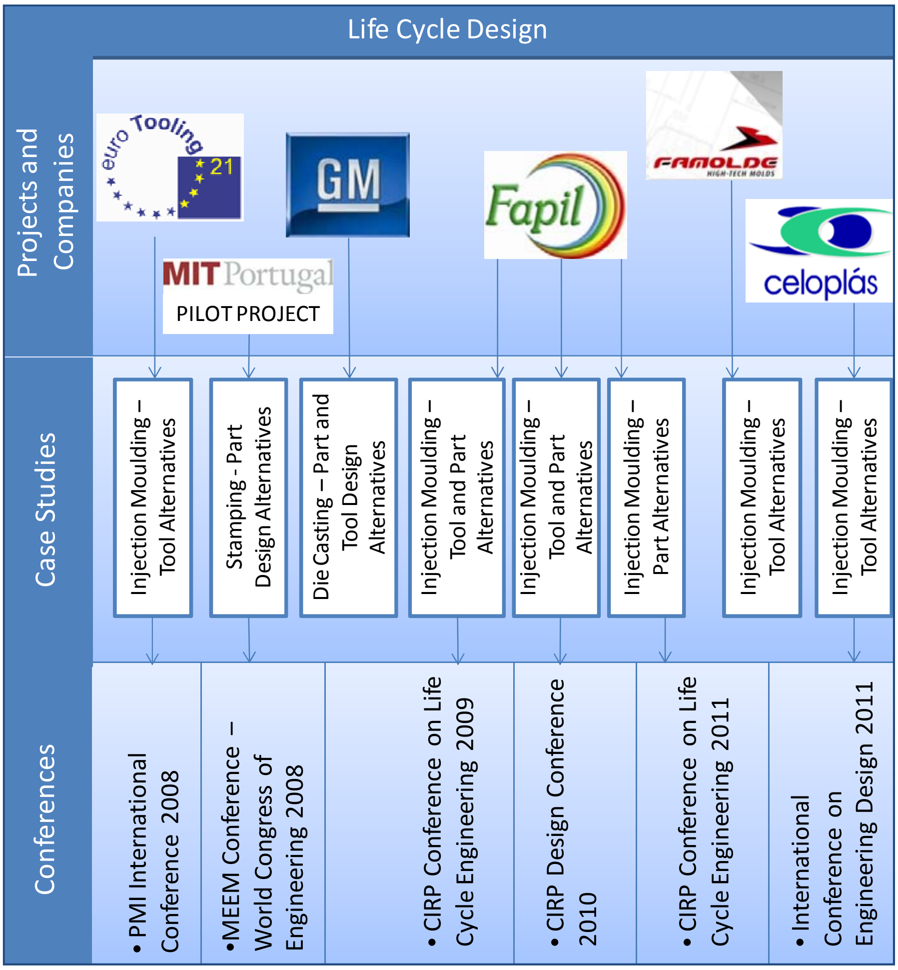


Figure 3.2. Companies involved, case studies and conferences attended

3.1.1. Companies involved

Celoplás is a Portuguese company currently certificated according to ISO 9001:2008 and TS 16949:2009 specialized in producing technically complex parts made of polymeric materials. Besides producing the parts Celoplás produces also the required precision moulds for their own use, meaning that the company is simultaneously the mould producer and the mould user. The company is mainly in the exportation sector, supplying mainly parts for the automotive and electronic industry. With a total of 59 injection machines, Celoplás produces more than 100 million pieces per year, using more than 160 different grades of engineering thermoplastics as well as thermosettings, BMC's and silicones.

Fapil is a Portuguese company specialized in household products, established mainly on the domestic market, certified by the norm ISO 9001:2008. The company is equipped with several machines, among them 4 plastic injection machines. Currently the company is starting to produce disposable products made of biodegradable polymers from renewable resources, namely Polylactic acid (PLA).

Famolde is a certified Portuguese company by the norm ISO 9001:2008, specialized in the manufacturing of high technical moulds of small and medium sizes, destined to injection of thermoplastics, mainly for the automotive industry. The company is equiped with modern technology, from HSM centers to EDM, laser and ultrasonic machining. Besides, the company has also its own injection department which allows testing the moulds from 50t to 450t machines.

General Motor (GM) is an American corporation headquartered in Detroit, Michigan. The internship took place in GM Research and Development, headquartered in Warren, Michigan. GM R&D is today a network of six laboratories, six science offices, and collaborative relationships in over twelve countries including working relationships with universities, government groups, suppliers, and other partners from across the globe.

3.1.2 Materials

The materials and processes used in the case studies were available in the companies where were developed, being detailed when appropriate. In this section are described materials used in most case studies.

- Simapro software

The SimaPro software is nowadays probably the most used software for LCA, in which many published works are based on. SimaPro includes several LCIA methods such as Eco-indicator 99, EDIP 1997 and 2003, EPS 2000, among others. It allows viewing parts of the life cycle at different scales, displaying their contributions to the total score.

- Power Analyser PROVA 6830

The measurement of injection machines energy consumption was performed using the equipment PROVA 6830, a power and energy quality analyser. This equipment is easy to manipulate and with great precision, allows calculating a very complete set of values and presents several measurement and monitoring functions, from the voltage and current intensity to power, active and reactive, energy, harmonics analysis, among other.

Figure 3.3. Power analysed PROVA 6830

4 COMPREHENSIVE LIFE CYCLE FRAMEWORK

4.1 CLC – General framework, relations of impact between life cycle phases

Products are more or less complex systems of parts. These parts require specific materials and manufacturing processes. Furthermore, almost all parts found in nowadays products are produced by various processes, namely forming, moulding and casting each of them requiring dedicated tools. Despite the intrinsic relation between parts and dedicated tools, life cycle design approached so far have restricted the life cycle phases to the traditional scope; focusing only on the part life cycle, disregarding the tool life cycle.

This chapter addresses to a comprehensive life cycle framework as a new approach to fulfil the challenge of capturing the main impacts of a design decision in the scope of parts produced by dedicated tools. This brings the need for integrating two life cycles, tool and part, as dedicated tools are specifically designed for the particular part and are closely linked with the part design and the part production performance. Furthermore, the part is often designed bearing the tool required to produce it, namely the tool cost. Finally, this framework aims to forecast in early design phases the impacts of design decisions of tools and/or parts in both life cycles with the use of process based models applied to all operations and phases in the life cycle.

This framework starts with the definition of the analysis scope for each part, where the life cycle stages to analyse are defined, as well as the manufacturing processes included in each phase. The subsequent step is to model each process using process-based models, integrating additional models when relevant in order to further explore critical aspects. These are for example models to estimate tool reliability, energy consumption and maintenance performance. The need to develop them depends on several aspects, namely the processes involved and the design alternatives. If for example a process is mainly manual and therefore requires very low energy, then there is no need to develop an energy model. As already stated, an approach to fill the need to assess the life cycle impacts of design decisions in the area of dedicated tools and parts produced by them is proposed in this chapter. Therefore, although the framework can cover the universe of dedicated tools, the models developed vary case by case. Finally, all costs and

environmental impacts are computed according to the resources requirements driven by the design specifications.

4.2 Scope – Tool and part integrated life cycle

The proposed framework expands the product life cycle by integrating the life cycle of the tool required to produce it (see Fig. 4.1). As dedicated tools are allocated to only one product, the tools life cycle is exclusively allocated to the product life cycle and the total life cycle includes both. Notice that there is a common phase, the part production/tool use phase, which depends on both design decisions (tool and product), becoming a two dimensional analysis. Additionally, there are some life cycle stages that may occur outside an industrial context, as for example the part use or some EOL scenarios such as landfill or recycling. These stages need to be evaluated individually. However, depending on the case and the purpose of the analysis, some stages may be disregarded if no costs or environmental impacts are entailed (the use phase some household plastic parts) or if they are not affected by the design solutions under evaluation. .

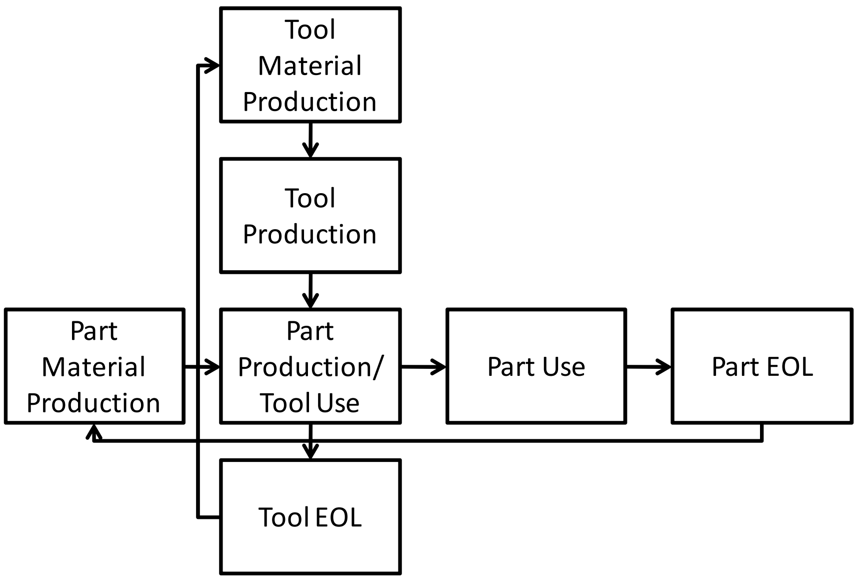


Figure 4.1: Product/Tool Life Cycle.

4.3 Process based cost models

In the proposed framework, processes involved in each life cycle stage are modelled using process-based cost models in order to compute the resources requirements and,

further on, the costs. This is a demanding task, as a significant number of manufacturing technologies can be involved in the process, and furthermore the relations between part design and the technological requirements along the process needs also to be considered. For this task engineering knowledge of each technology in the process is required, as the modelling is not simply a cost accounting procedure.

Process-based cost models start from the description of the intended product (part(s) material(s) and geometry(ies)). The process(es) required for its production is(are) then modelled regarding the cycle time, resources (equipment and labour) specifications, etc. This can be obtained with theoretical and empirical relations correlating the properties of the part and the requirements of the involved technologies. By adding inputs regarding the operating conditions of a certain plant it is possible to build up the operations description, which allows computing the needed resources regarding the number of tools, equipment, operators, etc. (or, as far as equipment and operators might not be dedicated, the time allocated to the product being analysed). Finally, having modelled all the processes and the required resources to produce the part(s), and introducing the price factors to each cost driver, the economical model is completed and the part(s) cost computed (see Figure 4.2).

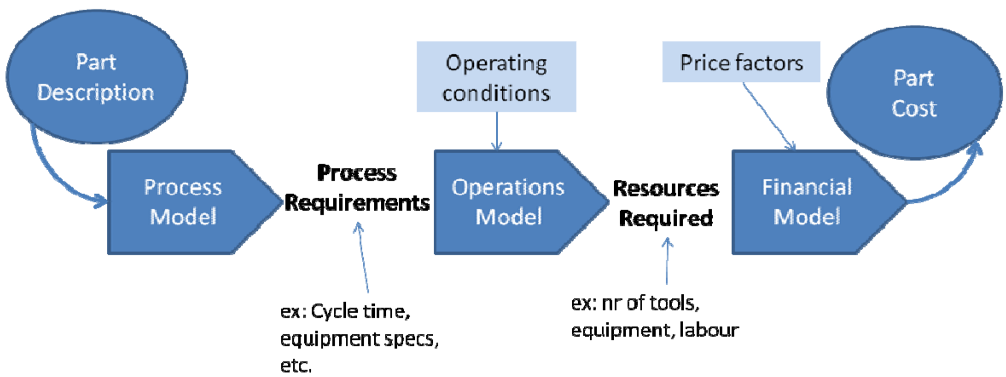


Figure 4.2: Process-based cost model.

The proposed CLC framework further explores the process-based models potential, as it broaden the scope not only to the manufacturing process required to produce the part, but to all the processes involved in the part and tool life cycle. Regarding the part production/tool use phase, the process(es)' requirements are modelled as a function not only of the part design and material, but also of the tool design. In some cases it is even

possible to correlate the part design with the tool design, increasing the model flexibility and sensitivity to part design and material changes.

4.3.1. Financial relations used in process-based cost models

The financial model follows the approach of annual production costs, in which an annual expected demand is assumed. This annual cost is simply an annuity of the investment. The allocation rule is based on the percentage of the annual uptime time consumed. In these models is usually used the conventional method of grouping costs in two categories – variable and fixed. The first comprehend costs directly associated with the production volume, increasing roughly linearly with the number of units produced. Material cost is the typical example of variable cost, as by doubling the amount of units produced the amount of material consumed will also double, if one disregards material waste. In opposition, the fixed costs do not increase linearly with the production volume. These are usually related with sunk costs, that is, with expenditures for capital investment. The typical example for fixed costs is the equipment cost. If the production volume varies the amount of equipment and associated cost remains constant, at least until its production capacity is exceeded and more equipment is required. This cost grouping method may be confusing if one considered costs on a per piece basis. The variable costs in that case remain constant, while the fixed change. Moreover, depending on the cost calculation method, the same cost may be considered fixed or variable. For example, if one considers maintenance as a constant annual cost, dependent only on the number of machines to perform maintenance operations, then should be considered fixed. However, if one considers for example the maintenance of a dedicated tool, which will require substitution of components or repair, then its use will accelerate the required maintenance operations, being then dependent on the production volume and therefore, variable. For further information, these financial models have been extensively used and can be consulted elsewhere [Field et al. 2007, Fixson 2005].

However, as already explained, this framework goes beyond production costs, seeking to estimate and correlate tool or part design features with the subsequent processes in which the tools are used. With this it is possible to estimate the impacts of particular tool design alternatives in the product's production, use and end-of-life phases.

4.3.1.1. Total annual cost of a process

In order to build the overall life cycle cost model, each process included is decomposed in several cost drivers (Eq. 4.1), therefore building it with a backwards methodology . Each cost driver is decomposed first in price factors and resources requirements. These resources requirements are then analysed in terms of operating conditions and process requirements. This last phase is where technological knowhow is entailed. In order to understand the process requirements it is necessary to understand the technological process and if possible, to link these requirements to product specifications through theoretical or empirical relations between parameters.

$$C_{Total} = C_{material} + C_{labour} + C_{overhead} + C_{energy} + C_{building} + C_{equipment} + C_{tooling} + C_{maintenance} \tag{4.1}$$

4.3.1.2. Cost modelling concepts

To better understand some relations presented in the next sections, it is necessary to introduce some concepts used in the cost modelling of the process. The following tables present the main definition and variables generally used in process-based cost models (table 4.1) and the equations to compute the variable and fixed costs of each process (table 4.2).

The concept of uptime regards the productive time (see figure 4.3), that is, the time in which the plant/line/workstation/machine/worker is producing. On the opposite, downtime regards non-productive time. This includes all types of breaks, no shifts periods, maintenance and even idle times. This last concept, idle, is the time in which the plant/line/workstation/machine/worker is available to produce but has no work. This is the difference between uptime and available time. The concept uptime in process based cost models can be defined as the time in which parts or products are being produced, being the plant costs allocated only in this time. Therefore, uptime is the available time for production minus the fixed resources idle time. As only during the uptime parts or products are being produced, meaning that the fixed costs should be allocated based on the uptime consumption. Regarding non dedicated tools and machines, they may be available for nearly 24 hours, but its costs are only allocated in the uptime – that is, when parts/products are being produced. In the dedicated tools

case, the same principle is kept – production costs are only allocated in the tool uptime. However, only one part/product is produced, being the total uptime the specific part/product uptime – there are no other parts manufacturing time. Therefore, in the production of parts using a dedicated tool, the uptime of the tool is highly dependent on two main aspects – production demand and the maintenance time, scheduled or unexpected. Being the first fixed by the client and external to production, the second is important to analyse and optimize. The tool maintenance requirements are influenced by the tool design and part design. To accommodate that a maintenance model of the tool was developed, linking part and tool design features with tool maintenance level (chapter 5).

Regarding the dedicated tool production, the required processes are modelled considering a unit production volume. However, tool spare parts may be required over time during tool use/part production. The part production is highly dependent on the dedicated tool reliability (replacement of tool components is usually required). Therefore the integration of a model to capture the tool reliability cost in the LCC is also important. This model includes not only the replacements of tool components but also the probability of tool failure and cost of penalties (chapter 5). Finally, dedicated tools influence other aspects such as engineered material waste, reject rate and energy consumption. These aspects are also further developed in order to capture the tool design impacts on them. The modelling of the impacts of part and tool design in the LCC is explored in the following sections.

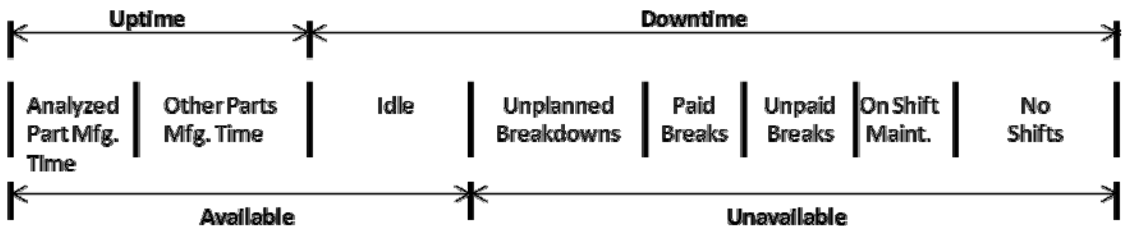


Figure 4.3. Line Utilization for a 24 hour day

Table 4.1 - Definitions and variables

Name	Term	Description
Downtime	*DT*	Non productive time – breaks, no shifts periods, maintenance

		and idle.
Idle time	*Idle*	Time in which the plant /line/workstation/machine/worker is available to produce but has no work
Uptime	*UT*	Time in which parts or products are being produced, being the plant costs allocated only in this time
Gross Volume	V_{gross}	Annual volume of produced parts
Net Volume	V_{net}	Annual volume of accepted parts
Rejected rate	r_{rej}	Percentage of rejected parts
Cycle time	t_c	Time required to produce a part
Number of setups	n_{setup}	Number of machine setups required between batches to produce V_{net}
Setup time	t_{setup}	Time of one machine setup
Tool life	$life_i$	Available hours of tool *i* before replacement
Annual required time	*t*	$T=V_{gross}*t_c+n_{setup}*t_{setup}$ (4.2)
Price factor	p_i	Price factor of item *i*
Investment	I_i	Investment in equipment or building *i*
Weight	w_i	Weight of item *i*
Annual discount rate	*r*	Interest rate
Social taxes	r_{social}	Social taxes over salaries paid by company
Nr of paid months	n_{PM}	Per year
Nr of workers	n_W	Number of workers per process step
Working days	*WD*	Per year

Table 4.2 - Variable and fixed costs

Cost Driver	Term	Financial Relations	Eq.
Variable Costs			
Material Cost	$C_{material}$	$C_{material}=w_{material}*p_{material}$	(4.3)
Direct Labour	C_{labour}	$C_{direct\ labour}=(p_{dir}\ n_{PM}\ n_W\ r_{socia\ charges})/(WD\ UT)\ t$	(4.4)
Indirect Labour	$C_{indirect}$	$C_{indirect\ labour}=(p_{dir}\ n_{PM}\ n_W\ r_{socia\ charges})/(WD\ UT)\ t\ indir/dir$	(4.5)
Energy	C_{energy}	$C_{energy}=Energy\ p_{energy}$	(4.6)
Tooling	$C_{tooling}$	$C_{tooling}=\sum tool_i * {}^{t}/_{life_i} * p_{tool_i}$	(4.7)
Fixed Costs			
Equipment, Building	$C_{equip,build}$	$C_{,equip,build}=I_i *r(1+r)^{ni}/((1+r)^{ni}-1)\ t/UT$	(4.8)
Maintenance	$C_{maintenance}$	$C_{maintenance}=\%C_{tooling,\ equipment,\ building}$	(4.9)

4.4 Process based environmental models

Similarly to the cost analysis, the assessment of the environmental impacts of the tool and product life cycle was introduced in the comprehensive framework. Having already defined the scope of the analysis, similar for both dimensions of analysis, environmental impact and cost, the process based models are applied to all processes of the product/tool life cycle, linking the product and tool design to the material and energy consumption and emissions (see figure 4.4). In fact, most of the energy and material flows were already identified in the assessment of the life cycle costs, meaning that the environmental model can be integrated in the process-based models, using the data previously obtained.

Other required inputs for the environmental analysis need to be added to the model and the environmental model can be developed using LCA software [e.g. SimaPro, 2011].
The proposed method to address LCA by using process based models to assess the environmental impact rather than unvarying models allows not only the early estimation of the environmental impacts (EI) in a design stage, prior to part production, but also comparing and performing sensitivity analysis to possible changes in the part and/or tool design.

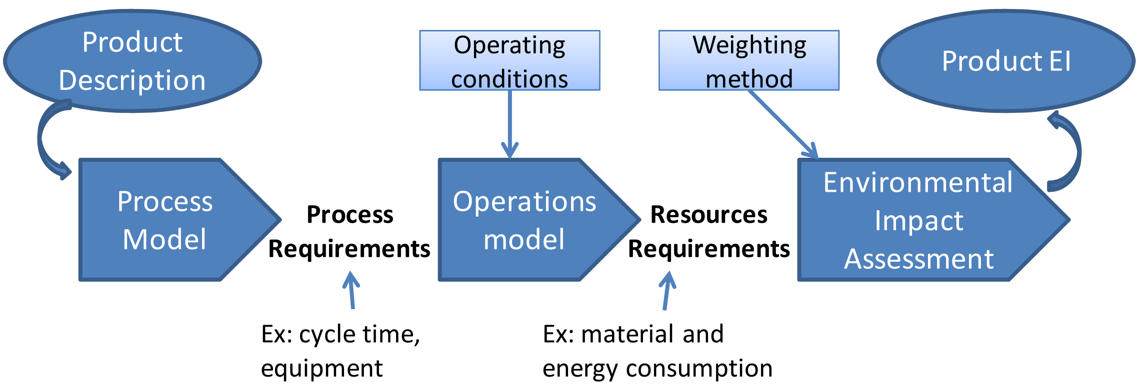


Figure 4.4: Process-based environmental model

4.5 Linking part and tool design with process requirements

Albeit some relations are already patent in the cost equations, one of the main operational purposes of process based cost models is to avoid time-consuming inputs when changing a specification. That is, if a change is performed in the part geometry, the model is supposed to accommodate this change and to compute the new cost and environmental impact. So it is required to develop relations between design features and consumption of resources, depending on the focus of the analysis and on their availability for the processes involved. Furthermore, as this model integrates the life cycles of two elements, the product and the tool, dependencies arise between them. Figure 4.5 illustrates general relations that exist in most part/tool situations. Starting with part design, its geometry and material influences the tool's geometry, material and some of its components. However, it still leaves some field for alternatives in tool design, as different architectures and materials, subsystems and other components can produce the same part. But these alternatives introduce different tool production cost (changes in the needed technologies and production time, in the standard components or subsystems, and even in the required subcontracts if the technology is not available) and different part production/tool use performance. This brings in another dependency: part production/tool use phase is dependent obviously of the part specifications, but is also clearly dependent of the tool design decisions. Most of these dependency relations are not possible to generalize for all part/tool life cycles, as different parts require different production processes and therefore quite different tools. Despite this, there are important and common aspects in most part/tool life cycles, as the dependence of the part production phase on the tool reliability, the impact of both the part and tool design in energy consumption, material waste, downtime and equipment required. Additionally, the tool maintenance cost depends on the part material and tool complexity and architecture. Finally, the part and tool end-of-life (EOL) scenarios are constrained by the materials they are made of and by the product/part/tool easiness to dismantle (design for dismantling), and therefore by part and tool design.

To introduce the impact of part and tool design in the comprehensive life cycle these intricate net of influences needs to be modelled applying both theoretical and empirical engineering know-how, as illustrated in Figure 4.5. The CLC framework further explore the interactions between part and tool life cycles, namely as regards tool reliability, tool

maintenance and energy consumption in the part production/tool use phase. Depending on the particular processes involved, other key aspects may arise fostering the development of other correlations or models.

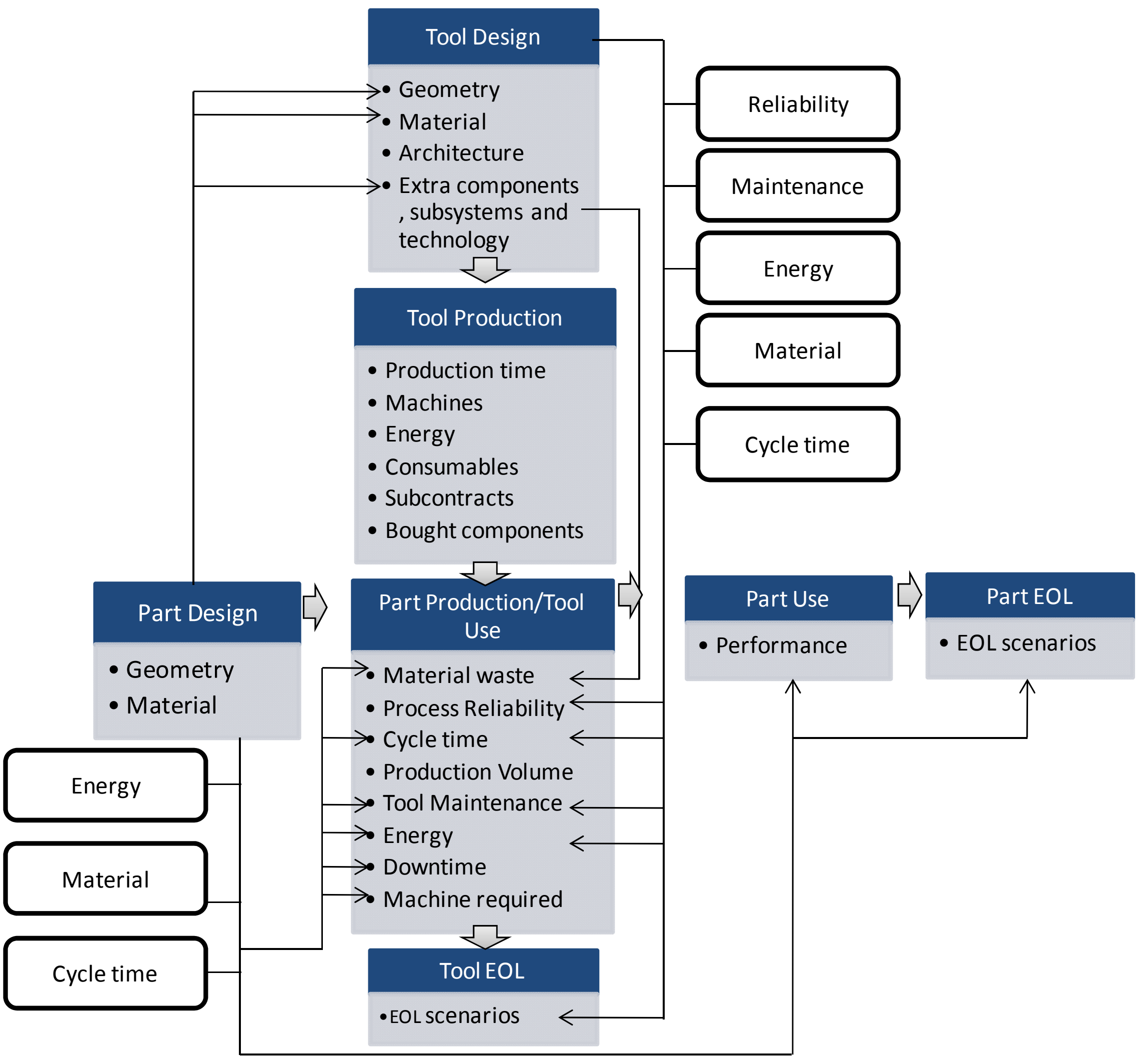


Figure 4.5: Part and tool relations

4.6 Development of models integrating CLC framework

Having in mind the need to link the part and tool specifications with the process requirements, it is necessary to understand the processes involved and the theoretical and even tacit engineering knowledge, to make use of already known interactions and correlations between design specifications and process parameters or to explicit and code new ones from the tacit knowledge of expert practitioners. The first step in developing a relations model is to search in existent bibliography similar studies that

can serve as a base for the particular process. The most common approach is to use theoretical or statistical models, defining with them physical parameters that link the part or/and tool with an output of the process (e.g. cycle time, material consumption).

The second step consists in experimental analysis *in situ* with the aim of obtaining experimental results, along with the application of the theoretical model to the same process. This allows two main assessments: (1) the ability of the theoretical model to estimate the output in the specific process; (2) the identification of the technological or physical parameters, not included in the model, that are responsible for the deviation between the experimental and theoretical results. Notice that the experimental analysis can be of different types (purpose-based tests, analysis of historical data, questionnaires or surveys), depending on the particular case.

The third step is to develop empirical relations to fill the gaps or to introduce new data in the theoretical models. However, if no similar studies were found in step one, it is then required to develop from the process analysis a new model from scratch, which again can be based on empirical relations (e.g. statistical/historical data). Finally, the last step is to validate the developed model with case studies and again with *in situ* measurements/data collection. Figure 4.6 illustrates the methodology.

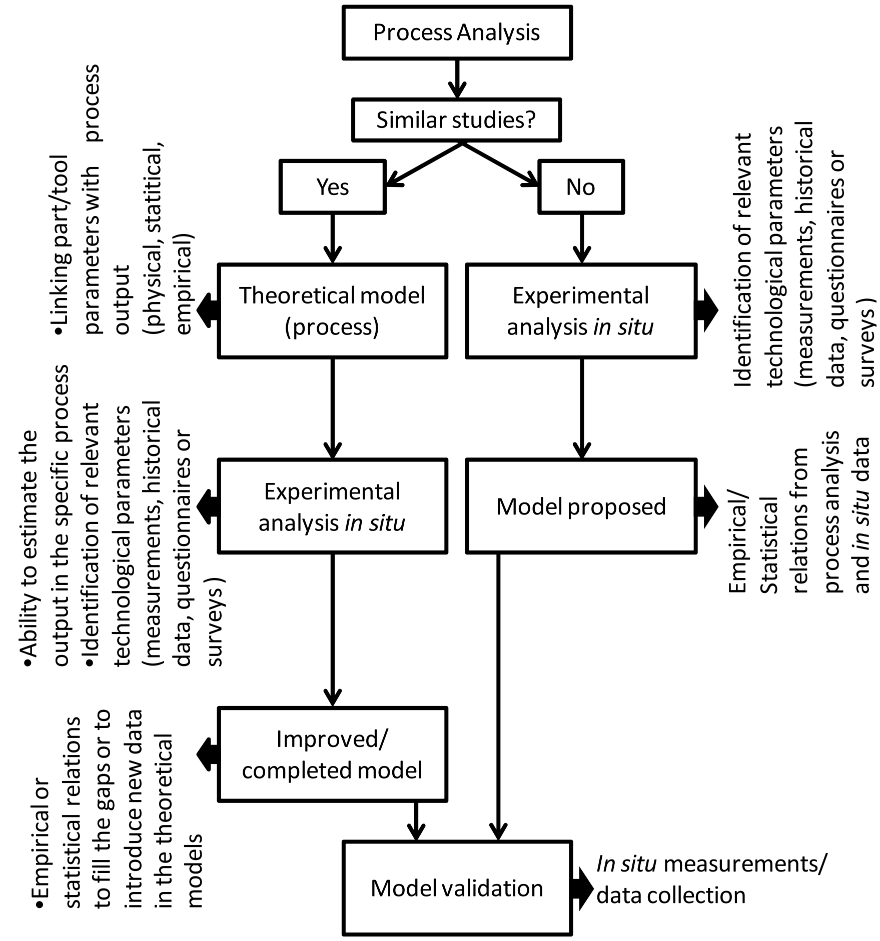


Figure 4.6 – Developing models

4.7 Integrated comparison of economic and environmental life cycle performance

The proposed framework addresses to two aspects subject to controversy. First, the question of adding costs (although considering an interest rate) allocated to the different stakeholders involved in the whole life cycle, namely the tool maker, the part producer and the downstream stakeholders involved in the use and EOL phases. Second, the separation between costs and environmental impacts (EI) that forces the decision maker to choose a design alternative with two dimension of analysis, often with opposite performances evolution. The proposal is to map the performance of the design alternatives for the two performance dimensions: cost and EI. The idea is to avoid having to predefine the importance of the cost and EI, but allowing the design team to

proceed with an informed decision-making process. Despite other ways to map the performance, a graphic-based comparison is proposed in this study.

The proposed analysis is based on two coordinates of performance mapping. The x-axis corresponds to the importance given to the costs of downstream phases. This definition requires the basic definition considered in this thesis of upstream and downstream costs. The upstream costs are the costs incurred by the stakeholders in upstream positions. The upstream costs are considered to have full importance and correspond to the full costs of production. The downstream costs are the costs incurred by the stakeholders in downstream positions regarding the decision maker position. The x-axis is therefore the importance given by the decision maker to the costs incurred by these stakeholders. Again, the upstream and downstream phases depend on the type of case study and on the type of comparisons to be mapped. Throughout the case studies presented in chapters 6 and 7 different situations will be covered.

The y-axis corresponds to the importance given to the environmental impact of the overall life cycle. This dimension of analysis comprehends the full life cycle environmental impacts, as the controversial aspect of adding costs incurred by different entities is not a critical issue when addressing to the LCA analysis. Furthermore, this allows giving importance to the LCA results and not just to the importance of stakeholders, simplifying the interpretation of the analysis.

Prior to the integrated analysis proposed it is necessary to normalise the results from the application of the CLC framework regarding life cycle costs and environmental impacts. Therefore, for the design alternative *k* (*k* = 1 to *r*) of the set of *r* candidate alternatives the procedure for the normalisation of costs can be done as follows:

$$LCC_k = CU_k + CD_k \quad (4.10)$$

$$\text{Normalised } CU_k: \; nCU_k = \frac{min\left[CU_k\right]_{k=1}^{r}}{CU_k} \quad (4.11)$$

$$\text{Normalised } CD_k: \; nCU_k = \frac{min\left[CD_k\right]_{k=1}^{r}}{CD_k} \quad (4.12)$$

where, for alternative k, LCC_k is the total life cycle cost, CU_k and CD_k are the aggregated costs regarding the upstream and downstream phases, respectively. The same procedure can be done for the EI:

$$\text{Normalised of } EI_k: \; nEI_k = \frac{min[EI_k]_{k=1}^{r}}{EI_k} \qquad \text{(eq.4.13)}$$

where EI_k is the total life cycle environmental impact.

The integrated performance score can now be written to each k alternative ($Score_k$) in different ways. The authors proposed the following:

$$Score_k = nCP_k + \alpha.nCU_k + \beta.(EI_k) \qquad \text{(eq. 4.14)}$$

where α is the importance given to the costs of downstream phases and β the importance given to the environmental impacts of the integrated life cycle.

This approach assumes that the cost of the upstream life cycle phases is fully important for any stakeholder involved in the decision making process. So the performance mapping can be assessed based on the variation of the importance given to the EI and to the downstream life cycle phases. In other words, in the (α, β) space the domains of the "best alternatives" (the ones with the highest *Score* for each pair of α and β values) can be plotted, allowing their characterization (Fig.4.7):

- Type C: "Cost-based best alternatives". These alternatives are the ones with the lowest cost on the upstream life cycle phases.
- Type L: "Low total impact best alternatives". These alternatives achieve the best score when a high importance is given to the EI and to cost, the last in both the downstream and upstream life cycle phases. So, these alternatives are the ones with the lowest overall cost and environmental life cycle impacts among the candidate alternatives
- Type U: "User-based best alternatives". These alternatives have a reduced impact of the use phase regarding costs. Its best score is achieved when high importance is given to the downstream phases, in addition to the upstream phases cost. In general, the design alternatives with these alternatives show low downstream cost.

- Type B: “Balanced best alternatives”. These alternatives achieve the best score when the importance is balanced between the downstream phases and the environmental impact, in addition to the upstream phases cost.
- Type E: “Environment-based best alternatives”. These alternatives achieve the best score when high importance is given to the EI and low importance is given to the downstream phases cost, in addition to the upstream cost. In general, these alternatives show low EI.

The proposed characterization helps to understand the influence of the candidate alternative in its performance on the several impacts during its life cycle. Some candidate alternatives will be the ones to select over more than one. Other will not be “visible” in the performing mapping, meaning its performance is lower than the alternative ones.

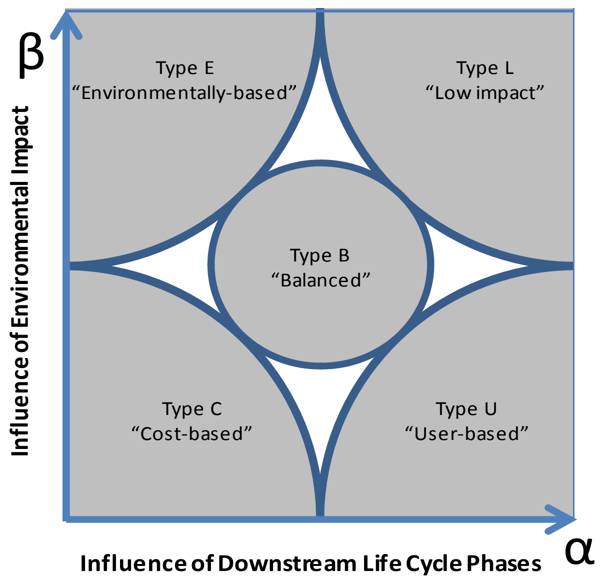


Figure. 4.7: Typical zones for each type of best alternatives

Finally, the development of the proposed CLC framework is further explored and applied to the life cycle of plastic parts and the dedicated tools required to produce them – plastic injection moulds. Throughout chapter 5 the application of the CLC framework is explained, developing the required models to capture the impacts, both economic and

environmental, of tool and parts design decisions within the scope of the injection moulding process as the part production/ tool use phase. Notice that all the general relations already described in the present chapter are not duplicated in the following, focusing mainly on the development of particular relations connecting the injection mould design and the part design not only to the downstream life cycle phases but also between them.

5 CLC FRAMEWORK APPLIED TO INJECTION MOULDING

As previously explained, this chapter explores the development of the CLC framework and its application to the life cycle of plastic parts produced by the injection moulding process and the moulds required to produce them. The first part of this chapter defines the scope of the approach when applied to this type of parts and tools, with all the processes included in each life cycle stage to be analysed. The relevant interaction and relations between the part and tool design are presented together with the integrated life cycle within the defined scope. Several outputs are modelled according to the design variables, namely energy and material consumption during injection moulding, mould reliability and maintenance. The second part of the chapter describes the application of LCC and LCA methodologies following the CLC framework and using the models previously developed to compute the outputs, translating them in terms of costs and environmental impacts correspondingly.

5.1 Scope of the CLC framework

The scope of the framework is illustrated in Figure 5.1., presenting all the phases and the elementary processes considered. The part material production considers the production of polymers, being the part production phase the processing of these polymers through injection moulding. Within this phase there is a secondary process, the reutilization of the polymers by shredding the wasted material (rejected parts or scraps) and its reintroduction in the process. Part use depends on the part analysed and on the subsequent product in which it is integrated. The part is then recycled, composted (e.g. in the case of biodegradable polymers) or sent to landfill, depending on several aspects - the material, type of product and social context.

The tool production comprehends the machining and finishing processes to produce the mould, usually milling, grinding, drilling, laser, EDM, and Assembly. The tool material production considers the mould material – steel, aluminium or even resin, depending on the mould technology. Finally, the mould material, usually steel or aluminium, can be sold to recycle the material.

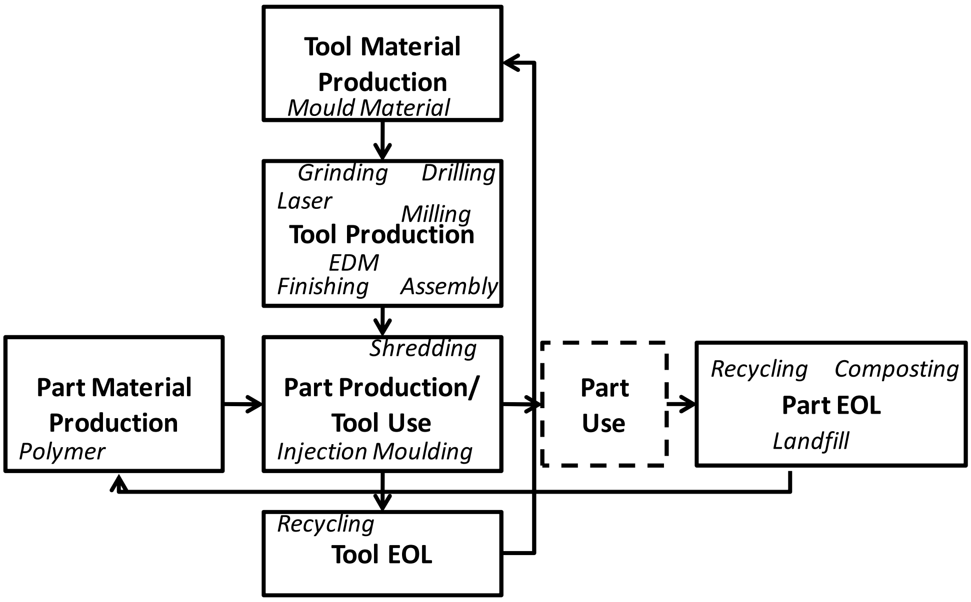


Figure 5.1. – Scope of the CLC Framework

5.2 Modelling relevant interactions in injection moulding

This section presents an overview of the set of relations built to model some relevant interactions. The overall aim is to capture the impacts of part/tool design options in the comprehensive life cycle of a plastic part, in particular in the part production/mould use phase. The most relevant modelled impacts regard cycle time, which itself affects most cost drivers, energy and material consumption, process reliability and the mould maintenance. All of them are in fact predetermined in the design phases but launch their main cost influence in the part production/mould use phase. The following models and relations reflect these dependencies aiming to link part and tool design to the dependent process parameters and consequently to the cost and environmental drivers.

5.2.1. Cycle Time

An empirical relation, largely accepted in scientific and technical communities, correlates the part material (injection and ejection temperatures and effective thermal diffusivity) and part geometry properties (thickness), depending on the mould runner system (hot or cold runners) and mould temperature, with the time required to cool the part inside the mould. This relation, adapted from [Osswald et al. 2001], is presented in

equations 5.1. and 5.2. In the injection process, the cooling time is the main element in the cycle time. If one considers the injection cycle starting with the closing of the mould, the cooling starts when the material is injected and ends when the mould is opened and the part ejected. Therefore, being the opening and closing of the mould only dependent on the machine, it is possible to estimate the cycle time by estimating the cooling time.

$$t_{cooling} = \begin{cases} \dfrac{s^2}{\pi^2 \alpha_{ef}} ln(kY), \quad hot\ runners \\ \dfrac{D^2}{23.14\alpha_{ef}} ln(0.692Y), cold\ runners \end{cases} \qquad (5.1)$$

$$Y = \frac{T_{inj} - T_{mould}}{T_{ext} - T_{mould}} \qquad (5.2)$$

Where s is the maximum part thickness [m], *D* is the runner maximum diameter, *k* is the part thickness coefficient (k=4/π if s ≤ 3 mm, K=8/π2 if s > 3 mm), α_{ef} is the average effective thermal diffusivity of the part material (µm2/s), T_{inj} , T_{mold} and T_{ext} are correspondingly the injection, mould and part ejection temperatures.

5.2.2. Energy Consumption

Being injection moulding an energy intensive process, the estimation of energy consumption becomes especially important. Furthermore, throughout the injection cycle the machine power demand is not constant and the simplification of energy computation through the machine power and cycle time becomes very deficient. Therefore, a more sensitive and accurate estimation is required and a model was developed following the methodology explained in 4.6 (see figure 5.2). Having in mind the developments in this area through a bibliographic research of related studies, an experimental analysis of the injection moulding process was performed in order to both analyse the process and assess the accuracy of the pre-existent models found in bibliography. Then an energy consumption estimation model is proposed. This model was based on pre-existent thermodynamic fundamental relations and on the knowledge acquired regarding the process and machine functioning. It is then presented a model based on relations of

different nature, theoretical and empirical, in order to estimate in a design stage the energy consumption to produce a certain part.

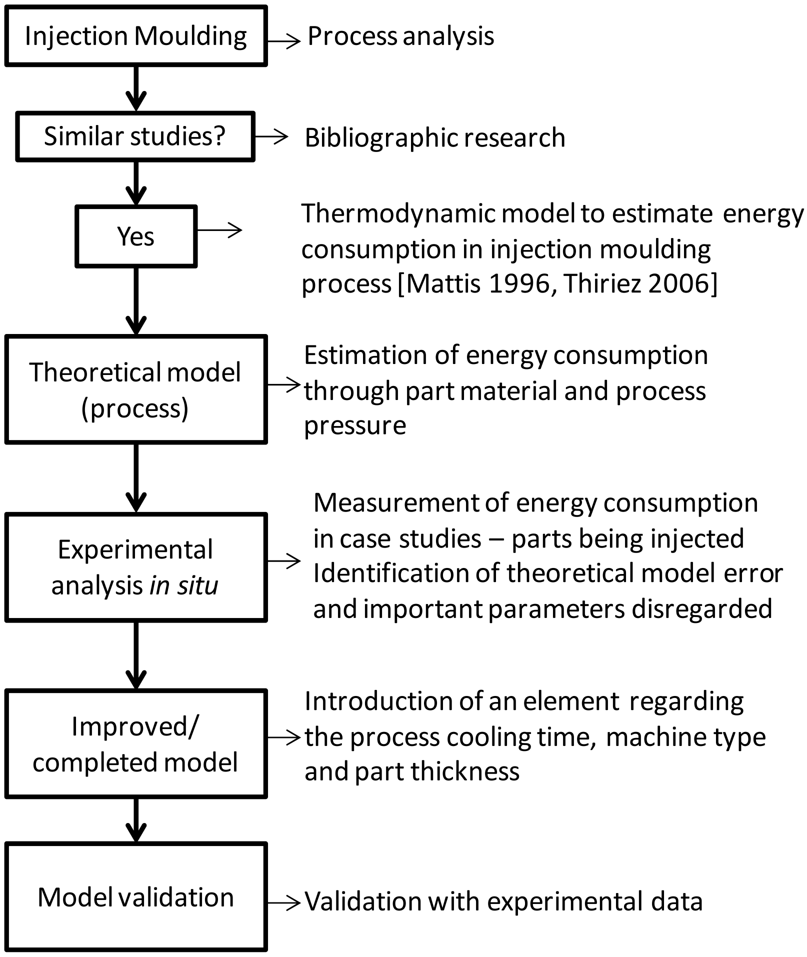


Figure 5.2. Methodology to develop the energy model

5.2.2.1. Bibliographic research

Energy consumption in industrial processes has been analysed in several aspects. Research has been published regarding the development of material and energy consumption indexes for several manufacturing processes [Gutowsky et al. 2006, Duque et al. 2010], comparing injection machines in terms of energy losses [Thiriez 2006], assessing the energy efficiency for several manufacturing processes [Gutowski 2010, Rosato and Rosato 2000, Santos et al. 2011] and investigating the influence of injection parameters and die design [Guilong et al. 2010, Kordonowy 2002]. The former have estimated indexes for specific energy consumption, that is, energy requirements

per kg, for several manufacturing processes, including the injection moulding process. Although very useful for estimating a product overall energy consumption, this approach doesn´t take into account the part material and design, or the mould architecture. The studies regarding the processes efficiency determine a general efficiency value for different manufacturing processes, but again do not go further than an interval of efficiency disregarding the part, mould and machine specifications. Literature regarding the comparison between hydraulic, hybrid and electric machines claim that electric machines can save up to 50% of the energy consumption when compared with the full hydraulic ones [Thiriez 2006]. However, electric machines apart from the higher investment have also limitations regarding the clamping force, making them inadequate for parts with high surface area. Some contributions have been made in understanding the injection parameters impact on the energy consumption. In fact, Mattis et al. [1996] studied the percentage of total specific energy variation for several injection parameters, being the wall thickness and the mould, polymer and melt temperature the major contributors of variations in energy consumption. Kordonowy [2002] isolated the power consumption of the machine components. Finally, other authors focused on energy estimations and its possible reduction, calculating the consumption either based on the absorbed power and cycle time [Nadeau et al. 2010, Fuchs et al. 2008] or through thermodynamic fundamentals [Gutowski et al. 2009, Thiriez 2006]. The former lacks in including the part properties or the process specifications in the calculation, the last do not incorporate the process and machine specifications.

5.2.2.2. Theoretical Model

Having in mind the goal of developing a model to estimate in an early design stage the energy consumption during injection moulding the thermodynamic model used by Mattis et al. [1996] and Thieriez [2006] is particularly useful. By linking part material and process specifications, it dismiss the need for in situ measurements. However, several aspects are disregarded, namely the type of machine and part geometry. It starts with the premise that most of the total energy required is to melt (E_{melt}) and inject the material into to mould (E_{fill}), as described in equation 5.3:

$$E_{thermo} = E_{melt} + E_{fill} \tag{5.3}$$

In theory, the energy to melt the polymer can be obtained through the fundamentals of thermodynamics, which depends on the crystallinization degree of the polymer (equation 5.4).

$$E_{melt} = \begin{cases} mc_p(T_{melt} - T_{ambient}), & for\ non-crystalline\ polymers \\ mc_p(T_{melt} - T_{ambient}) + \lambda m H_F, & for\ crystalline\ polymers \end{cases} \tag{5.4}$$

Where m is the mass of injection shot, c_p is the specific heat of polymer, T_{melt} is the melting temperature of the polymer, $T_{ambient}$ is the ambient temperature, λ is the degree of crystallinization and H_F is the heat of fusion for 100% crystalline polymer.

The energy to fill the mould and runner system occupied by the melt can be obtained by integrating the instantaneous pressure p at each volume increment V. Although it varies with the wide range of mould and part geometries, it can be estimated by multiplying the average injection pressure, $\bar{p}$ by the volume of polymer injected, V_{inj} (equation 5.5).

$$E_{fill} = \int p\,dV \approx \bar{p} V_{inj} \tag{5.5}$$

So, the Thermodynamic Model to estimate the consumed energy for the injection of non-crystalline polymers can be expressed by

$$E_{thermo} = mc_p(T_{melt} - T_{ambient}) + \bar{p} V_{inj} \tag{5.6}$$

and for crystalline polymers can be expressed by:

$$E_{thermo} = mc_p(T_{melt} - T_{ambient}) + \lambda m H_F + \bar{p} V_{inj} \tag{5.7}$$

5.2.2.3. Experimental Analysis in situ

This section comprises the experimental analysis required to obtain data to understand the injection machine consumption profile, assess the accuracy of the pre-existent theoretical model and develop a more accurate model if required. Therefore, the experimental analysis was developed in an injection moulding company following the

need to understand what machine, part and process specifications are the most determinant factors in energy consumption. Having in mind the literature stating that electric machines use around 50% of the hydraulic machines energy consumption [Thiriez 2006], the first part of the experimental analysis focused on comparing similar parts injected in each machine type. The second part aimed to both assess the thermodynamic model found in literature to estimate the energy requirements to inject a specific part and to correct if necessary possible deviations. Therefore, this experimental phase focused on measuring in situ the energy consumption of several machines, both electric and thermodynamic, injecting different parts.

- *Electric Machines vs. Hydraulic*

To analyse the power consumption of hydraulic and electric machines, three pairs of parts were analysed, in six different machines. These pairs of similar parts, in terms of material and shape, were analysed in machines with the same or very similar installed power but with a different type of motors – electric vs. hydraulic. The power consumption was measured with the power analyser equipment - Qualistar CA8334B. Table 5.1 shows some specifications of the pairs A, B and C regarding the parts, process and machine together with the results of the experimental measurements in terms of energy consumption and specific energy consumption (SEC), that is, the amount of energy per unit of mass of injected polymer. It is possible to identify 48.5% savings with the use of all-electric injection machines. One should note that the study was performed in an industrial environment and limited to a small group of parts each one being produced in a specific machine. However, the results are in agreement with a study [Thiriez 2006, Thiriez and Gutowski 2006] that also identified 50% savings with the use of all-electric injection machines when compared with hydraulic ones. The values computed in this study are close to the low SEC values stated by Thiriez and Gutowski [2006] - 3.99 MJ/kg and 1.8 MJ/kg of hydraulic and all electric machines correspondingly, with approximately the same relation between the SEC values - 50% savings with the use of all-electric machines.

Table 5.1. SEC coefficients of electric and hydraulic machines (PBT - Polybutylene terephthalate, PMMA - Poly(methyl methacrylate, PP – Polypropylene).

Nr	Material	Shot mass [g]	Cycle time [sec]	Clamping Force [tons]	Installed Power [kW]	Energy consumption	Electric [E] Hydraulic [H]	SEC [MJ/kg]

						per cycle [kJ]		
A1	PBT	14.35	14.30	100	32.2	48.11		
B1	PMMA	49.84	33.03	100	32.2	119.54	H	2.885
C1	PP	102.35	30.80	200	36.9	312.84		
A2	PBT	48.89	21.40	100	31.0	28.29		
B2	PMMA	10.76	36.07	100	31.0	72.93	E	1.399
C2	PP	149.07	28.30	180	36.0	190.71		

- *Experimental analysis expanded to other parts and machines*

In the second part of the experimental procedure the energy consumption of several machines injecting different parts was measured in situ. The same equipment was used, the power analyser Qualistar CA8334B. Several different parts injected in seven different machines were measured covering a wider range of injection machines type. The machines differ on the tonnage and installed power, as well as the type of motor or motors – electric or hydraulic. Table 5.2 presents the main properties of the parts, the number of cavities of the mould, the cycle time and the machine used to inject the parts. In this experiment 10 different parts were analysed, differing on the material, surface area, thickness, on being mono or bi-material (part 8).

Table 5.2. Injected parts, moulds and machines properties measured for this study.

Part					Mould	Process	Machine		
Nr	Material	Surface area [cm2]	Thickness [mm]	Shot weight [g]	Number of cavities	Cycle time [sec]	Force [tons]	Installed Power [kW]	Electric [E] Hydraulic [H]
1	PBT	7.84	1.40	14.35	4	14.30	100	32.2	H
2	PMMA	180.63	6.50	49.84	2	33.03	100	32.2	H
3	PMMA	27.12	1.80	10.76	5	36.07	100	31.0	E
4	PP	306.02	3.00	102.35	2	30.80	200	36.9	H
5	PP	182.28	2.90	149.07	2	28.30	180	36.0	E
6	PP	322.22	3.90	177.20	2	37.30	275	91.0	H
7	PP	148.56	2.40	337.70	2	44.20	400	154.0	H
8a	PP	41.40	2.00	284.71	2	31.20	300	53.2	H
8b	Rubber	744.30							
9	PP	78.00	20.00	568.80	4	59.00	300	53.2	H
10	PP	1530.00	2.00	276.62	1	19.90	300	53.2	H

- *Profile of the power consumption of an injection machine*

First was profiled the consumption of an injection moulding machine and its components. The overall machine consumption was measured for 1 hour, recording data every two seconds. This procedure was performed for all the parts. Results show that as the machine components are working simultaneously, it is not possible to define in the part cycle a consumption pattern, both in electric and hydraulic machines, as illustrated in Figure 5.3 to 5.6. With the data from the measurements the average power consumption of each part and the correspondent energy consumption per injection cycle were then obtained (Table 5.3).

These experimental results will be the basis to assess the error magnitude of the models available in the literature to estimate energy consumption of injection moulding. Additionally, they will be used to understand the terms that must be added to those models aiming to develop a hybrid model that estimates the energy consumption with an acceptable accuracy.

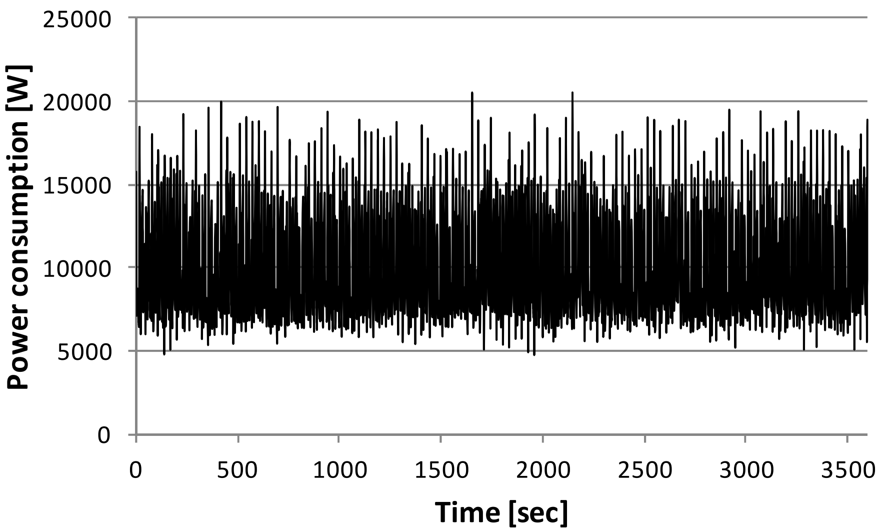


Figure 5.3 - Power consumption profile of part 5 – Hydraulic machine 200T (cycle time (t_c)=30.8 s).

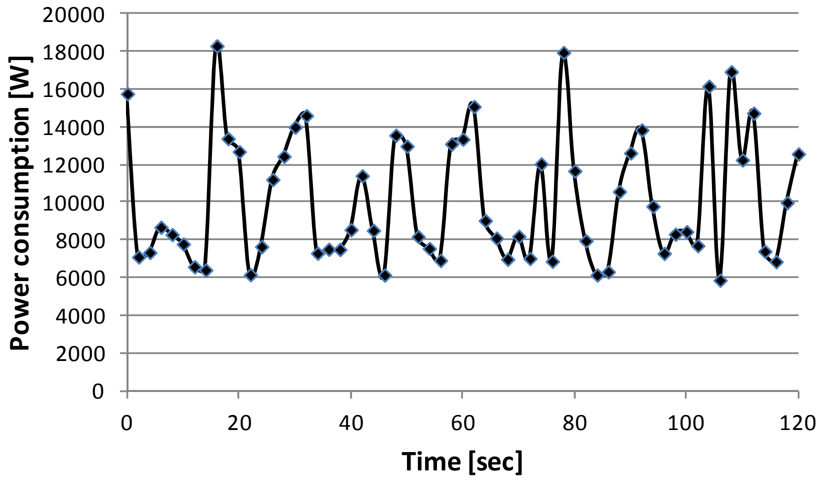


Figure 5.4 - Power consumption profile of part 5 – Hydraulic machine 200T (t_c=30.8 s).

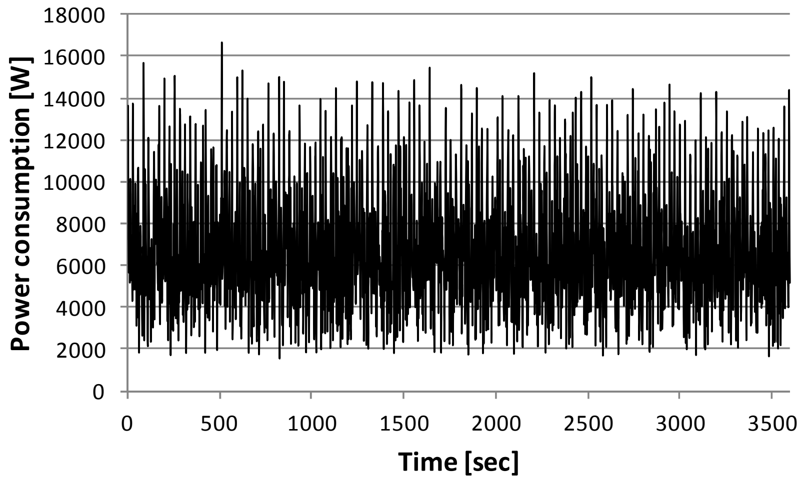


Figure 5.5 - Power consumption profile of part 6 – Electric machine 180T (t_c=28.3 s).

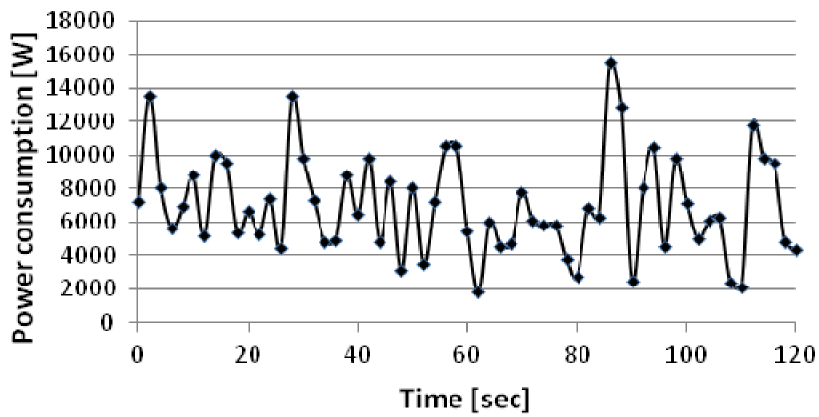


Figure 5.6 - Power consumption profile of part 6 – Electric machine 180T (t_c=28.3 s).

Table 5.3. Average power and energy consumption for the set of parts studied.

Parts	Average power consumption [kW]	Energy consumption per cycle [kJ]	Machine Electric (E); Hydraulic (H)
1	3.364	48.11	H
2	3.619	119.54	H
3	2.022	72.93	E
4	10.157	312.84	H
5	6.739	190.71	E
6	12.393	462.26	H
7	20.828	920.60	H
8	19.330	603.06	H
9	12.176	718.38	H
10	20.645	410.82	H

5.2.2.4. Accuracy of the thermodynamic model

This model is solely thermodynamic, not considering the functioning of an injection machine. So it only will estimate the energy consumption in theory required to melt the polymer and fill the mould cavities. Therefore, in order to understand the differences between the real energy consumption and the theoretical values, the thermodynamic energy was estimated using equations (5.6) and (5.7) for the parts presented in table 5.3. Table 5.4 presents the comparison of values for energy consumption using the thermodynamic model with the experimental data. The error regards the deviation of the model from the experimental results in absolute values (kJ) and in percentage. Results show that this model is not accurate for any of the parts. Three possible reasons can be given: 1) There are heat losses that are not considered in the model, usually included in the concept of machine efficiency; 2) There is energy consumption beside the one consumed during melting the plastic or filling it into the mould, mainly during the cooling time as analysed through experimental data; 3) The influence of part and machine parameters that affect the cooling time extension (e.g. part geometry) and the level of the demanded power during the overall cycle time (e.g. installed machine power, type of machine).

In the following section additional components are consider aiming to match the influence of the former two factors. Regarding the first mentioned factor, the influence

of the machine efficiency can be considered aiming to get close of the actual energy required for the melting and filling physical processes. This can be considered as a simple and obvious correction of the thermodynamic model since that model estimate the strict energy required for the physical process not including its energy losses in a mechanical base device.

Table 5.4. Comparison of experimental data with estimated values for energy consumption using the thermodynamic model.

Part	Thermo. model (eq.5.6 & 5.7) [kJ]	Cycle Time (sec.)	Power consumption [W]	Experimental results [kJ]	Error	
					Δ [kJ]	Δ [%]
1	4.56	14.30	3364	48.11	-43.54	91%
2	15.55	21.40	1322	28.29	-12.74	45%
3	18.69	33.03	3619	119.54	-100.85	84%
4	4.03	36.07	2022	72.93	-68.90	94%
5	49.50	30.80	10157	312.84	-263.34	84%
6	72.09	28.30	6739	190.71	-118.62	62%
7	85.70	37.30	12393	462.26	-376.56	81%
8	163.31	44.20	20828	920.60	-757.28	82%
9	137.14	31.20	19329	603.07	-465.92	77%
10	275.10	59.00	12176	718.38	-443.29	62%
11	133.78	19.90	20644	410.82	-277.04	67%
Average						75%

- *Thermodynamic model with efficiency coefficient*

It is stated in literature that injection machines have an average efficiency of 80% [Mattis et al. 1996] regarding the required thermodynamic energy. Starting from that, it is possible to include a coefficient related with the efficiency of the melting and filling processes ($\varepsilon_{melt,fill}$) to estimate the consumed energy (equation 5.8):

$$E_{thermo,\varepsilon} = \frac{E_{melt} + E_{fill}}{\varepsilon_{melt,fill}} \tag{5.8}$$

The terms E_{melt} and E_{fill} are the ones expressed by equations (5.6) and (5.7).

The experimental results (energy consumption, measured), the energy consumption estimated by the thermodynamic model (equation 5.6 and 5.7) and the energy estimation including the average machine efficiency (equation 5.8 with $\varepsilon_{melt,fill}$=80%) are

plotted In Figure 5.7. It is possible to observe the evolution of these values with the P_{thermo}/P_{inst} ratio, that is, the machine power required using the thermodynamic model divided by the installed power of the machine where the parts were injected. This ratio translates the suitability of the machine used to inject the part (smaller ratio means an oversizing of the machine dimension/power compared to the required to inject the part). It is identifiable a pattern between the estimated and experimental values and the contribution of the efficiency coefficient to reduce this gap. Despite the gap reduction, this is clearly not enough to model the process, reinforcing the need to consider the influence of other factors.

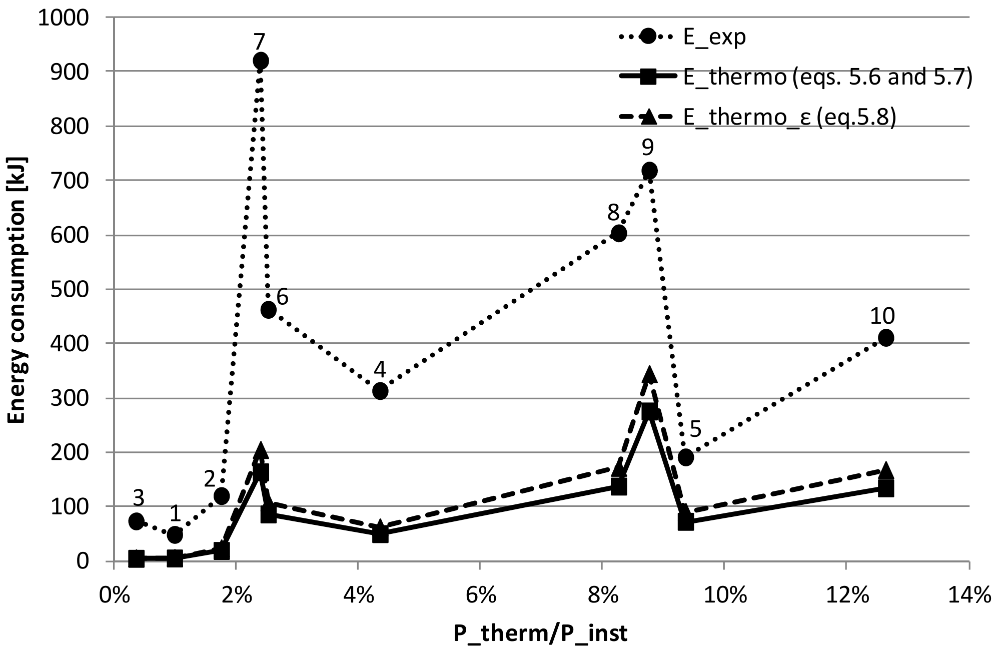


Figure 5.7 – Experimental energy consumption values, energy consumption estimated by the thermodynamic model (equation 5.6 and 5.7), and the ones estimated by the thermodynamic model with 80% machine efficiency variation with the P_{therm}/P_{inst} ratio (equation 5.8).

In order to identify a possible relation between the energy theoretically required to inject a part and the actual energy consumption measured experimentally, the influence of the machine installed power was analysed with the available data. The racio P_{thermo}/P_{exp} measures the error of the thermodynamic model in estimating the average power consumed in the injection cycle. As already explained, the racio P_{therm}/P_{inst} translates the suitability of the machine used to inject the part. It is possible to notice a major relation between the machine power installed/thermodynamic power required and the thermodynamic model accuracy. Figure 5.8 shows that the relation between the

required power for the part using the thermodynamic model and the actual installed power of the machine is a particularly important aspect, meaning that the machine choice highly influences the energy consumption.

In the next section, an element related with the injection machine installed machine power and its consumption during the cooling time is proposed to be added to the model.

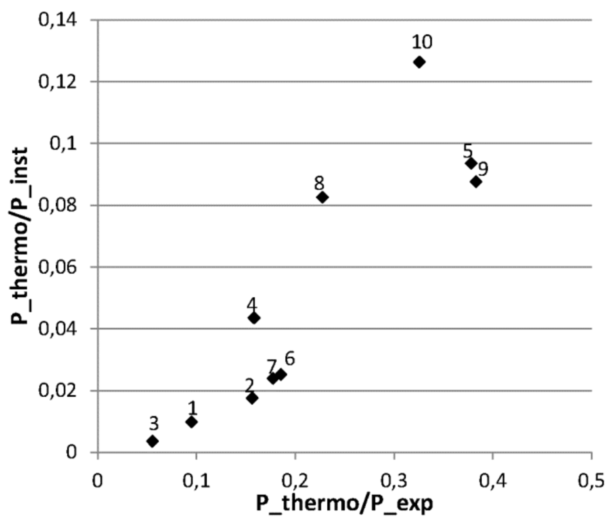


Figure 5.8 – Chart plotting relation between relation P_{therm}/P_{inst} and P_{thermo}/P_{exp}.

5.2.2.5 Proposed model - Thermodynamic-empirical model

The experimental analysis showed that the thermodynamic model is not enough to estimate energy consumption, as the installed power of the injection machine plays a major role in the energy consumed, as well as the type of machine – hydraulic vs. electric. Moreover, the cooling time is also disregarded in the theoretical model, despite the machine is being used and consuming energy during this phase of the injection cycle. In fact, the cooling time of an injected part is usually the main element of the total cycle time. The cooling time is closely related with the part thickness, being this variable effect on energy consumption further investigated in the following sections. Therefore, the energy consumed during the cooling time must be included in the model having in mind that the consumption depends on the machine type. In fact, in this period of the production cycle the machine is not in idle namely is filling the injection unit with polymer for the next injection among other actions.

- *The contribution of the machine type and machine installed power*

Aiming to include the influence of the machine type and installed power on the consumed energy estimation, the addition of a component to the previous model (equation 5.8) is proposed in equation (5.9) to adjust the energy estimation (E_{est}). It consists in a percentage of energy consumption of the installed power times the cooling time. This percentage is here named Correction Factor (*CF*). An efficiency coefficient (K_M) is also included to represent the different performance observed between hydraulic machines (K_M=1) and electric machines (K_M=0.5) as regards to installed and demanded power.

$$E_{est} = \frac{E_{fill} + E_{melt}}{\varepsilon_{melt,fill}} + P_{inst}\, t_{cooling}\, K_M\, CF \qquad (5.9)$$

Where $t_{cooling}$ is the cooling time, P_{inst} is the installed machine power, K_M is the machine type coefficient. *CF* represents in fact a correction factor regarding the percentage of machine power used during the cooling time.

It is now necessary to analyse of the evolution of the correction factor *CF* with the injection machine power and process parameters. The *CF* value should be the percentage that equals the estimated energy (equation 5.9) to the real energy measured (E_{exp}). The values of the computed *CF* (CF_{comp}) coefficients are the values of equation 5.9 when E_{est}=E_{exp} (equation 5.10) and are plotted in Figure 7 that shows its evolution with the P_{thermo}/P_{inst} racio. The racio P_{thermo}/P_{inst} measures the adequacy of the machine power to the work that is performing.

$$CF_{comp} = \frac{E_{\exp} - \dfrac{E_{fill} + E_{melt}}{\varepsilon_{melt,fill}}}{P_{inst}\, t_{cooling}\, K_M} \qquad (5.10)$$

From the evolution of the CF_{comp} values required to equalize the real energy consumed with the one estimated (equation 5.10) is possible to notice a general rising trend with the P_{thermo}/P_{inst} racio (Figure 5.9). The magnitude of the energy consumed during the cycle time increases with the increase of the injection machine inadequacy to the work that is being performed. In fact the thermodynamic parcel of the model estimates the required energy related with the plastic part processing. Therefore, the higher the extra

power installed in the machine the higher must be the CF coefficient to include the real consumption of a more power demanding machine.

Despite the general rising trend present in Figure 5.9 it can be noticed that part 9 doesn't follow this trend. This is possibly due to the extremely high thickness of the part (20 mm), highly uncommon in injection moulding process. Knowing that the cooling time is directly related to the part maximum thickness, it means that in relative terms the cooling time of this part is very high. The major amount of power demanded during the cooling time occurs in the beginning of the cooling time due namely to the machine components movements and material preparation for the next injection. After this phase the machine tends to demand less power since it is almost in an idle state waiting to open the mould. Therefore, it is understandable why part 9 is out of general trend present in Figure 5.9 – the percentage of installed power used (*CF*) is lower during the long cooling time.

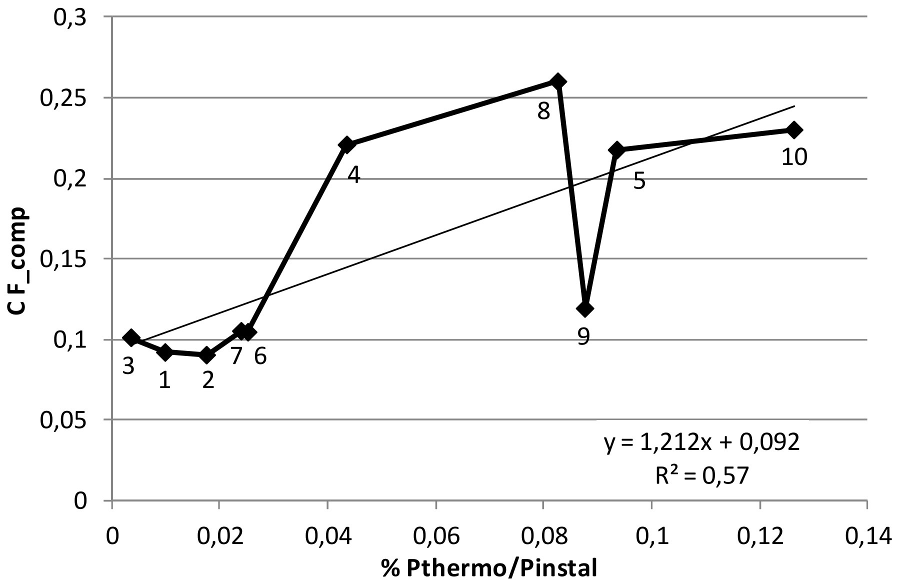


Figure 5.9 – Trend of Correction Factor (CF_{comp}) of analysed parts.

The fitting equation present in Figure 5.9 cannot be considered universal since is based on the samples used in this study. Nevertheless it can be for the final proposed model. The equation (5.11) comprises the contribution of the energy consumption during the cycle time for the estimation of the total energy consumption. As can be observed in Figure 5.10 the influence of this energy parcel allows estimating a value of energy consumed more closed to the real values. Nevertheless, the remaining differences will be analyzed having in mind the influence of the part thickness.

$$E_{est} = \frac{E_{fill} + E_{melt}}{\varepsilon_{melt,fill}} + P_{inst} t_{cooling} K_M CF_{est} \tag{5.11}$$

$$CF_{est} = \frac{P_{therm}}{P_{inst}} 1.212 + 0.092 \tag{5.12}$$

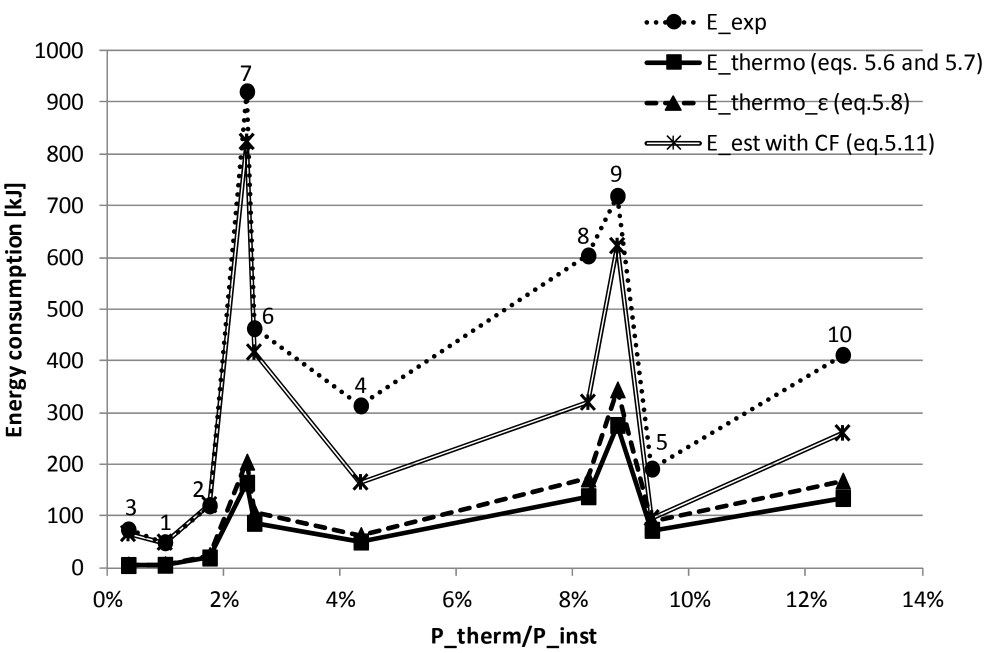


Figure 5.10 - Chart plotting experimental energy consumption values and estimated values using equations (5.6) and (5.7), (5.8) and (5.11).

- *The contribution of the part geometry (maximum part thickness)*

From the above observed for part 9 it can be suggested that the part thickness also influences the energy consumption by its direct influence on the cooling time extension. In order to analyse the impact of the part thickness in the percentage of the machine power used while cooling, it was considered a thickness related coefficient (*TH*). As stated in equation (5.13) the second term of the model proposed in equation (5.11) is divided by this coefficient since for higher thicknesses the contribution of this term tend to reduce.

$$E_{est} = \frac{E_{fill} + E_{melt}}{\varepsilon_{melt,fill}} + \frac{P_{inst}\, t_{cooling}\, K_M\, CF_{est}}{TH} \tag{5.13}$$

The same method used for the *CF* coefficient was applied to the *TH* coefficient, related with the part maximum thickness. Its computed values (TH_{comp}) values were obtained using equation (5.13) and replacing the estimation of energy (E_{est}) by the real consumption measured. The obtained TH_{comp} represents value of *TH* required in equation (5.13) to equalize the estimated energy to the real one consumed for each injected part. The values of the TH_{comp} are presented in Figure 5.11 for the different injected parts maximum thicknesses. A linear rising trend of TH_{comp} with the increase of the part thickness can be observed. So, as the part thickness increases the deviation of the equation (5.11) on the estimation of the real energy is higher. For low thickness parts the deviation of the equation (5.11) is low while for higher thickness parts, the deviation increases, in particular parts 2 (6.5 mm) and 9 (2.0 mm).

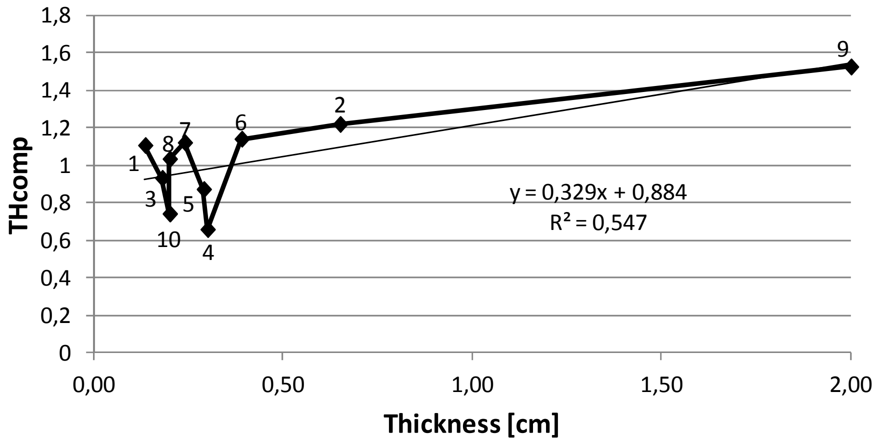


Figure 5.11 – Evolution of the estimated value of thickness related coefficient (THcomp) with the part maximum thickness.

Using the fitting equation from Figure 5.11 a more complete model is proposed in equation (5.14). This thermodynamic/empirical model includes not only the thermodynamic energy but also another element related with the cooling time ($t_{cooling}$), with the machine power (P_{inst}), its adequacy to the part - CF_{est}) and the influence of the part thickness (TH_{est}). Moreover, as shown by the experimental data, the machine type is also an important aspect, being the energy savings around 40% with the use of all-electric injection machines (K_M).

$$E_{est} = \frac{E_{fill} + E_{melt}}{\varepsilon_{melt,fill}} + \frac{P_{inst}\, t_{cooling}\, K_M\, CF_{est}}{TH_{est}} \quad (5.14)$$

Where CF_{est} (estimated CF coefficient), K_M and TH_{est} (estimated TH coefficient) are coefficients regarding machine and part specifications:

$$TH_{est} = 0.329s + 0.884 \quad (5.15)$$

Where s is the part maximum thickness. The other coefficients and terms were described above.

5.2.2.6. Results and assessment of the accuracy of the proposed model

Having proposed the model, it is now important to assess its accuracy. For this the experimental results were again compared with the values obtained through the final thermodynamic/empirical model (equation 5.14). The results are present in Table 5.5 and Figure 5.12 as well as the deviations between the experimental values and the estimated values of energy consumed. Results show that the proposed model highly decreases the error of the estimated values, in particular for energy intensive parts.

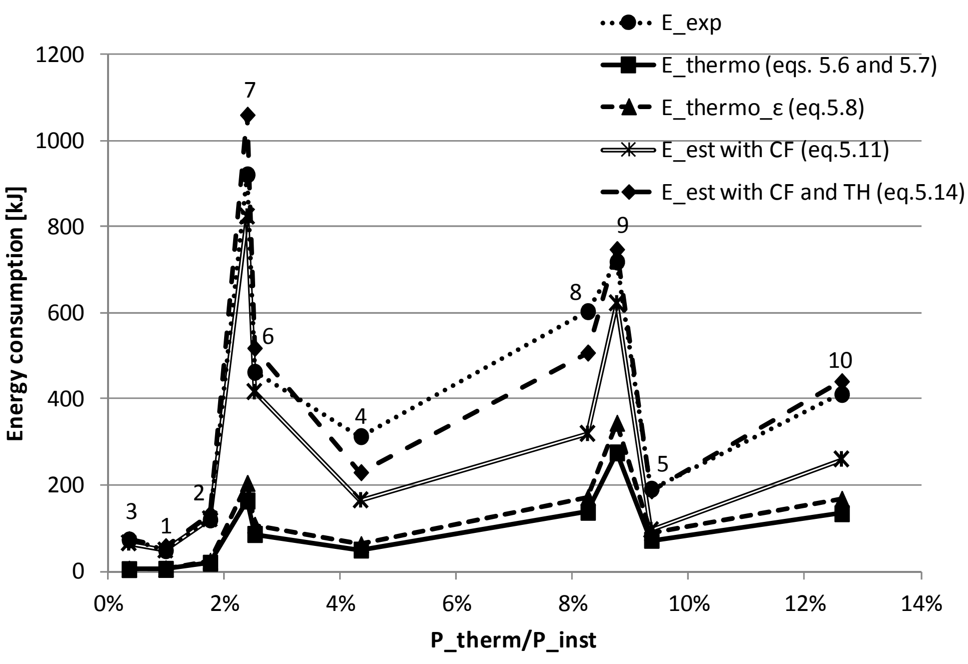


Figure 5.12 - Chart plotting experimental energy consumption values and estimated values using equations (5.6) and (5.7), (5.8), (5.11) and (5.14).

Table 5.5. Comparison of values for energy consumption using the thermodynamic-empirical model (equation 5.14) with the experimental data.

Part	Proposed model (eq. 5.14) [kJ]	Cycle Time [sec]	Experimental results [kJ]	Error	
				Δ [kJ]	Δ [%]
1	57.22	14.3	48.11	-9.12	19%
2	132.97	33.03	119.54	-13.44	11%
3	73.50	36.07	72.93	-0.57	1%
4	229.14	30.8	312.84	83.69	27%
5	186.98	28.3	190.71	3.74	2%
6	517.70	37.3	462.26	-55.44	12%
7	1059.01	44.2	920.60	-138.41	15%
8	506.92	31.2	603.07	96.14	16%
9	746.87	59.0	718.38	-28.49	4%
10	440.27	19.9	410.82	-29.45	7%
Average					11%

According to the results presented in Table 5.5, the proposed approach represents a considerable improvement of the thermodynamic model (equations 5.6 and 5.7), although still with 11% of average error for the energy consumption measured experimentally. Given that the parts were injected in different machines, of different suppliers and different ages, it is virtually impossible to model a perfect relation suitable for every machine. However, in a context of part and tool design, this model gives an acceptable approximation of the energy requirements during production phase, with the minimum machine inputs – only the machine installed power and the type of machine, hydraulic or electric, both machine specifications with no need for in-situ measurements. However there is another type of machines, hybrid, that have both type of motors. One possible way to improve the proposed model would be to analyse also the efficiency of hybrid machines. Also other cases can be incorporated in order to improve the relations that lead to the coefficients CF_{est} and TH_{est}.

5.2.3. Material Consumption

In injection moulding, material consumption is highly dependent on the mould type and on the material reuse rates allowed by the client. During injection moulding two types

of waste are generated: engineered wastes (wastes inherent to the planned process) and wastes from rejected parts (quality problems). Depending on the mould runner system, there is a different amount of material waste. With a cold runner system, the sprue and runners (excess material retained in the feed channels) is cooled and ejected together with the part from the mould cavity. With a hot runners system, only the part is ejected. However, if the system is mixed, that is, with a manifold but also with runners, or even without a manifold (cold runners), there is a percentage of material wasted in the runners. So to calculate the effective material consumption it is necessary to consider not only the part volume, but also the amount of material wasted in the mould feeding system and the material wasted in non-quality parts.

The equation 5.16 for computing material waste considers the gross annual production volume, V_{gross}, the part weight,, w_{part}, the ejected runner weight,, w_{runner}, the net annual production volume, V_{net}, and the percentage of reused (recycled) material per part allowed by the client, $w_{recycle}/w_{part}$, being $w_{recycle}$ the material weight allowed per part of recycled material, usually from the wastes generated in the process.

$$Material = \begin{cases} if\ M_{waste} < M_{gross} * \%reuse & Material = M_{gross} - M_{waste} \\ else & M_{gross}(1 - w_{recycle} / w_{part}) \end{cases} \tag{5.16}$$

Where

$$M_{gross} = V_{gross}(w_{part} + w_{runner}) \tag{5.17}$$

$$M_{gross} = (V_{gross} - V_{net}) * (w_{part} + w_{runner}) + V_{net} * w_{runner} \tag{5.18}$$

The relation explained above allows estimating the required material consumption during an injection moulding process taking into account not only the part weight and the annual production volume, but all the material wastes generated during the process regarding both the rejected parts and the scrap generated by the cold runners.

5.2.4. Mould Maintenance

Injection moulds are complex mechanical (or electro-mechanical) systems, and therefore subject to wear, stress concentrations, thermal shocks and cyclical loads.

Depending on some critical aspects, maintenance operations are required, albeit there is no standard maintenance schedule or procedures for all moulds. The maintenance level, that is, the frequency of maintenance operations established for each mould, varies from mould to mould and is a function of their critical characteristics, inducing different maintenance costs. Even though there is no adequate data regarding the mould maintenance, the mould designers and users have an experience-based capability to assess these aspects.

So, within the objective of modelling the effect of mould design decisions in the mould maintenance costs, empirical field work was done to retrieve the experts' experience and capture their tacit knowledge into a structured form that links the part/mould critical design features with the mould maintenance levels. The maintenance levels comprehend intervals of injection cycles between a preventive maintenance operation, being the critical part/mould features the defined by the maintenance experts to have an important influence on mould failure and subsequent machine downtime. In an effort to reduce the mould and machine downtime, in fact, these features determine the maintenance level of a certain mould. Therefore, the first step of this approach is to define, with the information from interviews to maintenance experts, the critical design features for that specific industry. The following step is to define maintenance levels which can accommodate all type of moulds, again in that specific industry. With the defined critical features and maintenance intervals, a questionnaire is performed again to the experts mapping the expected downtime for each set of critical features, covering all possible combinations. Then, correlations can be drawn between expected downtime with the operational maintenance level regarding different combinations of critical aspects (Figure 5.13): part geometric complexity, part material abrasiveness and mould features (existence of thin features in the moulding cavity). With these relations it is possible to design maintenance curves and define suitable functions appropriate to a particular industrial context and again. One should note that the maintenance experts' support in this process is central. Typically the maintenance functions are power curves, as very low levels of preventive maintenance generally lead to very high levels of downtime, being especially critical when dealing with moulds for high volume or for just-in-time production. On the other hand, tight maintenance schedules lower to the minimum downtime levels.

Through these correlations it is possible to choose a suitable maintenance level that minimizes the downtime for a specific mould. Notice that this model does not address the tool critical failure, only relates maintenance level and downtime for the mapped combinations of critical aspects and is valid only to a specific industry with specific types of moulds and parts. However, this evaluation can be replicated in other industrial contexts using dedicated tools.

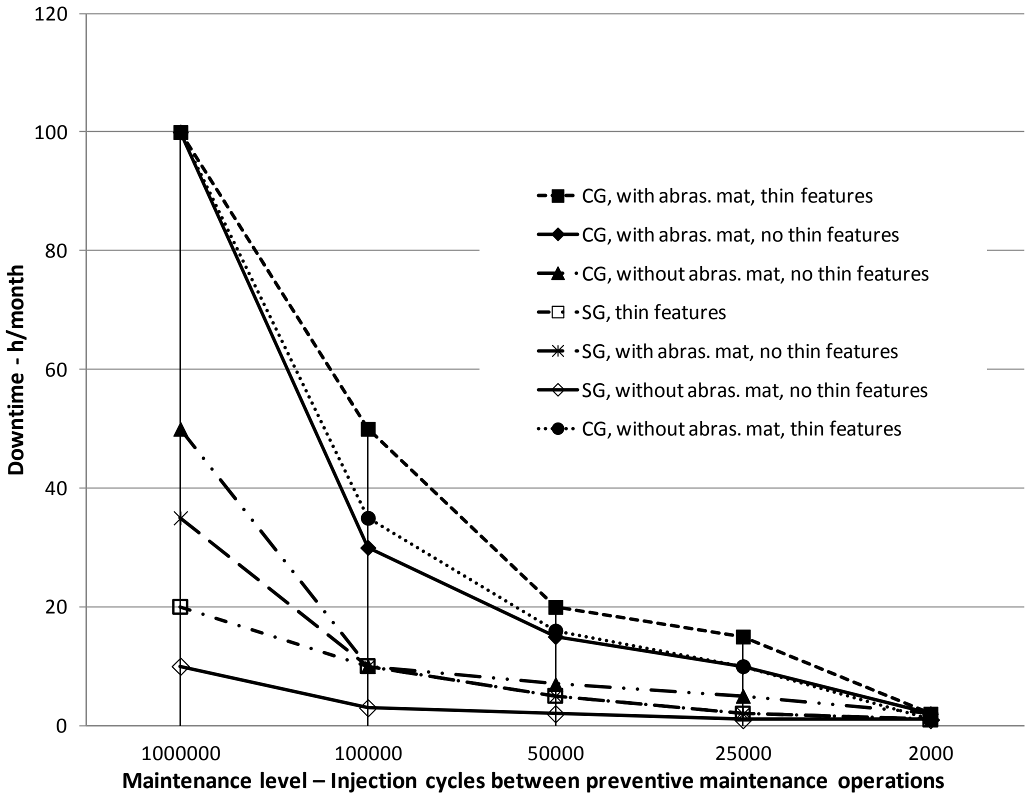


Figure 5.13- Example of an empirical relation between design characteristics, maintenance level and downtime. SG – Simple Geometry; CG – Complex Geometry

5.2.5. Mould Reliability

Dedicated tools have a one of a kind nature. So it is not easy or even possible to assess their failure probability in the design stage of a new mould based on historical data. However, despite being all different according to the part to be injected, the client requirements and the design choices, the moulds can be seen as systems with mechanical components, many of them standard. Therefore, it is possible to decompose the mould and assess the failure probability of each element. Regarding the non standard components, the core and the cavity, they are usually made of multi-elements

subject to causes of critical failures as stress concentration points, abrasiveness of the injected materials and very thin elements, among others. Despite the lack of historical information and quantification of reliability values, companies have a tacit qualitative knowledge regarding these critical aspects.

The development of a reliability model of plastic injection moulds comprises a research methodology with five main steps, from the bibliographic research to investigate similar studies to the proposed model and its validation. Through bibliographic research (step one), it was possible to find some reliability studies regarding mechanical components and a methodology to gather Weibull parameters based on experts knowledge. This was then applied to injection moulds, gathering in the field (through carefully conducted questionnaires) the information required to estimate the Weibull parameters. Finally, this estimation allowed the quantification of the failure probability and replacement of the mould components, with the corresponding material and energy requirements. The validation of the model should be then performed through the mould use during production, comparing the model results with the real data. The model can be then applied to other moulds, by analysing the components involved, the part geometry (regarding the stress points), the type of material and the geometry of the cavity/core elements. Finally, this model is validated through its application to a case study in the moulding industry. The development of the injection moulds reliability models is presented in Figure 5.14.

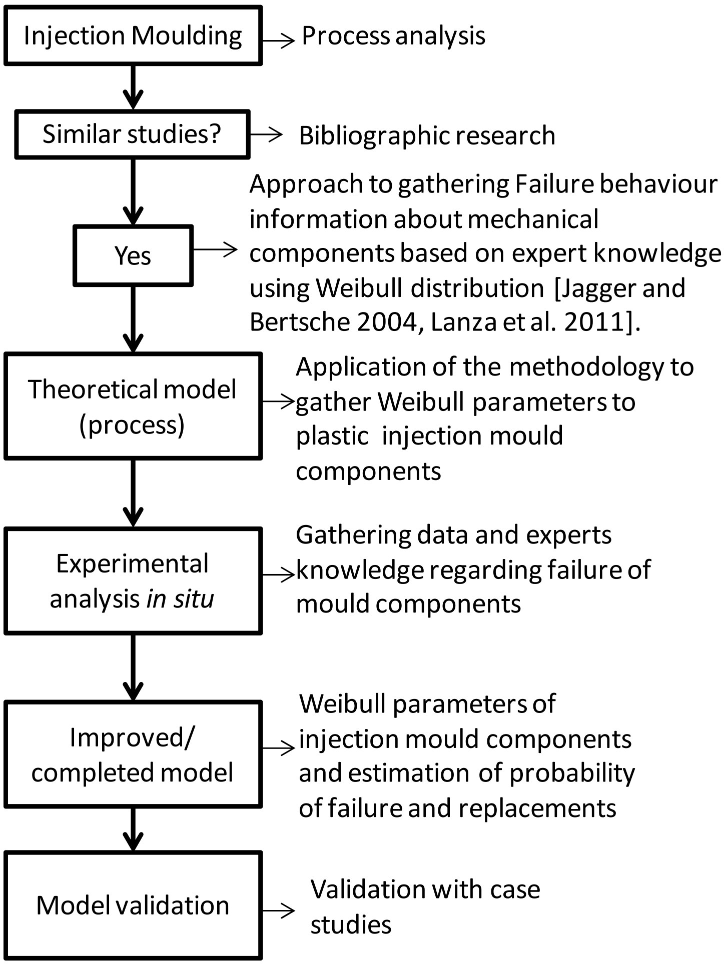


Figure 5.14 – Development of injection mould failure model

5.2.5.1. Bibliograhic research

Some authors have developed methods to assess tool reliability through the Weibull distribution [Jagger and Bertsche 2004, Lanza et al. 2011]. This distribution is widely used in many applications due to its flexibility and capability of modelling very different behaviours [Yang 2007].

The methodology proposed by some authors [Jagger and Bertsche 2004, Lanza et al. 2011] to assess tool probability of failure is based on Weibull distribution. The use of three parameter Weibull distribution entails the existence of three equations which enable the determination of the parameters. Given a component or a subsystem, the first equation is based on the knowledge regarding the mode where most components have failed. That is, based on the experts' experience in similar components, he is able to

estimate a time (or number of cycles) for which most similar components fail. This can be used for the failure density (Eq. 5.19), where *f(t)* is the failure density funciton, *b* is the shape parameter, *T* is the scale parameter, t_o is the location parameter and *t* is time parameter in the Weibull distribution.

$$f(t) = \frac{b}{T - t_0}\left(\frac{t - t_0}{T - t_0}\right)^{b-1} e^{-\left(\frac{t-t_0}{T-t_0}\right)}, \quad 0 \le t_0 \le t \tag{5.19}$$

The maximum of the density function can be determined by equation 5.20.

$$\frac{df(t)}{dt} = b - 1 - \left(\frac{t - t_0}{T - t_0}\right)^b .b = 0 \tag{5.20}$$

Being t_{mod} the mode of failure times of the failure distribution, this term correspond to the term *t* of the previous equation (5.20) and a first equation (Eq. 5.21) is defined to determine the parameters.

$$t_{mode} = \sqrt[b]{\frac{b-1}{b}}(T - t_0) + t_0 \tag{5.21}$$

For defining the second equation, the failure probability can be used (Eq. 5.22), which entails additional information.

$$F(t) = 1 - e^{-\left(\frac{t-t_0}{T-t_0}\right)^b} \tag{5.22}$$

Although an expert is usually not able to give a value for the failure probability, he knows how many similar parts have been replaced. This allows determining the failure probability according to the longest and shortest observed life-time (t_{max} and t_{min}) by using the equation for the Benard medium rank relation, where *n* is the number of failures observed in a component type (Eqs. 5.23 and 5.24). Medium ranks is a popular method of estimating Y-axis plotting positions and are recommended as most accurate and therefore, best practice. Benards's approximation for medium rank is used because it shows the best performance and it is the most widely used to estimate $F(t_i)$, being accurate to 1% for *n*=5 and 0.1% for *n*=50 [Abernethy 2006].

$$F(tmax) \approx (n-0.3)/(n+0.4) \tag{5.23}$$

$F(tmin) \approx (1-0.3)/(n+0.4)$ (5.24)

Finally, when associating both this extreme probabilities to the failure probability equations, along with the mode of the failure distribution, three equations are defined in order to determine the three Weibull parameters (5.21, 5.22 using 5.23 and 5.24).

5.2.5.2. Experimental Analysis in situ

Being the process injection moulding, each mould component was analysed following the above methodology, gathering in the field through carefully conducted questionnaires (full results in Annex 1) information required to estimate the Weibull parameters (see table 5.6). The questionnaires were conducted according to the method developed by Jagger and Bertsche (2004) to two maintenance experts. This is very useful because the Weibull parameters are allocated to elements and not moulds, being possible to use this information to other moulds. Finally, this estimation allowed the quantification of the failure probability and replacement of the mould components. This data can be then applied to other moulds, by analysing the components involved, the part geometry (regarding the stress points), the type of material and the geometry of the cavity/core elements. Notice that all elements present the parameter $b>1$, which indicates wear out failures. This is expectable considering this analysis regards only the normal functioning of injection process and not the testing phase. Having the Weibull parameters defined for the mould components presented in table 5.6, the nest step in section 5.2.5.3. to apply this information to estimate the expected replacements required during the part production life.

Table 5.6. Weibull parameters allocated to mould elements

	t_0	*T*	*b*	*MTBF*
Swinging gear	24000	534230	2,11	475898
Ejector pins	24000	246100	2,36	220836
Nozzles	200000	623054	2,01	574899
Manifold	1000000	1701841	2,02	1621895
Stop block	300000	626613	1,74	590973
Slides	100000	1079309	3,71	983967
Mould cavity/core–	150000	344395	2,26	322186

abrasive material				
Mould cavity/core–non abrasive material	400000	735352	1,71	699140
Thin core pins	5000	73204	1,86	65569
Corepins/ abrasive material	150000	331818	2,57	311432
Corepins/non abrasive material	400000	679010	2,03	647200

5.2.5.3. Application of the model to access replacements of mould elements

When designing a dedicated tool there is no historical data to perform statistically valid analyses to the failure probability. So, it is not possible to follow the traditional methods to obtain the failure distribution parameters. However, the experts' knowledge can be used to estimate these parameters, using a method used for machine and tools components. Some authors have developed methods to assess tool reliability through the Weibull distribution [Jagger and Bertsche 2004, Lanza et al. 2011]. This distribution is widely used in many applications due to its flexibility and capability of modelling very different behaviours [Yang, 2007]. Weibull distribution is commonly applied to mechanical components, like the elementary components of dedicated tools. But tools are complex systems and it is very difficult to assess a probability of failure for the whole specific tool. Decomposing the tool in its subsystems facilitates the analysis of each failure mode. Different Weibull distributions can be defined for each component or subsystem and their expected number of failures and subsequent replacements (*E(R)*) during part production life computed (Eq. 5.25), as a function of the probability of failure, *F(t)*, and of the expected number of expected replacements during the production life, ProdLife. Notice that the replacement time was defined as a mean time between replacements, *MTBR*.

$$E(R)_{TOTAL} = \frac{ProdLife}{MTBR} \cdot F(t) \tag{5.25}$$

The reliability model proposed allows the quantification of the expected replacements of injection mould components during the production life due to components failure, despite the one of a kind nature of this type of dedicated tools. The expected replacements have impacts in both costs and environmental impacts, as a new component is required to be produced or bought, with the correspondent cost and mass, energy and emissions flows. Furthermore, the failure of a component may incur in costs beyond the simple replacement, in particular if the component production time is higher than the time covered by the security stock. In conclusion, the proposed reliability model aims both to be applicable to plastic injection moulds by analysing their components and to estimate the expected costs and environmental impacts of design decisions as regards to the mould failure.

5.3 LCC Methodology in CLC Framework

The previous section focused on developing models correlating design parameters with the life cycle outputs, which may represent both costs and environmental impacts, as in energy and material flows case. The translation of these outputs, estimated through the models developed into costs throughout the part and tool life cycle is now presented using LCC methodology. LCC have been widely used and is life cycle oriented, in this case applied to an extended life cycle – tool and part.

This section explores the life cycle impacts of design decisions in terms of costs, within the scope defined in 5.1 and using the outputs estimated though the models developed in 5.2. For this, the life cycle cost methodology is used, seeking to translate into costs all the impacts driven by the models and relations determined in the previous sections. In this case the LCC methodology scope is widened from the traditional scope of part life cycle to the integrated part and tool life cycle, considering the relations defined and developed by the models in 5.2. This methodology starts by defining the part and the injection mould required to produce it. However, several part designs may be possible, either regarding the material choice or the geometry. Additionally also several mould technologies and designs may be possible, considering only alternatives capable of producing the part with the required quality specifications. Having defined the design alternatives, each life cycle stage is then investigated regarding the required processes

and furthermore, the existent relations between design and process parameters. The total life cycle cost is then the sum of all costs of all processes within the tool and part life cycle (see figure5.1), being each process computed using equation 4.1. The following sections present each life cycle stage and the translations of each process flow within these stages into costs.

5.3.1. Part Material Production and Mould Material Production

The materials related production costs can be assumed as the material acquisition cost to the mould producer (in the case of mould material) and to the part producer (in the case of part material). Although it is not strictly the same as the material production cost, in a design decision regarding dedicated moulds and parts, the material enters as a cost input to the mould or part producer. As the aim is not to study the material production processes but the design decisions of parts/moulds made of these materials, the material production phases are considered as inputs regarding the cost dimension (price/kg). Regarding the mould, if one considers the traditional moulding technologies, the usual materials are steel and aluminium. Others technologies have been developed in particular for very low production volumes, as spray metal shell tooling filled with resin and other prototyping technologies applied to mould manufacturing. Regarding the part material, the polymers injected may vary from thermoplastics, thermosets, elastomers or even biopolymers.

The mould material cost (equation 5.26) is obtained multiplying the weight of the initial raw material blocks to be machined by the price, *p,* per unit of mass of the material. The scraps resulting from the machining, computed as the difference between the initial and the final weight, w_i-w_f, can be sold for recycling at a price p_{scrap}. Additionally, injection moulds have standardized components as structural elements or the hot runner system which are usually bought from a specialized supplier.

$$C_{material} = w_i * p - (w_i - w_f) * p_{scrap} + C_{Bought\_components} \qquad (5.26)$$

The material cost of the injected part (equation 5.27) is highly dependent on the mould type and on the recycling material rates allowed by the client. Depending on the runners system, there is a different amount of material waste. With a hot runners system, only

the part is ejected. However, if the system has cold runners there is a certain amount of polymeric material that solidifies in the feeding channels, being ejected with the part (see figure 5.15) The basic formula for calculating material waste generally considers the gross annual production volume, V_{gross}, the part weight, w_{part}, the ejected runner material weight, w_{runner}, the virgin material price, p_{mat}, the net annual production volume, V_{net}, and the scrap price, p_{scrap}.

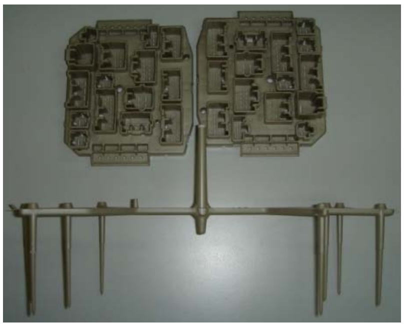


Figure 5.15 – Parts ejected simultaneously with cold runners

$$C_{material} = V_{gross} * (w_{part} + w_{eng\_scrap}) * p_{mat} - (V_{gross} - V_{net}) * w_{part} * p_{scrap} - V_{gross} * w_{eng\_scrap} * p_{scrap} \quad (5.27)$$

5.3.2. Mould Production

As already explained, different mould alternatives are possible to produce a specific part. Notice that injection moulds are dedicated tools, produced through machining processes (milling, drilling, grinding, EDM) and usually a single mould is produced, being a unique product. It is relatively labour intensive, having some operations exclusively manual (assembly, finishing).Therefore, the mould design alternatives may require different machining, finishing and assembly times, different technologies, components and structural elements. The following items address to each cost element that need to be assessed to each alternative under analysis. This cost elements are divided by 3 main elements; variable costs, fixed costs and bought components. Despite material cost being a variable cost, it was addressed already in the previous section 5.3.1. This cost items need to be computed for each process comprising the mould production. In the end, the sum of all these cost items for each process of mould alternative allows comparing the different moulds costs.

5.3.2.1. Variable costs:

In the processes regarding the mould production, the labour cost can be assessed based on the labour cost per hour and the required time of the process, as shown in equation 5.28. The labour cost per hour of a production process (*i*)considers the direct workers wage per month, p_{dir}, the number of workers in the process, n_{Wi}, the number of paid months per year, n_{PM}, the social charges ratio r_{social} paid by the company, the working days per year, *WD*, and the uptime, *UT,* of the workstation. The labour cost per hour is then multiplied by the operating time of the process t_i.

$$C_{direct\ labour} = \frac{p_{dir} * n_{PM} * n_{social\ charges}}{WD * UT} * t_i \tag{5.28}$$

The overhead cost (equation 5.29) of process *i* considers the indirect labour using a ratio between the number of indirect and direct workers. Indirect workers are paid at wage p_{ind}.

$$C_{direct\ labour} = \frac{p_{dir} * n_{PM} * n_{social\ charges}}{WD * UT} * t_i * \frac{p_{indir}}{P_{dir}} \tag{5.29}$$

In the machining processes to produce the mould, the energy consumption is modelled using the power requirement P_{req} and the operating time t_i. Its cost (see equation 5.30) is computed by multiplying the energy consumption by its unit price p_{energy}.

$$C_{energy} = P_{req_i} * t_i * p_{energy} \tag{5.30}$$

Having the variable costs defined, that is, the costs sensitive to the production volume, the next step is to determine the fixed costs, following explained.

5.3.2.2. Fixed Costs:

The fixed costs, regarding building, equipment and tooling, are considered capital investments. In the approach used in this model the investment is distributed along time through series of annual costs, financially equivalent to the initial investment. The

annual cost of an investment is defined in equation 5.31, where *n* is the life of the investment in number of years and *r* is annual discount rate. The investment, *I,* regards the equipment, the tooling or the building acquisition cost.

$$Investment\ Annual\ Cost = I\,\frac{r(1+r)^n}{(1+r)^n - 1} \tag{5.31}$$

As most equipment, the building and machine tool are not dedicated to the product, it is then necessary to allocate their investment annual costs based on the percentage of time consumed. Similarly to the variable investments, the uptime *UT* and time required for the process t concepts are used. Notice that each investment cost has a specific life, acquisition cost (*I*) and consuming time. The fixed cost of an equipment or building can be determined using equation 5.32.

$$C_{equipment,building} = I\,\frac{r(1+r)^n}{(1+r)^n - 1} * \frac{t}{UT} \tag{5.32}$$

The maintenance costs of building and equipment are modelled to be dependent on the fixed costs regarding items with maintenance requirements and considered as a percentage of the fixed costs.

- *Bought components*

The injection moulds are products with several standard components, namely the structure and the injection system. The costs for the standard parts are estimated and/or obtained through relationships based on data gathered from mould components manufacturers and dealers. The relationships and data used in the model are presented in Annex 2.The basic structure of a mould is composed by cavity, clamping, backing and ejector plates, risers, ejector assemblies and thermal insulating sheets. These components depend on the necessary height, length and thickness, being the approximate costs presented also in Annex 2.

5.3.3. Part Production/Mould Use

The part production/mould use phase comprehends the injection moulding process and possibly the auxiliary process of shredding the rejected parts and engineering scraps from the part production to re-introduce the material in the process. This depends on the allowed recycling rate per part . Having developed the models and relations in 5.2 and defined the part design and mould design alternatives to analyse, it is possible to estimate the injection moulding costs (part production/mould use costs) of each design alternative (regarding the part and/or the mould)..

Again, the costs are divided in two main types, variable and fixed costs. Unlike the mould production phase, the injection moulding phase is highly automated and specially adapted to large production volumes. Although the cost structure is identical, the cost relations are different.

5.3.3.1. Variable costs

Labour cost can be modelled similarly to the mould production case, using equations 5.33 and 5.34. Notice that in most injection moulding plants the number of workers n_W per machine is less than one. The time required to produce one part, the cycle time, t (the process is repetitive) can be estimated using the relation in 5.2.1. Similarly, the uptime (*UT*) depends on downtime introduced by the mould maintenance level, which by itself is determined by specific design features of both the mould and the part. The maintenance downtime may be estimated using the maintenance relation presented in 5.2.4. The other inputs, working days per year (*WD*), direct workers wage p_{dir}, the number of workers n_W, the number of paid months per year n_{PM}, the social charges ratio r_{social} paid by the company are exogenous inputs to the model, specific to each industrial context.

$$C_{direct\ labour} = \frac{p_{dir} * n_{PM} * n_{social\ charges}}{WD * UT} * t \qquad (5.33)$$

Also the overhead costs are determined as in mould production case.

$$C_{direct\ labour} = \frac{p_{dir} * n_{PM} * n_{social\ charges}}{WD * UT} * t * \frac{p_{indir}}{P_{dir}} \qquad (5.34)$$

The energy cost (equation 5.35) is computed by multiplying the energy consumption E_{total} by the energy unit price p_{energy}. In the case of the injection moulding process, energetically intensive in which significant amounts of energy are consumed, the model developed in 5.2.2 is used in order to better estimate the energy consumption of the injection moulding process and correlate it to the design and process features. However, in processes with lower energy consumption or with a stable power consumption profile, a more simplistic method of estimating the energy consumption can be used, by multiplying the machine power by the processing time (*E=P*t*).

$$C_{energy} = E_{Total} * p_{energy} \tag{5.35}$$

The maintenance cost was considered in the injection moulding process a variable cost, as it depends on the production volume required. This cost can be computed through equation 5.36 as a function of the mould critical features using the relation in 5.2.4. It is therefore related with the number of injection cycles between consecutive maintenance operations (Maintenance level), with the correspondent expected downtime and with the average cost per maintenance operation. The average cost per maintenance operation, $C_{maintenance}$, can be assessed with historical data for similar moulds. The downtime may affect not only the mould availability but also the machine availability, as explained in chapter 4.

$$Maintenance\ Cost = \frac{V_{gross}}{Maintenance\ level} C_{maintenance} \tag{5.36}$$

Being a unique and dedicated tool, the mould reliability is a very important aspect in part production, in particular in very high production volume scenarios. When a mould component or subsystem fails, the cost of the failure can be simply the cost of its replacement or, in high volume demand and just in time scenarios, may cause delays in the parts delivery and subsequent penalties. To estimate the cost of mould failures, the model explored in 5.2.5 is used, being the expected failure cost during part production life computed (Eq. 5.37) as a function of the cost of one failure, $C_{failure}$, of the probability of failure *F(t)* in a certain period of time (in this case in number of injection cycles) and of the expected number of planned replacements during the production life, *ProdLife*. Notice that the replacement interval was defined as a mean time between replacements, *MTBR*.

$$E(C)_{TOTAL} = \frac{\text{ProdLife}}{MTBR} \cdot F(t) \times C_{failure} \quad (5.37)$$

The cost of failure is, depending on the component or subsystem, a simple replacement cost or, in a more critical case, it might include also penalties costs due to production and delivery delays.

In case no data is available regarding planned replacements, the mean time between failures, *MTBF*, can be computed through equation 5.38 and can be a useful metric for estimating the number of replacements required.

$$E(t) = MTBF = (T - t_0) \cdot \Gamma\left(\frac{1}{b} + 1\right) + t_0 \quad (5.38)$$

Where b is the shape parameter, T is the scale parameter, t_o is the location parameter, t is time parameter in the Weibull distribution and Γ is the Gamma function.

The cost of a failure can be estimated by relating the safety stock and the demand of moulded parts with the replacement time of the mould faulty component, with the penalties incurred and the replenishment of the safety stock (see equation 5.39).

$$C_{failure} = C_{replace} + \begin{cases} SS(1 - D.t_r)Cp_u, & SS > D \\ P(t_r - \frac{SS}{D}) + SS.Cp_u, & SS \leq D \end{cases} \quad (5.39)$$

Where SS is the safety stock (number of parts), D is the demand (parts/day),t_r is the replacement time (days),Cp_u is the part production cost and P is the penalty cost per day.

Finally, the Weibull parameters can be estimated through the methodology found in biblographic research [Jagger and Bertsche 2004, Lanza et al. 2011], based on the experts' knowledge.

5.3.3.2. Fixed Costs:

The fixed costs are estimated according to the same relation used in the mould production phase (see equations 5.40 and 5.41). The main difference is related to the estimation of the time required to produce the annual volume of parts. Being the injection moulding process a repeated process,, if the cycle time, tc, is known for a part,

then the total required time is dependent on the batch volume, the part cycle time and on the setup time. Again, the cycle time can be estimated using the relation in 5.2.1 and the uptime knowing the company's schedule context and maintenance downtime using the relation in 5.2.4.

$$C_{equipment,building} = I \frac{r(1+r)^n}{(1+r)^n - 1} * \frac{t}{UT} \tag{5.40}$$

$$t = t_c * V_{gross} + roundup\left(\frac{V_{gross}}{V_{batch}};1\right) * t_{setup} \tag{5.41}$$

5.3.4. Part Use

As previously explained, part use is very dependable on the type of product. As no process can be defined prior to the particular case being analysed, the costs can only be computed case by case. Some products have no costs involved, for example manual objects, being others integrated in products with consumption or degradation during its use, as for example automobiles. In these cases the part weight may influence the product consumption in the use phase.

5.3.5. Tool End-Of-Life (EOL)/ Part End-Of-Life (EOL)

Finally, the end-of-life costs are also added to the model. In this case the EOL costs are profits in the mould case, as the mould material in traditional materials, steel or aluminium alloys, can be sold to be recycled. In the polymer part case, it depends on the material type, the products and the social context. Some may go to landfill; some may be recycled or even composted, in the case of biopolymers.

This section presented the application of the LCC methodology following the CLC framework applied to injection moulding and the scope presented in 5.1. As a life cycle oriented methodology, there is no standard method to develop a LCC, being in this thesis proposed as a tool to assess all costs incurred throughout the integrated life cycle of plastic injection moulds and parts. Within the life cycle phases considered it was

shown how to estimate the cost through the assessment of the processes outputs. This allowed developing a life cycle cost sensitive not only to the part and injection mould design, but also to several variables dependent on the industrial context, namely the production volume, type of machines used and other industrial factors.

5.4 LCA Methodology in CLC Framework

This section follows a similar approach to the previous, also exploring the life cycle impacts of design decisions, but in terms of environmental impacts. Maintaining the scope defined in 5.1 and again using the models developed in 5.2, the environmental impacts translate the material, energy and emissions generated throughout the integrated life cycle. The methodology used in this dimension of analysis was the Life Cycle Assessment, again life cycle oriented and widely used. With the goal of evaluating design alternatives in terms of life cycle environmental impacts, an indicator was used (EI'99) in order to simplify the comparison between alternatives. Moreover, being this analysis bi-dimensional (costs and environmental impacts), the use of a single indicator enables an integrated comparison as the proposed in section 4.7. Following the phases of the integrated life cycle are described with the boundaries in terms of flows and processes considered, translating into the environmental indicator the inputs and outputs of the system (using as far as possible the developed models to compute the costs).

5.4.1. System boundaries and inputs required

Having in mind the defined life cycle stages, the relevant environmental flows considered in each stage are illustrated in figure 5.16. In the scope of environmental analysis, the impacts are driven from materials, energy consumption and emissions. Notice that both tool and part production in the plastic injection moulding case represent no relevant emissions. However, polymer material is consumed and injection moulding is an energy intensive process. All this inputs need to be defined in order to develop the first part of the LCA analysis, the Life Cycle Inventory. Each process of the tool and part life cycle is explored in terms of related extractions and emissions.

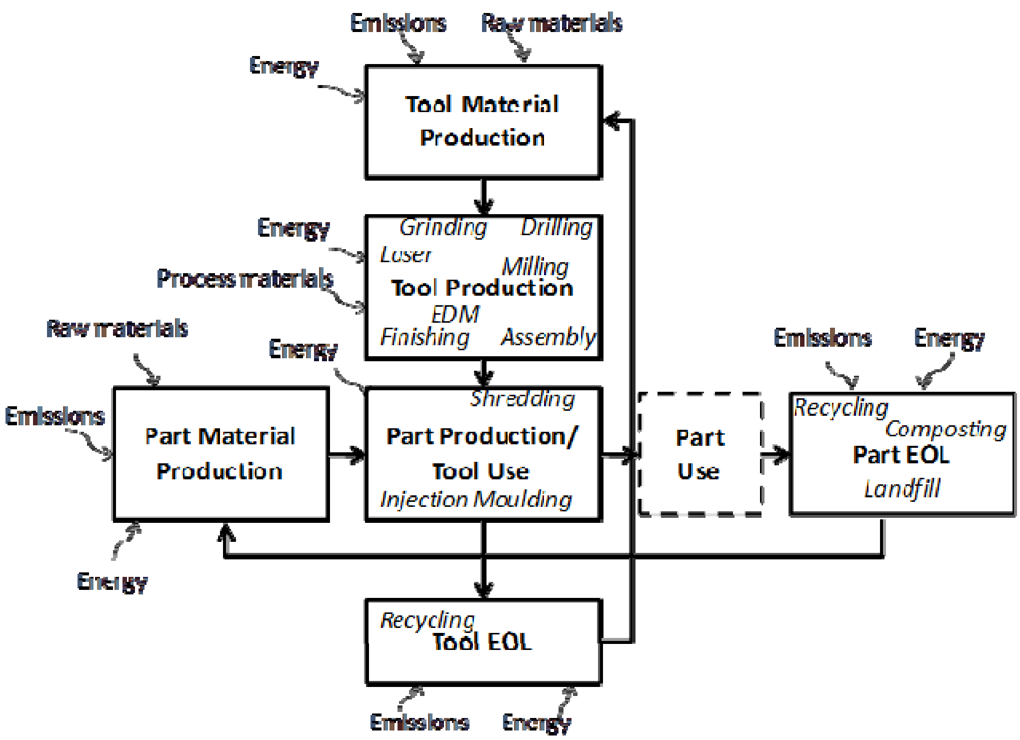


Figure 5.16 – Scope of the LCA analysis and material, energy and emissions flows considered

5.4.2. Eco Indicator 99

The SimaPro software (Goedkoop and Oele, 2008) is nowadays a popular LCA method, in which many published works are based (Pieragostini et al. 2011). SimaPro includes several LCIA methods such as Eco-indicator 99 (EI'99), EDIP 1997 and 2003, EPS 2000, among others, being the EI'99 still is one of the most widely used impact assessment methods in LCA.

The indicator EI'99 assesses the impacts of emissions on human health and ecosystems. The ecological impact is represented by the potentially affected fraction (PAF) or potentially disappeared fraction (PDF) of species, and the environmental impact is given by the global warming potential (GWP), by the potential destruction of the ozone layer (ODP), etc. The impact on human health is measured by DALY units, which represent the years of life lost or disabled as a result of the impacts of emissions. For a given process, emissions are classified into various categories of impacts and assigned in common units for each category based on impact factors. The improvements of these

indexes were developed in their own categories of impact, including land use and resource scarcity as a category of impact. The damage function wre also developed allowing the inclusion of cultural theories as tools for dealing with subjectivity. EI’99 method considers the analysis of three spheres, namely technosphere, the ecosphere and valuesphere, following the cultural theory. The technosphere represents the field of technological processes and systems developed by humans. The dominance of the ecosphere understands the processes and ecological systems, incorporating the technosphere. In valuesphere, which means choice of values, three perspectives have been developed. Depending on the attitude of three human archetypes (individualistic, equalitarian and hierarchic), the distribution of weight factors between human health, ecosystems and resources was determined (Table 5.7). Depending on the perspective chosen, one indicator can be obtained. The view generally accepted in the scientific community is the hierarchic perspective, being a more balanced perspective [Ermolaeva et al. 2004]

Table 5.7: Weights for categories and perspectives (Pre consultants)

	Perspectives		
Damage categories	Individualistic	Equalitarian	Hierarchic
Ecosystem	25	50	40
Human Health	55	30	30
Resources	20	20	30

A general scheme on how to obtain EI '99 is illustrated in figure 5.17. This diagram represents the method to calculate the score of EI'99 divided into three steps: inventory of the inflows and outflows of the processes in the lifecycle of the product, damage model of flows and assigning weights to the three categories.

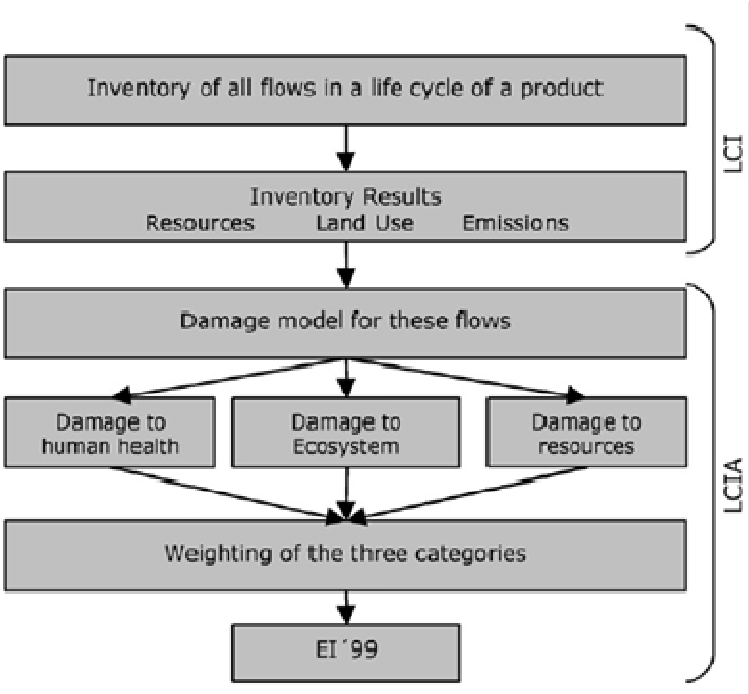


Figure 5.17: Eco Indicator 99 methodology [Ribeiro et al. 2008]

5.4.3. Environmental relations, linking environmental and cost drivers

To explore the life cycle impacts of design decisions in terms of environmental impacts within the same scope of the cost analysis presented in 5.3, the life cycle assessment (LCA) methodology is applied, seeking to translate into environmental impacts all the energy and material streams computed through the models and relations developed for the part and mould integrated life cycle. Despite some cost drivers as labour, overheads or maintenance costs do not represent environmental burden, the energy and material are impact streams in LCA. Therefore, the models developed in 5.2 can be used also to compute the energy and material requirements of each process within the integrated part and tool life cycle. Following each life cycle stream and the correspondent critical aspects in terms of environmental impacts are presented.

5.4.3.1. Part material production

Within the scope of injection moulding, the final part can be made of different type of materials., as already described in the LCC model. These different materials,

thermoplastics, thermosets, elastomers or biopolymers, require different production processes and different raw materials. Depending on the material or materials, in case of multi-material parts, different levels of emissions are emitted, energy required and raw materials extracted. Similarly to the LCC mode, the first step is to compute the required amount of polymer to enter the injection process, using equations 5.16, 5.17 and 5.18. Having the material consumption defined, it is then required to analyse the material or materials involved. To each material it is required to assess the corresponding eco indicator, in particular the EI'99 (equation 5.42). Notice that in case the part material is a design parameter to be analysed, different materials are compared and each alternative polymer needs to be assessed regarding its eco-indicator specific value.

$$Material_{EI} = \sum_{i=1}^{n} Material_i * EI'99_i \quad , n = number\ of\ different\ materials\ in\ the\ part \qquad (5.42)$$

Using the SimaPro software, it is possible to assess the indicator, in some cases using the software data base, in others it is required to analyse the material production process, in case no data is available regarding the specific material.

5.4.3.2. Mould material production

A plastic injection mould is usually produced using different of materials, even if within the same type, namely steel or aluminium. Traditional mould production technologies involve different types of steels; the structure is usually made of mild alloy steel, while the cavity and core are produced using tool steels to sustain the high levels of injection pressure, stress points and/or wear from abrasive materials. Moreover, other thermo-conductive materials are sometimes included, in particular in slender features, in which the heat is difficult to be removed. Therefore, it is necessary, similarly to the part material, to analyse case by case the materials included in the specific mould alternatives. Again, if the mould material is a varying design parameter to be analysed, the eco indicator of each alternative is assessed. In this stage, the recycling of the mould material is not included. Equation 5.43 presents the general environmental impact assessment of the mould material production.

$$Material_{EI} = \sum_{i=1}^{n} Material_i * EI'99_i^{Production} \quad , n = number\ of\ different\ materials\ in\ the\ mould$$

(5.43)

Using the SimaPro software it is possible to assume the use of steel or aluminium alloys with a percentage of recycled material instead of assuming primary material. The recycling of the machining processes scraps are addressed in the mould production phase.

5.4.3.3. Mould Production

The mould production using traditional technology comprises different machining processes namely milling, drilling, grinding and EDM and other assembly and finishing processes. The latter do not present significant environmental burdens due to their manual nature. However, the former use nowadays CNC machines with the correspondent energy consumption. Moreover, in the machining processes scraps are generated and this material waste is usually sold to be recycled in the case of steel or aluminium moulds. Using the process based models developed to assess the process cost, it is possible to use the energy and material consumption values already determined for each mould production process. The recycling of material scraps usually represent a negative value (negative eco-indicator indicates benefits to the environmental categories) due to the benefit from avoiding the extraction of virgin material, even considering the energy required in the recycling process. The energy represents an environmental burden, with the correspondent eco-indicator for the particular country where is consumed. During machining processes other materials are consumed, named process materials, in particular dielectric fluid and electrodes in EDM and lubricants in the machining processes. These can be also included in the environmental analysis, despite a former study has concluded that their impact in the overall life cycle can be disregarded [Ribeiro et al. 2008]. Equation 5.44 translates the mould production environmental impact assessment.

$$Mould\ Production_{EI} = \sum_{i=1}^{n}(E_i * EI'99^{Energy} + \sum_{j=1}^{m} Material_{ij} EI'99_j^{Recycle} + \sum_{k=1}^{l} Material_{il} EI'99_l^{Production})$$

n – number of processes, m – number of different materials in the mould, l - number of process materials

(5.44)

5.4.3.4. Part Production/Mould Use

This stage depends both on part and tool design. The amount of energy and material required to the process depends on several parameters, from the machine type to the part material and geometry and tool design. The model developed for the injection moulding process allows computing and accommodating variations in these parameters and estimating the energy and material requirements that are common both to the cost and environmental analysis. The input material was assessed in terms of environmental impacts in the material production phase. However, as already explained in the LCC analysis, the scraps are usually reused, depending on the percentage of recycled material allowed in the part. This avoids material wastes, but a shredding machine is required to process the material before reintroducing it in the injection process. Therefore, energy is consumed in the reuse of material in the part production. The environmental impact assessment of the mould use/part production phase is described in equation 5.45.

$$Injection\ moulding_{EI} = \sum_{i=1}^{2} E_i * EI'99^{Energy} - M_{waste} * EI'99^{production} \quad (5.45)$$

1 – Injection moulding; 2 - Shredding

5.4.3.5. Part and Tool EOL

The possible EOL scenarios, described in the LCC analysis, depend on the type of materials in the tool and the part. Equation 5.46 describes the environmental impact of these last stages of the life cycle. The EI’99 allocated to the EOL scenario needs to be computed case by case, either using the SimaPro data base or in case of not existing a EI’99 for the specific material and EOL process, the indicator needs to be developed by analysing the processes involved.

$$EOL_{EI} = \sum_{i=1}^{n} M_i * EI'99^{EOL_i} - M_{waste} * EI'99^{production} \tag{5.46}$$

$$n - number\ of\ materials$$

This section described the use of the LCA methodology in the CLC framework proposed in this thesis, fostering the impact assessment of design decisions regarding plastic parts produced by injection moulding and the moulds required to produce them. Using an already existent method and indicator to assess the life cycle impacts, it was applied to a wider scope comprising the life cycle of the part and the mould. Moreover, the analysis was performed using the developed model in 5.2, linking the part design with the mould design and both with the downstream phases. Having already developed models to estimate some outputs common to the LCC analysis, namely energy and material consumption, in this section these outputs were translated into a single environmental indicator, EI'99, and gaps were filled regarding other outputs not common with the cost analysis.

Finally, the assessment of cost and environmental impacts allows a two dimensional view of design decision problems, which can be integrated in a single comparison framework as the proposed in section 4.7. CLC applied to the life cycle of part and tools involved in the injection moulding process is further explored through case studies developed in industrial contexts.

6 CASE STUDIES

As previously described in the former sections, the proposed framework integrates the part and the tool life cycles and combines process-based models of all life cycle phases involved, introducing relations of dependencies and impacts between them. These process-based models regard cost as a function of technical factors, such as cycle time, downtime, reject rate, equipment and tooling requirements, or the material used. Additionally, as a dedicated tool is a critical element of the part manufacturing phase, the performance of the tool in its use phase is modelled as regards the part production cycle time, the part material waste and the energy consumption, and, finally, the tools expected maintenance and failure cost, all according to the tool and part design specifications. Finally, another factor sensitive to the tool and part design is the environmental impact. Increasingly important nowadays, it is normally disregarded in tool design, as the tool itself usually represents low environmental burdens. Yet, when analysing the impacts of design changes in material and energy consumption, the environmental impacts can be very sensitive to it. Therefore, the framework proposed aims to quantify the tool life cycle impacts by using process-based models, so that the costs and environmental impacts are assessed according to the processes modelled and are sensitive to design and manufacturing changes. From the geometry of the part, material used and other design inputs, each process is modelled taking into account the manufacturing requirements and both the costs and environmental burdens driven by them.

Finally, as explained in chapter 4, Comprehensive Life Cycle (CLC) results are integrated fostering the comparison of economic and environmental life cycle performance of the design (part and/or tool) alternatives under analysis. This enables the decision maker to visualize the best alternatives domains according to the part and/or tool design strategy.

In order to illustrate the application of the CLC framework, several case studies developed during internships in injection moulding and/or mould making companies are presented in this section. The case studies are separated according to the scope of the analyses; the first section comprises case studies with the tooling design as the only decision space, the second with the design alternatives in the part design with the tool

design frozen and the last section describes a case study with tool and part alternative designs. All the case studies follow the CLC framework and the developed models for the injection moulding process. However, depending on the type of design alternatives considered and their impact on the results of a particular case, different analysis are shown with more or less detail. Ultimately, the main goal of the case studies here presented is the illustration of the proposed approach and developed models.

6.1 Case Studies 1 - 4 - Tool Design Alternatives

This section presents case studies regarding tool design alternatives. The part design is frozen, being the analysis focused on assessing different mould architectures and mould making technologies as regards their life cycle performance. The case studies were developed during an applied research in an industrial company, Celoplás, specialized in producing technically complex parts made of polymeric materials. Besides producing the parts, the company also manufactures the required precision moulds for their own use, meaning that the company is simultaneously the mould producer and the mould user. Figure 6.1 illustrates the scope of the case studies and the impacts throughout the life cycle of the design decisions proposed. The main interactions happen in the injection moulding process, being the tool design influencing not only the energy and part material consumption but also the part production cycle time and probability of failure during the tool use. The first case study is explored in greater detail than the other three for a better understanding of the framework application and possible analyses.

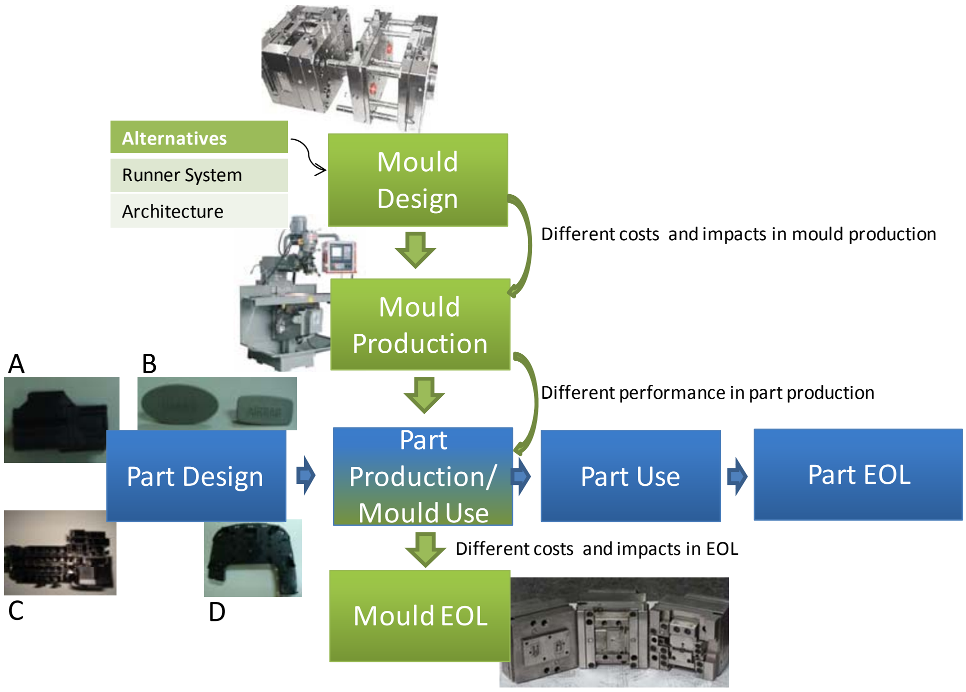


Figure 6.1 – Tool design alternatives and the impacts throughout the integrated life cycle of the analysed case study comprising parts A, B, C and D.

The parts produced in the part production/mould use phase are automotive parts, some for electronic components, with different levels of production volume and different materials, geometries and complexity. The presentation of the case studies is focused on showing the framework and models mechanism, flexibility and type of analysis possible to perform, rather than detailing the technical part of the design problem. For the sake of simplicity and concision the four cases are presented simultaneously due to the similar nature of the design problems.

Table 6.1 presents the main characteristics of the parts relevant to the study. For each one, with the support of the mould maker/injection moulding company, several mould design alternatives were defined as possible options, able to produce the part according to the requirements (see table 6.2). Regarding part A, four possible mould alternatives were defined regarding different mould architectures: each moulding cavity is a separate insert in the cavity plate vs. all cavities are machined in the cavity plate and runners system (hot and cold runners). In part B two different mould alternatives were considered to inject the part in: each moulding cavity is a separate insert in the cavity

plate; all cavities are machined in the cavity plate. Regarding part C, the alternatives regarded the options of separate inserts for each thin feature in the moulding cavity and less inserts (combining several thin features in the same insert), with the thin features machined in line in six separate blocks. Finally, the alternative moulds defined for part D differ in the runner system – hot-runners/cold runners.

Table 6.1– Parts characteristics - PBT – Polybutylene, Terephthalate, PP – Polypropylene, PPO - Poly(p-phenylene oxide) and ABS - Acrylonitrile butadiene styrene

Part	**A-Connector**	**B-Label Plate/ Dowel Clip**	**C-Battery Fuse Block**	**D-Housing Cover**
				
Material	PBT	PP	PPO	ABS
Part volume	3.73 cm^3	7.91 cm^3	37.4 cm^3	65.4 cm3
Projected area	279 mm^2	2327 mm^2	3157 mm^2	15817 mm^2
Max thickness	3 mm	2.85 mm	2 mm	3 mm
Runner diameter	6 mm	6 mm	6 mm	6 mm
Material recycle rate (Max)	30%	30%	30%	0%
Complexity	High	Low	High	Low
Part production life	8 years	8 years	8 years	8 years
Expected annual production Volume	6500000 parts/year	200000 parts/year	275000 parts/year	100000 parts/year

Table 6.2. – Mould alternative designs

Parts	**A-Connector**	**B-Label Plate/ Dowel Clip**	**C-Battery Fuse Block**	**D-Housing Cover**
Mould Alternatives	A1 - Separate cavities, hot-runners	B1 - Machined in block	C1 - High number of inserts	D1 - Hot-runners
	A2 - Machined in block, hot-runners	B2 - Separate cavities	C2 - Lower number of inserts	D2 - Cold runners
	A3 - Separate cavities, cold runners			
	A4 - Separate cavities, hot-runners			

6.1.1. Comprehensive Life Cycle - Costs

In this section the CLC model is explored in the cost dimension applying it to understand the impact of the tool design alternatives in the final cost of the parts. Therefore, the tool production cost was modelled through the manufacturing processes required to produce the mould, namely milling, electric discharge machining and turning. Additionally the mould finishing operations and its engineering design are also incorporated in costs.

- *Tool Production Cost*

After developing the process-based cost model for these case studies the production cost of each mould design alternative were computed (Table 6.3) following the models developed in chapter 5. Differences in cost are considerable, with a 16% cost difference between the lowest cost mould (alternative A3) and the higher cost one (A1). The same happens in the other case studies, with 9% mould cost difference between B alternatives and 15% cost differences between D alternatives. C alternatives have no relevant differences in cost (0.2%).

Table 6.3 – Moulds production cost

Mould alternatives	Characteristics	Production cost [€]
A1	Separate cavities, hot-runners	58,389
A2	Machined in block, hot-runners	57,477
A3	Separate cavities, cold runners	50,310
A4	Separate cavities, hot-runners	56,289
B1	Machined in block	21,527
B2	Separate cavities	23,622
C1	High number of inserts	53,571
C2	Lower number of inserts	53,411
D1	Hot-runners	44,864
D2	Cold runners	39,018

One advantage of developing process-based models in this approach is the flexibility to analyse the costs in different angles for different tools and alternatives. One possible

approach, illustrated in figure 6.2, is the comparison of costs of the different processes required to produce the injection mould. This allows the visualization of the contributions of each manufacturing process step to the whole production cost. As predictable, the parts with higher complexity lead to higher contribution of EDM and wire EDM in the production cost when compared with simpler parts (e.g. B and D). Moreover, the use of hot-runners increases significantly the percentage of bought components cost in the overall costs.

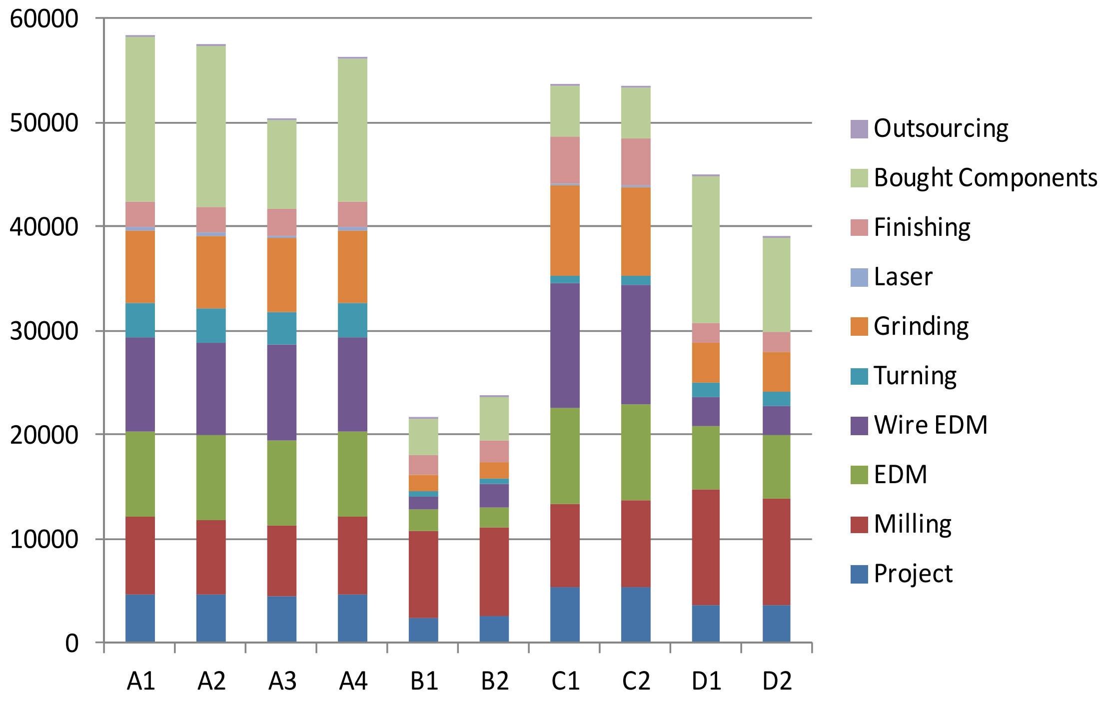


Figure 6.2. – Mould production costs by process step

Another interesting analysis easily extracted from the developed process models are the main cost drivers of each alternatives, in this case encompassing the whole mould manufacturing chain. An interesting conclusion from the results illustrated in table 6.4 is the minor differences between the percentage of variable and fixed costs in all mould alternatives for the four parts. In fact, the weight of each cost driver to the total cost does not present significant variations between the moulds alternatives. The only exception is the bought components driver, mainly due to different runner systems. In general, the main cost drivers are labour, machine usage and the acquisition of standard mould components. This is explained by the fact that a mould production is a time consuming activity, quite demanding in terms of qualified labour and capital intensive machines. The high cost of the standard components, in which the elements for the

mould structure and the runners system are included, is explained by the strategy of the company of taking advantage of the best standard solutions existent in the market and concentrating on what is really the mould dedicated engineering solution.

Finally, if the decision for the best alternative was made regarding only the mould production cost (an indicator for its price), the option would be the moulds with lower production costs (A3, B1, C2, D2). However, that decision would not take into account its performance in the injection moulding process, i.e. in its use phase. Only a simultaneous analysis of the mould production and mould use performance seems to provide the framework for an informed decision.

Table 6.4. – Cost drivers in mould production costs of each alternative

	A1	A2	A3	A4	B1	B2	C1	C2	D1	D2
VARIABLE COSTS										
Project Cost	8%	8%	9%	8%	11%	11%	10%	10%	8%	9%
Labor Cost	31%	31%	35%	32%	36%	35%	38%	38%	29%	33%
Energy Cost	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Process material cost	2%	2%	3%	2%	1%	1%	3%	3%	1%	2%
Material Cost	1%	1%	1%	1%	2%	2%	1%	1%	2%	2%
Total Variable Cost	**44%**	**44%**	**50%**	**46%**	**52%**	**50%**	**54%**	**54%**	**42%**	**47%**
FIXED COSTS										
Main Machine Cost	18%	18%	21%	19%	20%	20%	23%	23%	17%	19%
Tooling Cost	3%	3%	3%	3%	2%	2%	4%	4%	2%	2%
Fixed Overhead Cost	8%	8%	9%	8%	9%	9%	9%	9%	7%	8%
Building Cost	1%	1%	1%	1%	2%	2%	1%	1%	1%	1%
Maintenance Cost	0%	0%	1%	0%	0%	0%	1%	1%	0%	0%
Subcontracts/bought components	26%	26%	16%	23%	14%	16%	8%	8%	30%	21%
Total Fixed Cost	**56%**	**56%**	**50%**	**54%**	**48%**	**50%**	**46%**	**46%**	**58%**	**53%**

- *Part Production/Tool Use Cost*

The integration of both process based cost models is carried out linking the output and the input of the mould production and injection moulding models respectively. The mould specifications affect the mould cost, but also affect the injection cycle time, part material consumption, mould maintenance level, injection machine downtime and expected failure cost, which were calculated following the models presented in section

4.2. The design of the parts was considered frozen, so the changes in the cycle time and energy consumption are driven by the tool engineering solutions. Notice that the cycle time regards the production of one part, dependent on the number of cavities and is directly related with the labour, machine and building cost, as an increase in cycle time leads to an increase in resources used time. The material consumption depends on the runner system architecture, being the number of nozzles a factor for material efficiency. These variables are accommodated by the process models, allowing sensitivity analyses to the ones relevant to a certain design decision.

As the part geometry and material were frozen, the preventive maintenance level (and mould downtime) is equal for all the alternatives, following the model developed in chapter 5. Table 6.5 presents the outputs of cycle time, maintenance costs and energy and material consumption of each alternative of each case study, computed through the models developed for injection moulding. In this case, only the mould alternative with cold-runners leads to higher cycle time and energy consumption.

Regarding parts B and C, the alternatives are focused on improving tool reliability and maintainability. Therefore, the cycle time, maintenance costs and energy and material consumption are the same for the alternative tool designs. However, the mould reliability varies among the different alternatives, in particular the probability of failure of the alternatives and the cost to replace components when the failure occurs.

Table 6.5. - Cycle time, maintenance costs and energy and material consumption of each alternative tool design

Mould Alternative	Cycle time [sec/part]	Energy Consumption [Wh/part]	Material Consumption [g/part]	Maintenance Cost [10^{-3}€/part]
A1	4.51	0.53	4.87	0.04
A2	4.51	0.53	4.87	
A3	5.50	0.64	9.46	
A4	4.51	0.53	5.71	
B1	20.12	0.12	8.36	0.26
B2				
C1	43.13	0.26	37.59	0.37
C2				
D1	16.33	0.10	70.35	0.51
D2	19.12	0.11	89.81	

In order to assess the expected failure costs of each alternative tool design of each case study, the model developed in section 4.2.4 was applied, starting with the quantification of the number of critical elements present in each mould design (table 6.6).

Table 6.6. - Number of critical elements present in each mould design

Mould alternatives	**Characteristics**	**Number of elements**							
		Ejector pins	**Nozzles**	**Manifold**	**Moulding cavity/core**	**Moulding cavity/core – abrasive mat**	**Heel blocks**	**Slide rulers**	**Core inserts**
A1	Separate cavities, hot-runners	136	4	1	8	-	-	-	488
A2	Machined in block, hot-runners	136	4	1	1	-	-	-	
A3	Separate cavities, cold runners	136	1	-	8	-	-	-	
A4	Separate cavities, hot-runners	136	2	1	8	-	-	-	

B1	Machined in block	27	1	-	1	-	-	-	-
B2	Separate cavities	27	1	-	4	-	-	-	-
C1	High number of inserts	110	1	-	2	-	2	1	560
C2	Lower number of inserts	110	1	-	2	-	2	1	112
D1	Hot-runners	78	2	1	-	2	-	-	-
D2	Cold runners	78	1	-	-	2	-	-	-

With the Weibull parameters of each element defined, table6.7, each element was then associated with a failure profile, enabling the computation of the expected cost of failure considering the number of units produced per year and the production life. Notice that the number of failures of the mould elements observed by the experts varied from 5 to 300, according to the questionnaires performed to experts , being therefore suitable for the Bernard medium rank approximation. In this case the cost of failure was only the replacement cost, as the safety stock the company was enough to cover the maximum time of repair. Figure 6.3 presents the annualized failure costs of each alternative considering the production life (8 years), for different annual production volumes. However, despite the annualization for the sake of simplicity and input in the cost model, the expected costs are not the same throughout the years. In order to show this aspect, the expected failure costs per year in each production year of case study A are following presented. It is interesting to notice the significant increase of failure costs with the production volume of the moulds and possible alternatives developed by the company for lower production parts (B, C, D).

Table 6.7 – Weibull parameters t_0 and T [10^3 injection cycles], b [adimensional] and MTBF [10^3 injection cycles] of mould elements subject to failure.

Elements	**t_0**	**T**	**b**	**MTBF**
Ejector pins	24	246	2.36	221
Nozzles	200	623	2.01	575
Manifold	1000	1702	2.02	1622
Moulding cavity/core	400	735	1.71	699
Moulding cavity/core –abrasive mat	150	344	2.26	322
Core inserts	400	679	2.03	647
Slide rulers	100	1079	3.71	984

Heel Blocks	300	627	1.74	591

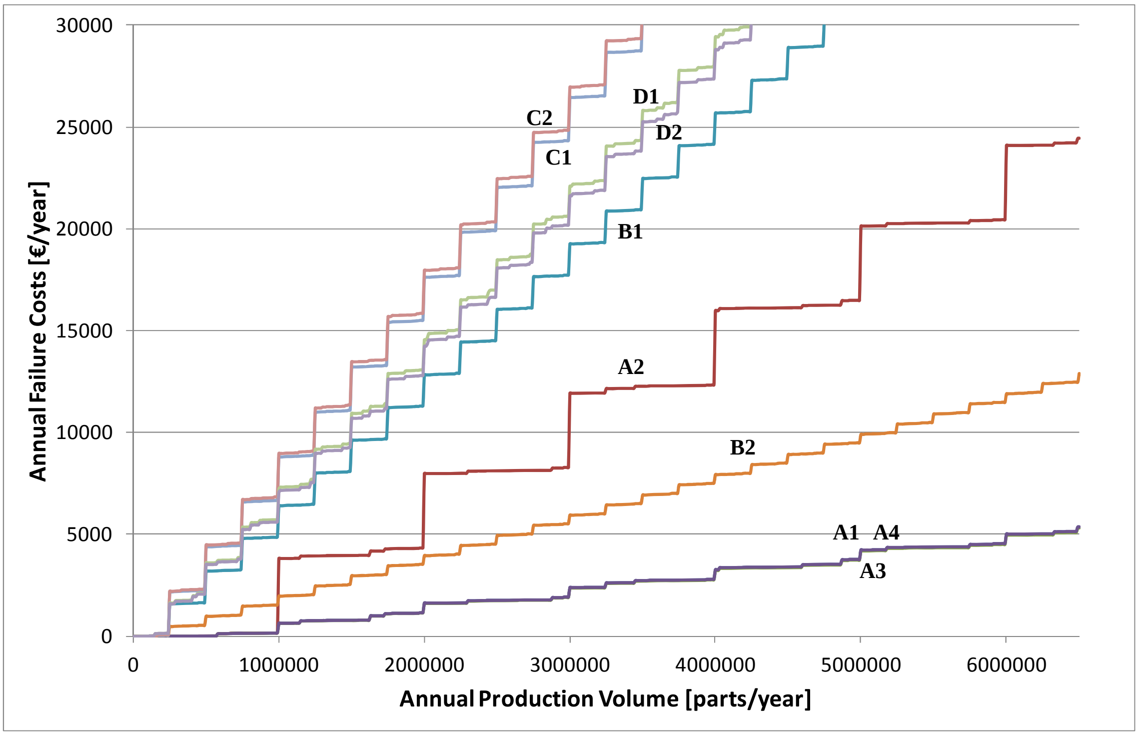


Figure 6.3. – Annual failure costs of mould design alternatives for different annual production volumes

The failure costs for each year of the part A production life are presented in table 6.8, considering now the expected annual production volume. These costs vary each year, as different elements present each year different failure probabilities.

Table 6.8 – Expected cost of mould failure throughout the part life

	Expected failure cost -A1 [€]	Expected failure cost - A2 [€]	Expected failure cost - A3 [€]	Expected failure cost - A4 [€]
1st year	5181	30639	5115	5181
2nd year	7911	33369	7845	7911
3rd year	6091	31549	6025	6091
4th year	7001	32459	6935	7001
5th year	7756	33214	7690	7756
6th year	6245	31703	6179	6245
7th year	7677	33135	7611	7677
8th year	5414	30872	5348	5414

Still considering the expected annual production volume of each part, another model output shows that the injection moulding cost is mainly driven by raw materials, machine use, and tooling. Table 6.9 presents the costs distribution of each part using the first tooling design alternative. Despite the high difference in the production volume, the main cost drivers are the same. Notice that as expected, the fixed costs gain higher importance with the decrease in the production volume (parts B, C and D). The fixed costs comprise only the mould, being the mould failure costs considered variable as these are dependent on the number of produced parts in the developed failure model. Maintenance costs regarding the preventive and small corrective maintenance operations consider the maintenance level selected for this type of mould and part),which results in a specific mould and machine downtime. It is also considered that preventive maintenance operations are performed during part production, that is, with the mould in the machine. This affects directly the machine and mould available time and therefore the machine, tooling, building and labour costs. The effects on costs are accommodated by the process models, allowing different sensitivity analysis to different maintenance levels and different part and mould designs.

Table 6.9 – Cost distribution (materials production, mould production and parts production/mould use phases) for Alternative A1 considering the expected annual production of each part.

	A1	B1	C1	D1	A1	B1	C1	D1
Cost Drivers	Cost per year [€]				Percentage [%]			
Labour Cost	5,880	663	2,183	270	4	6	3	1
Energy Cost	2,205	303	891	123	1	3	1	0
Material Cost	104,555	2,023	42,070	13,156	67	19	61	53
Mould Failure Cost	5,237	30,64	1,570	8	3	0	2	0
Mould Maintenance Cost	258	52	103	52	0	0	0	0
Total Variable Cost	118,136	3,071	46,818	13,608	76	28	68	55
Main Machine Cost	22,653	2,817	8,776	1,145	15	26	13	5
Mould Cost	13,062	4,802	12,551	9,994	8	44	18	40
Overhead Cost	588	66	218	27	0	1	0	0
Building Cost	1,015	126	393	51	1	1	1	0
Total Fixed Cost	37,318	7,812	21,938	11,217	24	72	32	45
TOTAL FABRICATION COST	155,454	10,883	68,756	24,825	100	100	100	100

- *Part and Tool EOL*

Finally, the end-of-life costs are also computed. In this case the EOL costs (in the part case) or profit (mould case) is extremely low compared with the overall life cycle. As shown in table 6.10, the moulds addressed in these case studies can be sold as steel scrap for recycling for between 100€-258€ (0.26 €/kg), depending on the amount of steel, at the end of 8 years (Future Value – FV). This represents an annual equivalent income of 7.33€-18.80€. The EOL of the plastic parts cannot be analysed outside the product EOL, which is outside of this study scope. More than that, as the design of the part was kept frozen its EOL did not change. However, assuming that it goes directly to landfill one can say that the induced costs in the landfill management (normally a local government cost) for the analysed parts is between $2.27*10^{-4}$ € and $4.90*10^{-3}$ € per part (Portuguese landfill data) and, so, also very low on the whole life cycle costs.

Table 6.10 – EOL cost of moulds and parts

Parts	Mould		Part
	FV (8^{th} year) [€]	Annuity [€/year]	[€/part]
A	100	7.33	$2.27*10^{-4}$
B	101	7.36	$5.90*10^{-4}$
C	101	7.36	$2.80*10^{-3}$
D	258	18.80	$4.90*10^{-3}$

- Comprehensive Life Cycle Cost Results

In figure 6.4 the life cycle costs per part and per stage are presented for each alternative mould in all case studies. Results show that within the proposed alternatives, the best choices considering the expected production scenarios are A1, B1, C2 and D1. Several conclusions may be taken from this analysis: (1), the importance of the tool cost and use, in this case with the failure costs included in the overall life cycle; (2) the low importance of EOL costs, either regarding the part or the mould; (3) as expected the increase of the costs per part with the decrease of the annual production volumes. The high material costs of part D are only related, due to the variable nature of this cost driver, to the higher weight of the part.

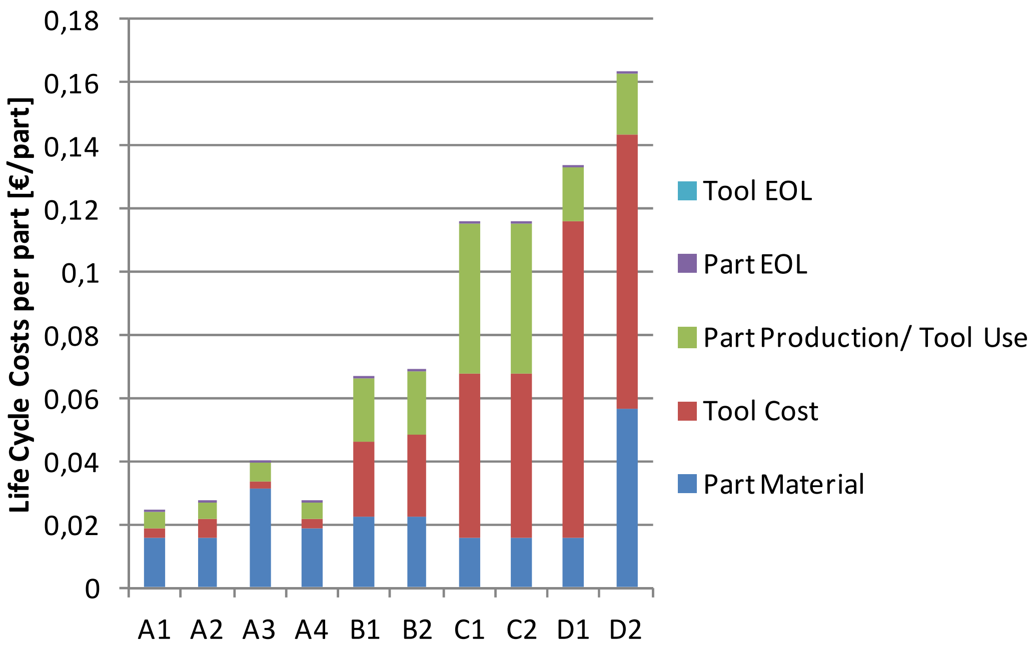


Figure 6.4 – Cost distribution of life cycle phases considering the expected production volumes

As noticed in figure 6.5, the production volume influences the cost per part. In fact, the best mould alternative in an economic point of view is highly dependent on the production volumes. Therefore, the final life cycle costs of each case study comprise not only the expected production volume, but a wider view of the best alternatives and their life cycle cost values according to this variable. Figure 6.5 presents the lower cost alternatives for a large range of annual production volumes (considering a constant part production life of 8 years). Indeed, different alternatives are the best economic choices for different production volumes in all case studies. This type of outputs regarding sensitivity analysis is easily computed due to the flexibility of the developed models.

Regarding case study A, for production volumes below 90,000 parts per year, the best choice is the mould with the lower production cost (alternative A3). With the increase of the annual production volume, the performance of the mould (injection cycle time, material waste and energy consumption) acquires importance over its production cost. For medium production volumes, between 100,000 and 1,000,000 parts per year, the best choice is alternative A2. For high production volumes, above 1,000,000 parts per year, the best choice is the mould with the highest production cost (alternative A1) but, with a better performance in terms of reliability and cost of failure when compared to alternative A2. Notice that mould 2, with all the 8 moulding cavities machined in a

single plate, leads to higher repairing costs if a major failure happens. The whole block needs to be removed and repaired. In the other moulds the cavities are separated and assembled as inserts in the cavities plate, making possible to repair them individually if necessary.

Moving to case studies B, results show that bellow an annual production volume of 250,000 parts the best choice is alternative 1. Above this production volume, the best choice is the alternative mould design 2. Currently, the demand for this part is 100,000 parts per year. Therefore, the company's decision, alternative 1, is the best choice considering the cost per part in the current production scenario. The cost distribution is similar to the previous case study, being in this case the failure cost insignificant (192 €) when compared with the tooling cost due to the lower annual production volume. Only for higher production volumes (above 250,000 part per year) the failure cost would be more relevant, becoming the higher investment alternative, with lower failure cost, the best choice.

Analysing results of case study C, alternative 1 is only the best choice for annual production volumes above 325,000 parts per year. Below that, alternative 2, the lower cost mould, is the one with lower cost per part. However, the company's choice was alternative one, which, considering the very low difference in cost, the production volume not far from the transition point in the best alternative domains and the higher simplicity to replace inserts, cannot be considered a bad choice in a real industrial context.

Finally, analysing CLC results of case study D, alternative one is the best choice for annual production volumes above 33,000 parts per year due to lower energy, material consumption and cycle time. . Bellow that, alternative 2, the lower cost mould, is the one with lower cost per part due to the lower investment in the mould production

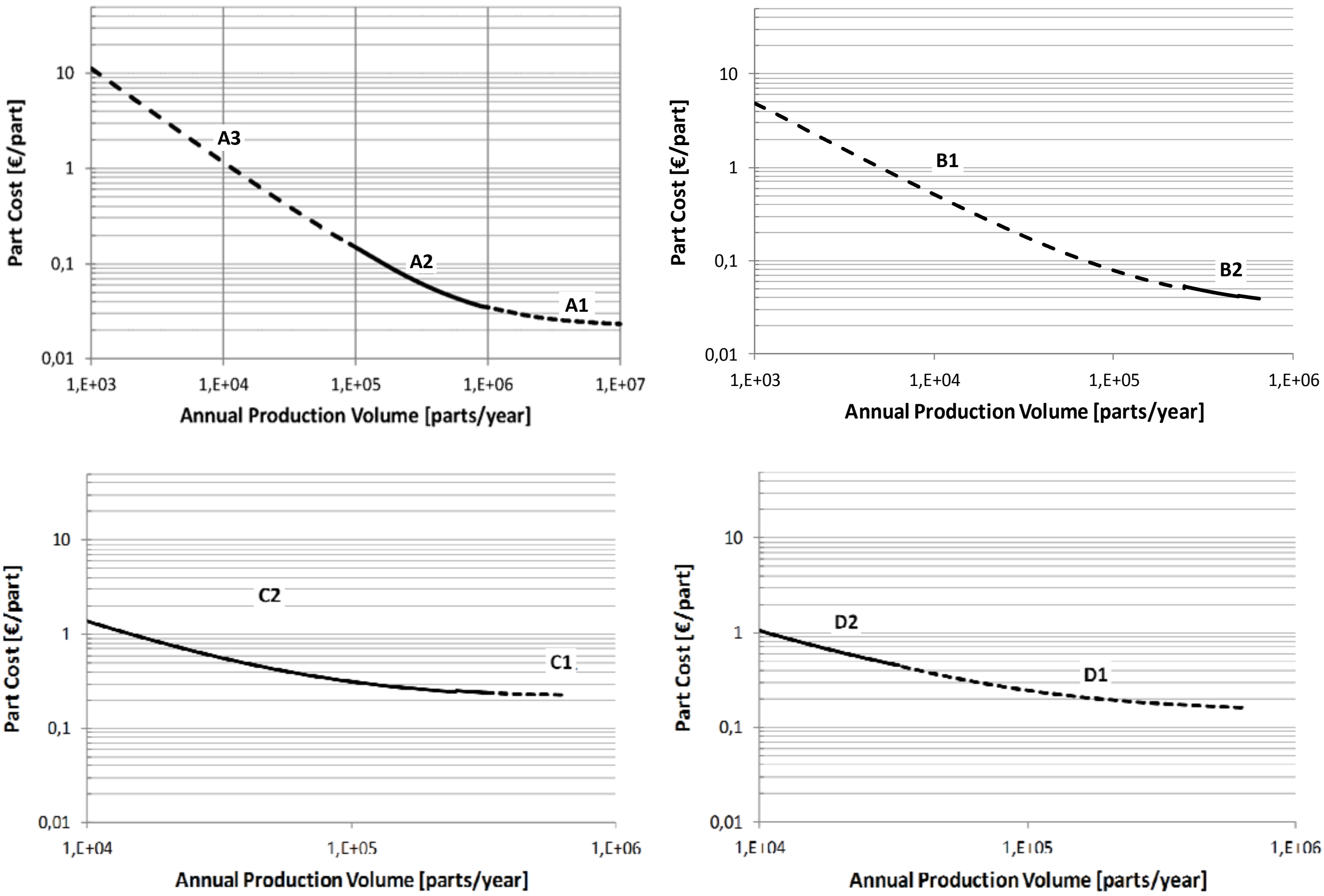


Figure 6.5- Best (lowest LCC) alternatives for different production volumes

To illustrate the importance of the mould failure model in supporting tool design decisions, the results obtained for the first case study, A, can be compared with a different approach of reliability and maintenance related costs calculation. A common basic approach considers simply the tooling maintenance cost as a percentage of tooling investment cost or is simply disregarded and doesn't consider the related reliability (Johnson & Kirchain 2009, Nadeau et al. 2010, Folgado et al. 2010) (Figure 6.6). The main difference is that in the basic model, as reliability is not taken into account, the need to replace the whole cavity in case of failure regarding alternative A2 is not taken into consideration. So, mould A2 appears as the best alternative for all annual production volumes above 200,000 parts. The lack of the failure model also extends the annual production volume scenarios where the lower cost and lower performance mould (A3) is the best alternative. Finally, differences also arise in the part cost for low production volumes. Being maintenance (corrective and preventive) in the common simplified model estimated as a fixed percentage of the tooling investment cost, which

is the main cost item for low production volumes (as a fixed cost is distributed through the number of produced parts), it increases the part cost in these scenarios when compared with the C-LCC model. Unlike C-LCC model, repairs and tool failure are disregarded and the number of components replacements does not increase with the tool use.

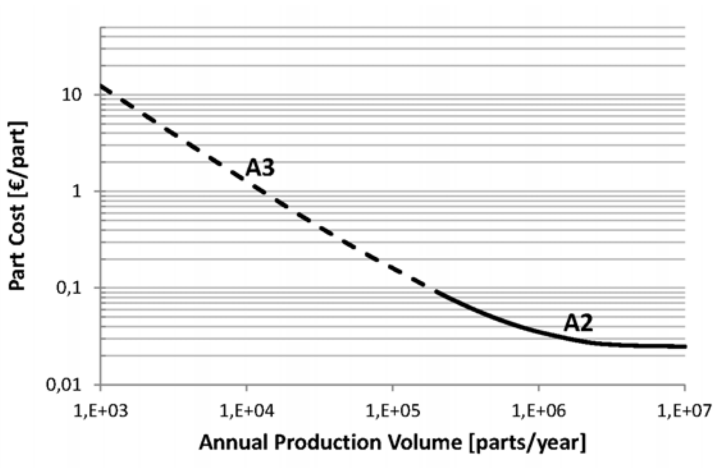


Figure 6.6 – Best (lowest LCC) alternatives for different production volumes of part A disregarding reliability and maintenance models.

6.1.2. Comprehensive Life Cycle – Environmental Impact

- *Inventory Analysis and Impact Assessment*

Following the comprehensive framework aiming to estimate the impacts of design decisions in the design stage of products and tools, this section presents the Environmental Impact of each case study regarding the whole life cycle. The framework described in section 5 is here applied, using information from the develop models for the LCC cost. The case studies and alternatives have different impacts throughout the part and tool life cycle, namely in energy and material consumption. Having these flows already determined, the life cycle inventory phase, it is now required to assess the specific impact (EI'99) per unit of energy and materials involved in the processes. Following are described the types of environmental impact drivers involved (table 6.11). Notice that moulds and parts production take place in the same company, so the specific energy environmental impact is the same. The environmental impact of each

environmental driver were defined using the SimaPro® software according to the raw materials, energetic sources and emissions generated in its production.

Table 6.11. Types of environmental impact drivers involved in the life cycle phases

Impact driver	Material	EI'99 [pts/kg]	Energy	EI'99 [pts/Mj]
Mould Material Production	Tool Steel Mild Steel	0.551 0.181	-	0.0136
Part Material Production	PBT	0.490	-	
	PP	0.380	-	
	PPO	0.500	-	
	ABS	0.400	-	
Mould Production	Dielectric Fluid Cutting Fluid	0.250 0.207	Portugal	
Part Production	-	-	Portugal	
Mould EOL Recycling	Tool Steel Mild Steel	-0.070	Portugal	
Part EOL Landfill/ Recycling	PBT	0.004/-0.404		
	PP	0.004/-0.294		
	PPO	0.004/-0.414		
	ABS	0.004/-0.314		

- *Life Cycle Impact Assessment (LCIA)*

With the specific impact values presented in table 6.11 and the quantities computed through the process-based models it was possible to compute the environmental impacts throughout the integrated life cycle. Notice that the expected production volumes per year were considered, along with the alternatives of each case study, already described in section 6.1. Although a previous study (Ribeiro et al. 2008) has concluded that the process materials used in the mould production processes can be disregarded, in these first case studies they are presented for the sake of validation.

Table 6.12 presents the EI'99 values for each impact driver of the integrated life cycle for the first alternative mould of each case study. Results show that the main environmental driver is material consumption, in particular the part material, followed by energy consumption during the injection moulding process. This is true for all case

studies, with very different annual production volumes. Obviously the increase of the production volume (see part A) also increases the importance of the variable environmental drivers (e.g. part material) compared with the fixed environmental drivers (e.g. mould material). Additionally, the total environmental impacts, still considering the expected production volume are also illustrated in Fig 6.6.Expressly, results of case study A show that the process materials used during the mould production represents 0.1% of the overall impact of the part and mould life cycle. Additionally, the main driver of environmental impacts is material (88.38%), followed by energy consumption (11.45%), in particular in the part life cycle phases (part materials and part production/ mould use). Similarly to the life cycle cost, the EOL phase does not represent substantial burdens in the overall life cycle. Having considered the recycle of the mould steel and landfill for the plastic parts, the recycle represents a negative impact as it avoids the production of primary material. Regarding the four alternative moulds, results show that for the production volume of 6,500,000 parts per year, the economically best alternative is also the best alternative in terms of lower environmental impact. Similarly, the economically worst alternative, the alternative 3 with cold runners, and consequently with higher cycle time and higher material waste, is also the environmentally worst one.

In case study B part material production represents the main percentage of the overall environmental impacts. However, the mould production becomes more relevant when compared with the previous case study, as the annual production volume is much lower and, consequently, the mould as a dedicated tool and a fixed asset gains importance in the overall production context. When comparing environmentally both alternative designs (Figure 6.7), there is not a significant difference between them. The reason is that mould production is the main difference between them, which represents a low environmental impact in the overall life cycle. Regarding the part material and production, both moulds lead to the same amount of polymer and energy consumption.

Similarly, case study C results reveal the higher importance of part material production over the other environmental drivers, but with a significant percentage of the overall impact related with the mould material and production. This was expectable as the production volume is similar to the case study B, being the mould more relevant than in the high production volume context of case study A. Regarding the two alternative designs, no significant different in EI'99 values are found, as both lead to similar

consumptions of energy and material during the injection moulding process (part use/mould use phase).

Finally, addressing case study D, part material represents the major impact driver with 77.58% of the overall integrated life cycle impact, having the mould in this context of relatively low annual volume (100,000 parts/year) a significant impact in the overall impact assessment. Comparing both alternative moulds, it is clearly shown in Figure 6.15 that alternative 1 is the option with lower environmental impact, as the hot-runners avoid the material waste generated in alternative 2. Moreover, this option regarding the runners system also leads to lower energy consumption, and therefore lower EI'99 values, similarly with what happens with the economic dimension

Table 6.12 – EI'99 values considering alternative 1 of each case study and the expected annual production volume of each part.

Impact driver	Material [EI'99 points]				Energy [EI'99]				Process Materials [EI'99]			
	A1	B1	C1	D1	A1	B1	C1	D1	A1	B1	C1	D1
Mould Material	70	70	70	103								
Part Material	14226	1024	3928	2814								
Mould Production					623	244	694	431	28	7	34	16
Part Prod./Mould Use					1243	82	406	276				
Mould EOL	-27	-27	-27	-40								
Part EOL	127	8	41	28								

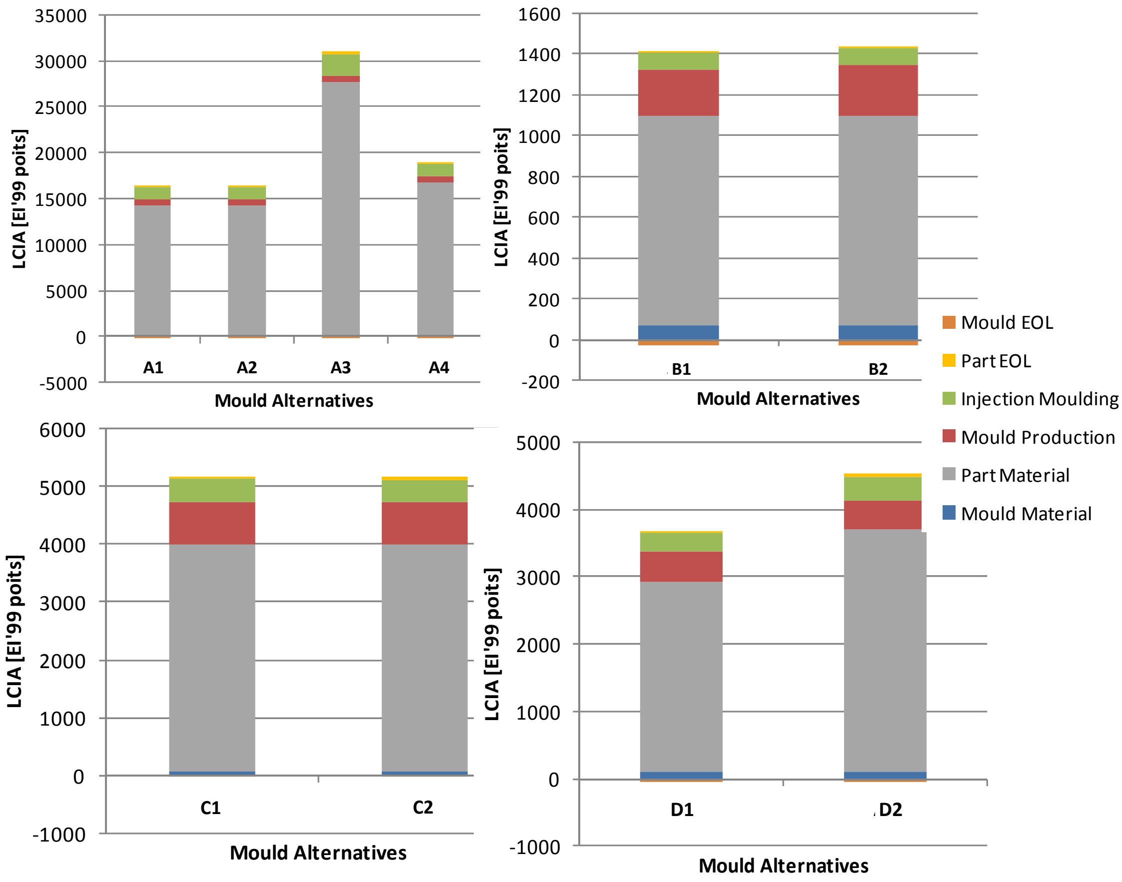


Figure 6.7. – EI'99 values considering all mould alternatives and the expected production volume of each case study.

A sensitivity analysis was also performed to the production volume, computing the environmental impact of each alternative for each case study considering the a wide range of annual production volumes between (Fig. 6.8).Regarding the first case study, the mould alternatives A1 and A2, which save energy and material, are the best alternatives for all production volumes. The same happens in parts B and C, in which alternatives B2 and D2 also lead to lower energy and material consumption, being the best environmental alternatives for any production volume considered. Finally, as both designs analysed for part C lead to similar consumptions of energy and material during the injection moulding process (part use/mould use phase), there is no significant difference in an environmental point of view between them. Finally, with all cost and environmental outputs relevant to this analysis computed through the process models, the last step of the proposed approach is the integrated analysis of both dimensions.

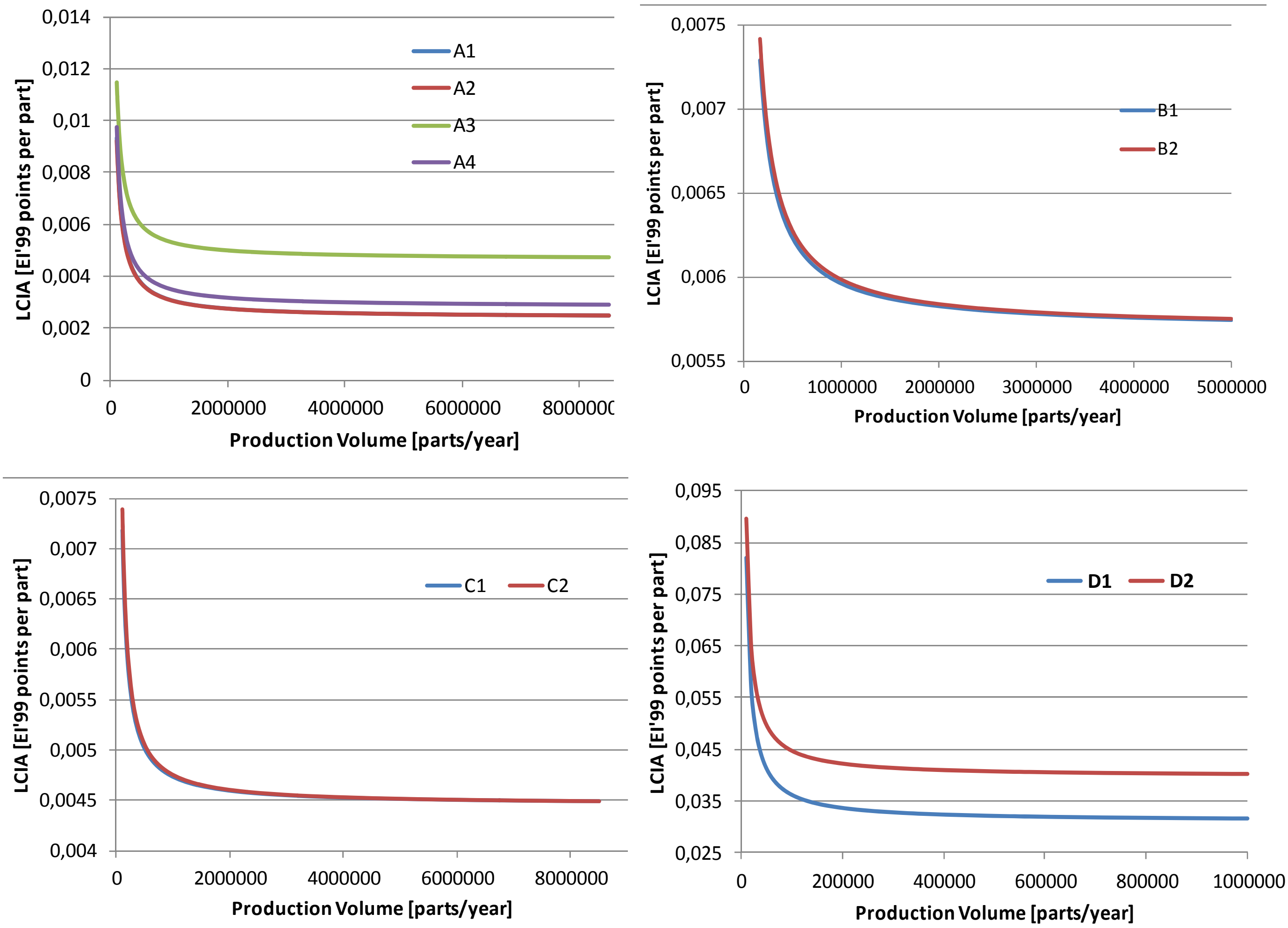


Figure 6.8. Sensitivity analysis to the annual production volume regarding the environmental impact (EI'99 points) of thealternatives in each case study.

6.1.3. Integrated comparison of economic and environmental life cycle performance

Finally, in order to map the best alternatives according to the importance given by the involved stakeholders to the environmental impacts and costs, the results of the integrated comparison proposed in chapter 4 are presented in figure 6.9. Results comprehend the expected production volumes of each part and the alternative mould designs. In this case study the decision maker is the tool maker, being the downstream phases the mould use/part production, part use and EOL. In fact, as the part use entails no costs or environmental impacts and the EOL impacts are also not significant, the aggregated costs for the upstream and downstream phases regard, respectively, the costs to the mould producer and the costs to the part producer.

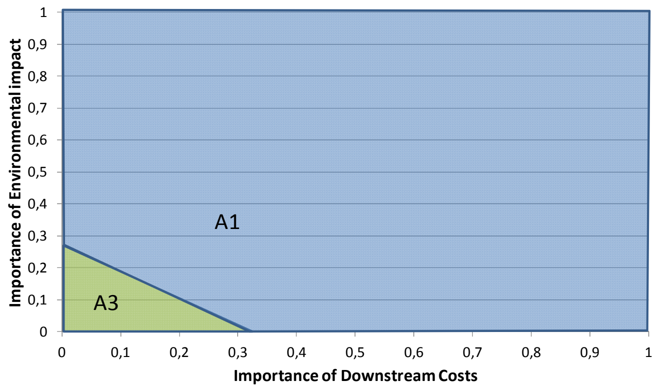
As expected, A1 is the best alternative in this production scenario for a wide area of influence. In fact, A3 can be considered as type C option, cost-based best alternative, to the mould producer, being the alternative with lower mould investment, while A1 is simultaneously a type L, U, B and E option – low total impact, user-based, balanced and environment-based best alternative. This is due to its good performance in material savings, injection moulding process and environmental impact. Only giving less than 0.27 importance to the life cycle environmental impact and less than 0.32 to the part producer A3 becomes the best alternative. Again, notice that this analysis does not consider other production scenarios and the annual production volume is static. Other scenarios would produce other results.

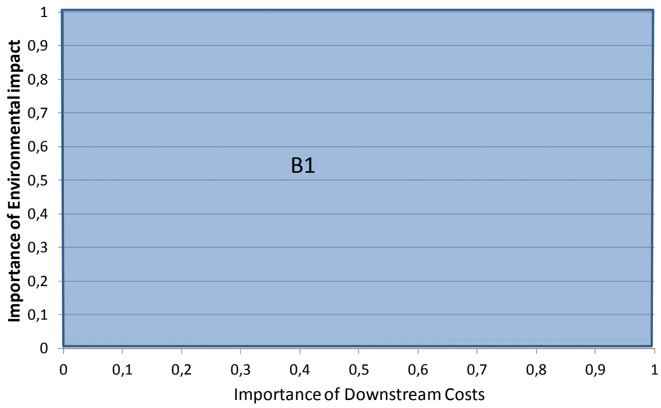
The integrated analysis of case study B showed that, for any importance given to downstream costs and environmental impacts, B1 is always the best alternative. The reason is that for the expected production volume, 250,000 parts per year, the failure costs are not significant and alternative 1 is the best choice in terms of life cycle costs. Environmentally there is no significant difference between the two performances. Therefore, in this production scenario B1 is the only best alternative in the integrated comparison map.

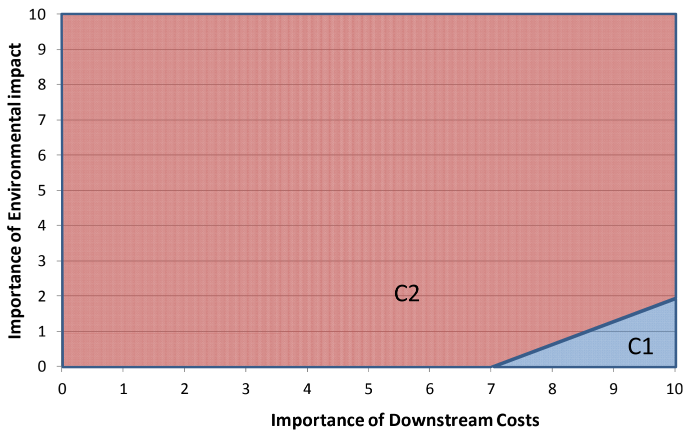
The integrated comparison of the CLC results considering the alternatives C1 and C2 and the expected production volume of 275,000 part per year showed that within the scope of [0;1] for α and β values the same happens as in case study A – the output is only one alternative – C2. However, if the scope of α and β values is widen to the interval [0;10], alternative C1 also appears as a user-based best alternative. This means that only giving much more importance to environmental performance and downstream costs this alternative is considered the best choice. Considering this case study and the very low production volume expected, these results are according with the company's choice. Give the low differences in the mould investment; the decision was to choose the most user-friendly mould – in this case the maintenance-friendly mould. Additionally, it is clear that if higher production volume scenarios are considered the C1 area increases in the integrated comparison map.

Finally in case study D and again considering only the expected production volume, 100,000 parts per year, D1 is the best alternative in this production scenario for a wide area of influences, being D2 a type C, cost-based best alternative to the mould producer

as it is the alternative with lower mould investment. On the other hand, D1 is simultaneously a type L, U, B and E – low total impact, user-based, balanced and environment-based best alternative. This is due to its good performance in the injection moulding phase, saving material and energy when compared with D2.







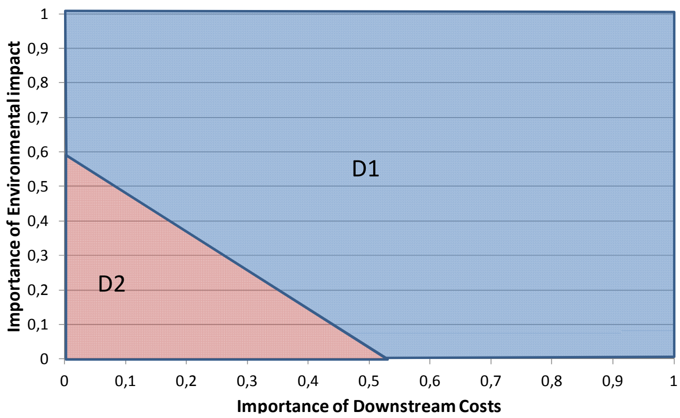


Figure 6.9. – Best-performing mapping of the alternatives

6.2 Case Study 5 - Part Design Alternatives

This section encloses a case study regarding only design decisions in the part design. It was developed in a company already described in chapter 3, FAPIL. The case study was developed in parallel with another thesis [Teixeira 2012] in which the parts were injected in order to characterise the process conditions and specifications. In this case where only the part is under study, the mould life cycle is only affected by part changes. If one part specification is changed, either in material or in geometry, the tool design may be affected besides the tool use/part production phase. For example, if part material changes, it is possible that changes occur in the tool material, cycle time, energy consumption, tool failure probability, among others. As in the previous case studies the life cycle models integrate both life cycles, but in this case the alternatives under study differ in the part design not in the tool design (see Figure 6.9). The aim is to analyse the impacts, both in terms of costs and environment, of the use of Biodegradable Polymers (BDPs) vs. a common fossil based polymer, Polypropylene (PP). The only changing design parameter is the part material, being the mould design frozen, due to the ability of the same mould to inject both types of materials.

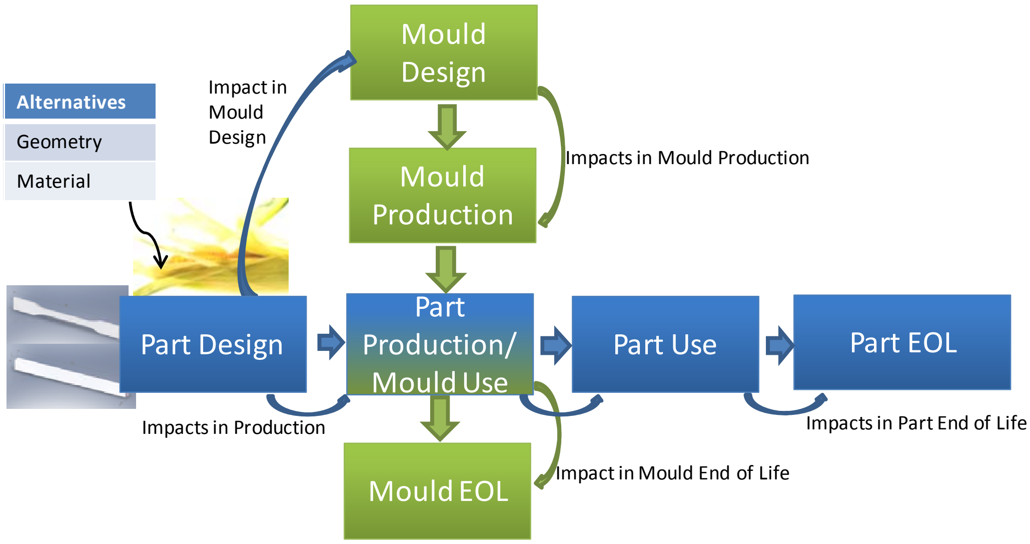


Figure 6.9 – Part design alternatives and the impacts throughout the integrated life cycle

The motivation for this study was the increasing awareness of today's society to the potentially huge environmental accumulation and pollution problem driven by the plastic products. This new context of an environmentally conscious society has fostered the development of new solutions for plastics, with allegedly lower environmental impacts, as BDPs. The development of these materials has been driven by the increasing concern in sustainable development, by the desire to reduce dependence upon finite resources and by changing policies and attitudes in waste management. However, it's crucial to understand the economic and environmental implications of the transition to these "greener" materials, both.

Within the developments in BDP materials, starch (STA) has been seen as a possible substitute for petroleum based polymers as it is both renewable and biodegradable. However, due to its water sensitivity and low mechanical properties, it's not suitable for many plastic products. One solution developed to overcome these limitations was to combine plasticized starch with another BDP, such as Polylactic acid (PLA). Following this research area, this study aims to compare four different types of BDPs with different amounts of STA and PLA, with PP, considering a final product produced by injection moulding. This case study, unlike the previous ones, does not consider a real product, but samples injected in the materials being analysed. The main focus is the material and not the part. However, the CLC framework is applied, considering the

mould and the part life cycle, being the sample considered a plastic part with a defined geometry, the same for all materials (Figure 6.10).

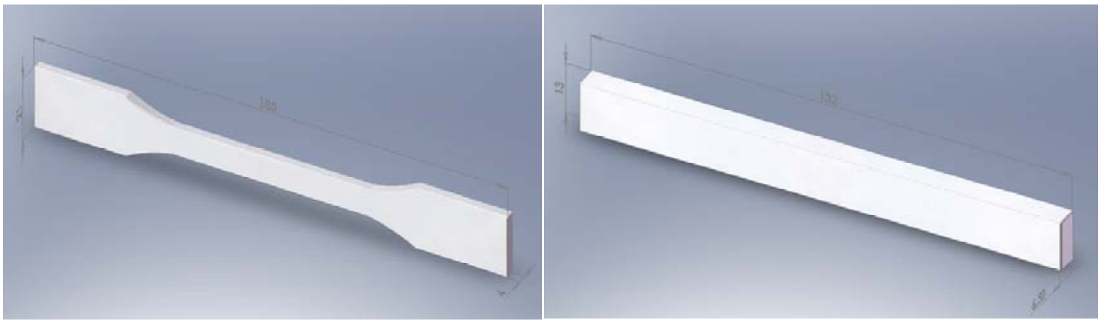


Figure 6.10 – Geometry of the samples to be injected with different materials

The following table 6.13 presents the possible materials analysed, regarding their composition in PLA and starch and the main process specifications particular of each material.

Table 6.13 – Alternative materials specifications regarding composition and process

Material	Manufacturer	Trade name	Composition	Density $[kg/m^3]$	Melting point [°C]
10/90	Cabopol	Biomind C004	10%PLA+90%STA	1200	90
40/60	Rodenburg Biopolymers	40/60anyl 35F	40%PLA+60%STA	1280	140-145
80/20	Cabopol	Biomind R006	80%PLA+20%STA	1250	130
90/10	Biotec	Bioplast GS 2189	90%PLA+10%STA	1300	130
PP	Total Petrochemicals	PPH 9020	-	905	165

6.2.1. Comprehensive Life Cycle Cost

- *Mould Production Cost*

As all polymers were injected using the same mould, it will not introduce any impact in the polymers comparison since. Still, the mould's cost will be reflected on the

material/sample final life cycle cost and for that it becomes important to introduce the mould's variables and its cost distribution (Table 6.14).

Table 6.14 – Mould material and production cost

Material	Steel PI20 (AISI)
Material Density	7850 kg/m3
Material Cost	3 €/kg
Material Quantity	168 kg
Production Cost	3,500 €

- *Part Production/Tool Use Cost*

The injected samples used to test the different polymers in this life cycle approach are present in Figure 6.11. The samples were injected in a Ferromatik Milacron K85D-S/2F machine, with 58 kW of installed power and a clamping force of 85 tons. Table 6.15 presents the main parameters of the injection moulding process of the samples with the same geometry but different materials. Regarding the production scenario, the annual production was set to 200000 units in batches of 25000 units.

Figure 6.11 – Sample injected in different compositions of PLA and starch

Table 6.15 - Main parameters of the injection moulding process of the samples with the same geometry but different materials[Teixeira 2012]

Material Alternatives	Composition	Cycle time [sec/part]	Energy [kWh/part]	Material consumption [g/part]
10/90	10%PLA+ 90%STA	48	0.107	26.676
40/60	40%PLA+ 60%STA	46	0.103	28.454
80/20	80%PLA+ 20%STA	41	0.092	27.788
90/10	90%PLA+ 10%STA	41	0.091	28.899
PP	-	29	0.067	20.118

The injection moulding cost was computed using the general cost relations explained in chapter 4 and the models for the injection moulding process presented in chapters 5. Notice that due to the different type of polymers involved, the cycle time considered was the experimental value [Teixeira 2012]. The cycle time estimated by equations 5.1 and 5.1. uses an expression derived for common fossil based polymers so it is not adequate for the BDPs. Table 6.16 shows that 10/90 is the one that has the most expensive production cost and in opposition to this, the 80/20 presents the lower production cost among the BDPs. It may also be seen that PP presents a much lower production cost. Hence, becomes necessary to understand the contribution of each injection cost categories on the total injection phase cost.

Taking advantage of the computing and parametric analysis of the developed injection moulding process model it is possible to observe that the main cost drivers are material consumption, labour and machine use. Energy costs are low but yet important (between 3.4% and 4.7% of total costs). Despite the lower melting point of BDP materials, promoting the use of low temperatures in the mould, the lower cycle time of PP fosters also lower energetic costs. Labour and equipment costs are directly related with the production time being in this case PP the most economic.

The materials in comparison have different densities, so consequently the amounts of required raw material vary. BDPs with higher concentrations of PLA are more

expensive relatively to those with higher concentration of STA. In particular, 90/10 is the most expensive BDP and 40/60 the cheapest. As it was expectable, PP's cost is much more inferior than BDPs'.

Table 6.16 - Injection moulding phase costs for 200,000 parts per year

	10/90	40/60	80/20	90/10	PP	10/90	40/60	80/20	90/10	PP
Cost Drivers	Cost per year [€]					Percentage [%]				
Labour	7596	7279	6488	6488	4591	14.4	14.5	12.8	12.1	16.2
Energy	2145	2056	1834	1830	1340	4.1	4.1	3.6	3.4	4.7
Material	14427	13407	17761	20721	4797	27.4	26.8	35.1	38.7	16.9
Total Variable	24168	22742	26083	29039	10728	45.9	45.4	51.6	54.2	37.9
Main Machine	27278	26156	23326	23326	16558	51.8	52.2	46.1	43.6	58.4
Mould	780	780	780	780	780	1.5	1.6	1.5	1.5	2.8
Overhead	156	149	133	133	94	0.3	0.3	0.3	0.2	0.3
Building	299	286	255	255	181	0.6	0.6	0.5	0.5	0.6
Maintenance	567	544	487	487	350	1.1	1.1	1.0	0.9	1.2
Total Fixed	28512	27372	24494	24494	17612	54.1	54.6	48.4	45.8	62.1
TOTAL FABRICATION	52680	50114	50577	53533	28340	100.0	100.0	100.0	100.0	100.0

- *Part and Mould EOL*

In this section the impact on costs of two extreme EOL scenarios for the plastic part is assessed:

Scenario 1 is an idealistic scenario of disposal. It assumes that selective collection of Biodegradable Urban Waste (BUW) is available for BDP parts and that PP parts are capable of being mechanically recycled, meaning that the parts are shredded into pellets or granulates and serve as new raw materials. This corresponds to the usual definition for recycling. It also assumes that BDP parts are properly labelled and that population does the separation of domestic wastes.

Scenario 2 is a worst case scenario of disposal. In this scenario none of the materials are selectively collected and all end at the landfill.

The real scenario depends on the country and social context, being between these two scenarios.

The mould EOL was here disregarded due to the fact that the same mould injects all the material choices and as no real product was defined, the mould productive life was unknown. Moreover, the mould revenue can be usually disregarded in injection due to the low present value when compared with the costs incurred throughout the mould life.

Table 6.17 shows the costs associated to the collection and disposal method/treatment used in the three different possibilities of disposal, as well as the profits generated by compost and products of recycling. Notice that the collection costs depend on their type: selective collection of BUW, undifferentiated collection of SUW (Solid Urban Waste) or selective collection of plastics.

Table 6.17 – End-of-Life (EOL) costs for different disposal scenarios

		Cost [€/ton]	Source
Collection	Selective collection of BUW	100	SPV
	Selective collection of plastics (Ecopoints)	110	SPV
	Undifferentiated collection of SUW	45	IRAR
Processes	Municipal composting	50	LIPOR
	Plastics recycling process	300	GrijoTubos S.A.
	Landfill fee	30	IRAR
Recycled products	Compost	90	LIPOR
	Recycled PP	600	Daniel J. Morais S.A.

Known the cost values related with the deposition methods, it's now possible to determine the costs of each EOL Scenario for every polymer in comparison. So for the 200,000 units that are deposited after usage, the collection costs are added to the deposition method costs (municipal composting process, landfill or plastics recycling process) and subtracted to the incomes generated from the recycled products (compost or recycled PP) resulting on the total EOL cost for both scenarios (table 6.18 and 6.19). Notice that the BDPs incur in higher costs in both EOL scenarios.

Table 6. 18- EOL costs in scenario 1 for a prod. volume of 200,000 parts

Costs	10/90	40/60	80/20	90/10	PP
Collection	540.00 €	576.00 €	562.50 €	585.00 €	447.98 €
Deposition method	270.00 €	288.00 €	281.25 €	292.50 €	1,221.75 €
Revenues	486.00 €	518.40 €	506.25 €	526.50 €	2,443.50 €
TOTAL	324.00 €	345.60 €	337.50 €	351.00 €	-773.78 €

Table 6.19 - EOL costs in scenario 2 for a prod. volume of 200,000 parts

Costs	10/90	40/60	80/20	90/10	PP
Collection	243.00 €	259.20 €	253.13 €	263.25 €	183.26 €
Deposition method	162.00 €	172.80 €	168.75 €	175.50 €	122.18 €
Revenues	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
TOTAL	405.00 €	432.00 €	421.88 €	438.75 €	305.44 €

- *Comprehensive Life Cycle Cost Results*

Having all costs computed for all life cycle phases (see Table 6.19), it is possible to assess the total life cycle cost (table 6.20 and table 6.21). Considering the production of 200,000 parts per year and the EOL scenario 1, the best economic choice is clearly the fossil based polymer, PP. The EOL costs are also minor in the overall life cycle cost and even considering the landfill scenario 2 the PP polymer is still the material leading to lower LCC costs.

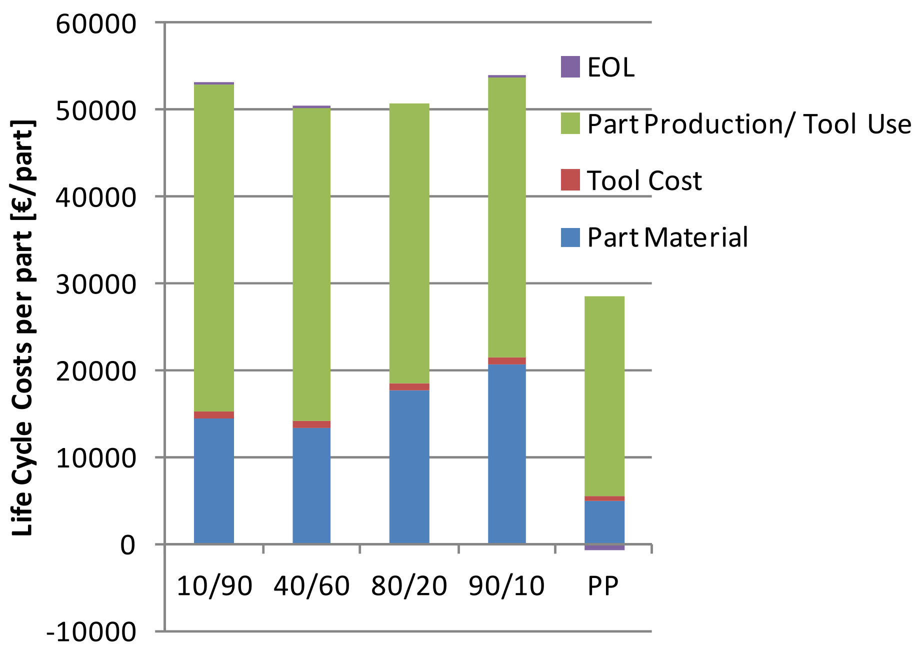


Figure 6.20 – Cost distribution of life cycle phases considering the expected production volumes and EOL scenario 1

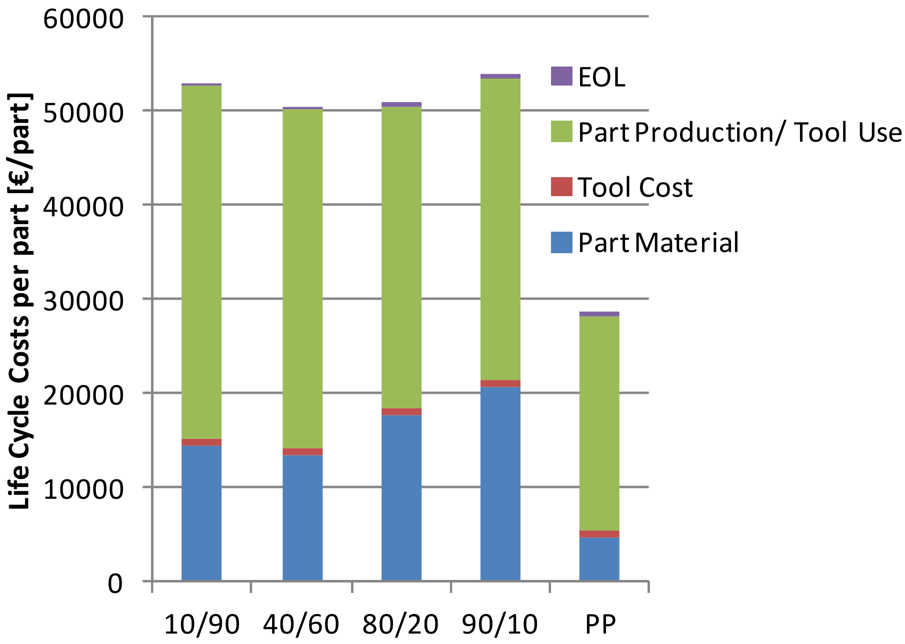


Figure 6.21 – Cost distribution of life cycle phases considering the expected production volumes and EOL scenario 2

Exploring the potential of the process based models developed, is possible to produce several sensitivity analysis. One of these analyses is presented in Figure 6.22, which illustrates the influence of the annual production volume on the cost per part (based on the LCC). For higher annual production volumes the cost per part decreases but the cost hierarchy is not altered, being the PP polymer the best economical choice for all annual production volume scenarios.

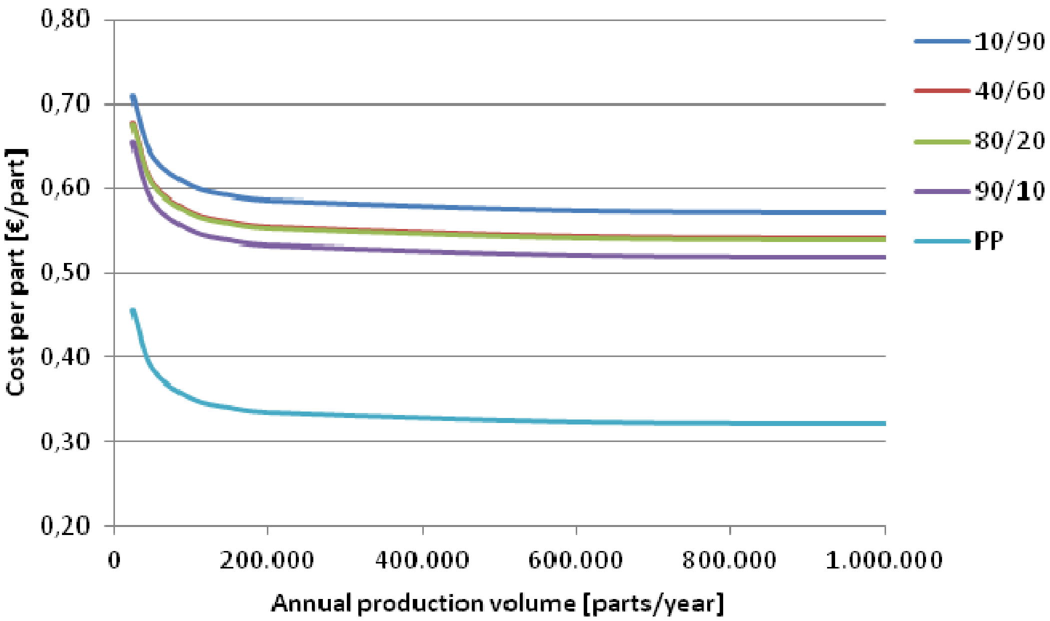


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Figure 6.22 – Integrated Life Cycle Cost regarding different annual production volumes, and EOL scenario 1

6.2.2. Comprehensive Life Cycle Assessment

At this stage, a cradle to grave approach to assess the environmental impacts of the several candidate polymers is performed, using all data previously collected for the injected parts/samples and considering an annual average production of 200,000 parts. As previously explained, the proposed LCA methodology uses the EI'99 method and Simapró databases. Following are presented the LCA stages, from LCI to LCIA of the present case study.

The boundaries of the LCA analysis have been defined in chapter 5, and can be applied to this case study. The part use stage was disregarded due to the lack of a real product in this case study. Again, the development of process-based models simplifies the assessment of all inputs and outputs of environmental impact drivers involved in the process. Having defined the amount of materials and energy required for each process of the integrated life cycle.

- *Inventory Analysis and Impact Assessment*

The main consumptions at each life cycle stages for the production of 200,000 parts is presented in Table 6.20. PP material option is the one that consumes less material and less energy. Among the BDPs, 10/90 option requires less energy to inject and less material consumption and 90/10 requires the most. The table also refers the amount of material sent to waste treatment. For the BDPs case, both the EOL of the injected parts and the engineering wastes from the injection process are treated, as for PP's case only the EoL of the injected parts are treated, since the injection wastes are shredded and re-enter in the injection process.

Table 6.20 - Consumptions over materials' life cycle stages(200,000 parts/samples)

Life Cycle Stages	Consumptions	10/90	40/60	80/20	90/10	PP
Mould material production	Material [ton]	0.168				
Mould manufacturing	Energy [kJ]	0.273				
Injection materials production	Material input [ton]	5.465	5.829	5.693	5.920	4.121
	PLA [ton]	0.546	2.332	4.554	5.328	-
	STA [ton]	4.918	3.497	1.139	0.592	-
Injection moulding	Energy [Mj]	77220	74027	66010	65885	48255
EOL	Material [ton]	5.465	5.829	5.693	5.920	4.073

Unitary impacts of material, energy, transport and waste treatment, were retrieved by Simapro7.2 software and are indicated in Table 6.21. These values are used in the LCIA analysis in order to obtain the impacts for the entire production volume of each polymer.

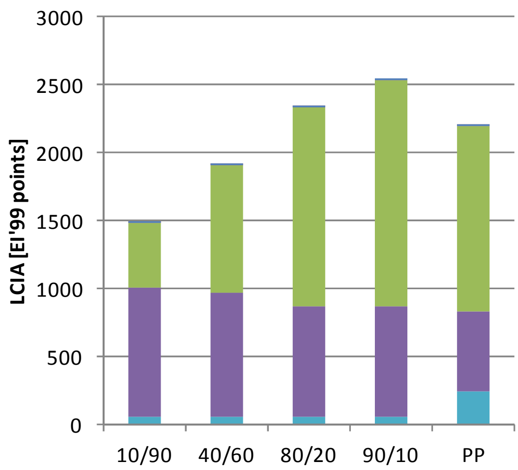
Table 6.21 - EI'99 unitary impact values

Impact driver	Material	EI'99 [pts/kg]	Energy	EI'99 [pts/Mj]
Mould Material Production	H13 Steel	0.551 0.181	-	0.0136
Part Material Production	PLA	0.3060	-	
	STA	0.0629	-	
	PP	0.3300	-	
Mould Production	Dielectric Fluid Cutting Fluid	0.250 0.207	Portugal	

Part Production	-	-	Portugal
Mould EOL Recycling	Steel P20	-0.070	Portugal
Part EOL Scenario 1/ Scenario 2	PLA STA	0.0046/0.0104	
	PP	-0.210/0.060	

With the results of the life cycle inventory, the overall life cycle impact of the 200,000 parts of each polymer type was calculated. Starting from the mould's material production and finishing at the parts end of life, the LCIA was computed for both EOL scenarios considered. Figures 6.23 a) and b) show the life cycle impacts, translated in EI'99 points, considering scenarios 1 and 2 correspondingly. Results show that injection material is the main environmental impact driver in the overall life cycle. Considering scenario 1, if all BDP parts are composted and all PP parts recycled, the material with lower impact is the BDP containing higher amount of starch (90%), being possible to notice an increase of the environmental impacts with a decrease of starch in the BDPs composition. This is due to the higher impact of PLA resulting from the higher energy and process materials for the fermentation and condensation processes to obtain PLA. PP polymer also presents low impacts if a full recycle scenario is considered. However, in scenario 2 PP polymer presents high impacts when compared with starch based BDPs. In fact, the increase of starch in the polymers composition is again the main environmental impact driver.

a)



b)

■ Mould material ■ Mould manufacturing ■ Injection materials ■ Injection moulding ■ End of Life

Figure 6.23 – Environmental impact of each alternative and an annual production volume of 200000 parts considering a) EOL scenario 1and b) EOL scenario 2

Finally, the extended analysis to other production scenarios regarding the production volume brings no further information, being the hierarchy of environmental performance of the several materials the same despite the produced units.

6.2.3. Integrated comparison of economic and environmental life cycle performance

An integrating comparison of the economic and environmental life cycle performance can then be made for both EOL scenarios following the same procedure as in the previous case studies. The part producer was considered as the user and the tool maker as the producer. . In scenario 1, as PP is economically and environmentally the best choice, it is the best choice for all sets of α and β values (weights given to the costs of downstream phases and β to the environmental impacts of the integrated life cycle, correspondingly). Regarding scenario 2, the 10/90 BPD appears as a type E choice - environmental-based best alternative within the scope of [0;1] for α and β values. This is due mainly to the lower environmental performance of PP in this scenario.

It is also important to comment on the work in progress regarding this study, being at this point developed new analyses with real products, optimizing the cycle time of the biopolymers and achieving different results. This case study is still on a testing phase at the time, but is still relevant to show the approach proposed and possible analysis and outputs from the models developed, along with the most important points to consider when dealing with only part design alternatives.

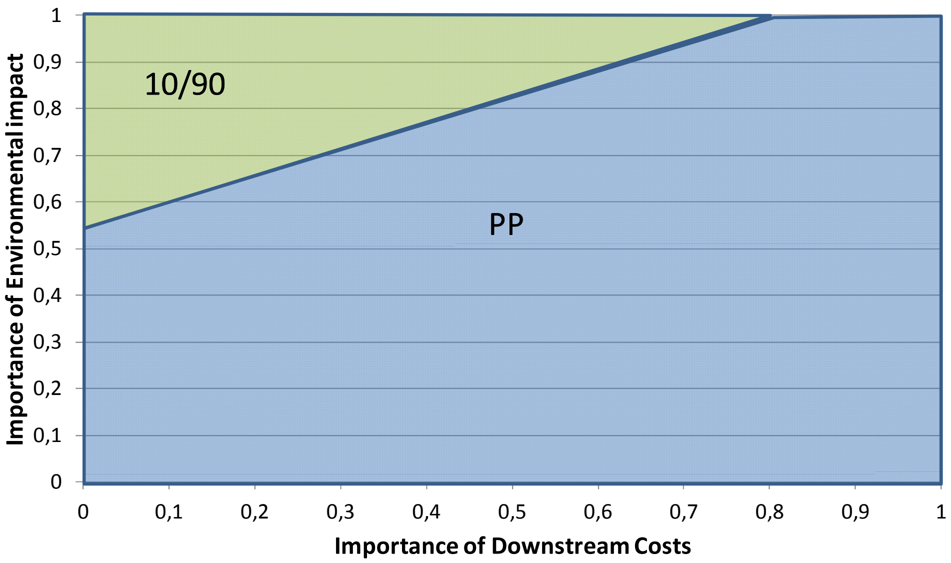


Figure 6.24 - Best-performing mapping of the alternatives – Scenario 2

6.3 Case Study 6 - Tool and Part Design Alternatives – Cloth Pegs

This section approaches a case study regarding design decision both in part and tool design. Figure 6.25 shows the interactions between both life cycles and the impacts of the design alternatives in the integrated life cycle. The part design influences the subsequent part life cycle, being the part production stage common to the tool life cycle. Additionally, part design affects mould production, as the mould is a dedicated tool with the negative geometry of the part and even part material changes may affect the mould design. By adding also mould design alternatives, another chain of impacts is included. Mould alternatives have impacts throughout the mould life cycle, being the part production/tool use phase subject to impacts from mould design and part design. Following the case study (based on a simple product - a cloths peg) is described illustrating the application of the CLC framework to an integrated life cycle where both the part and the mould are subject to design changes.

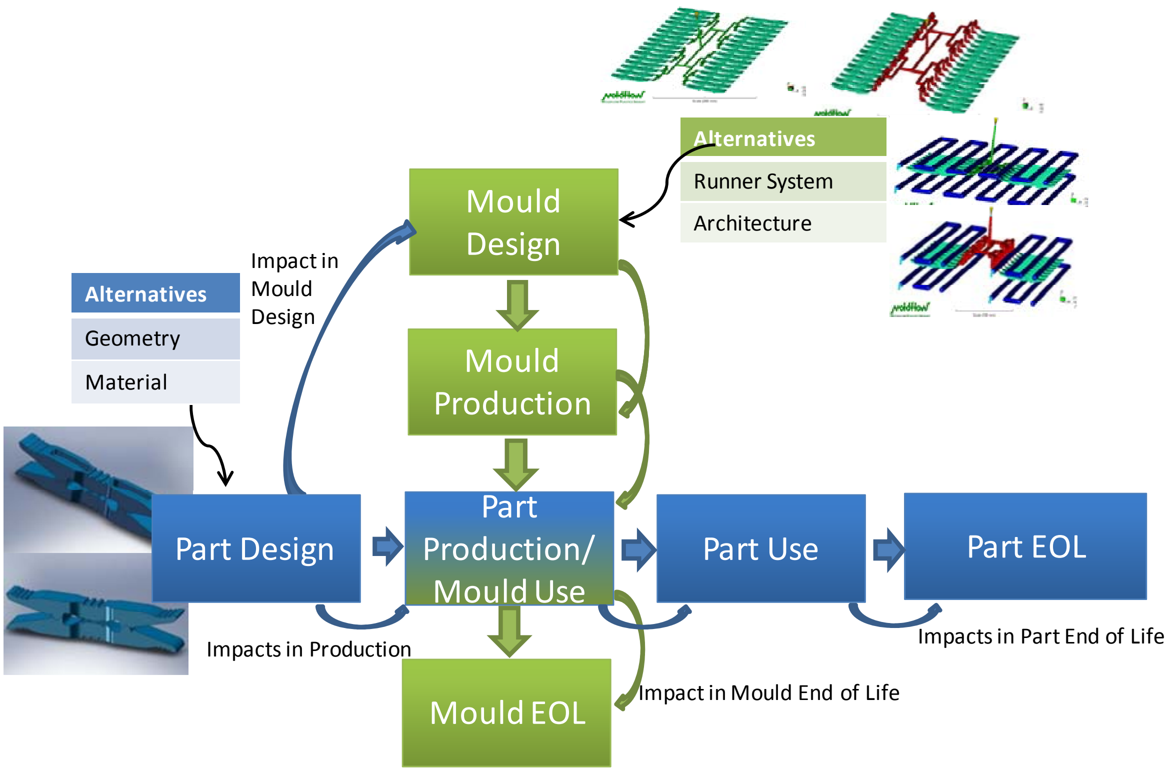
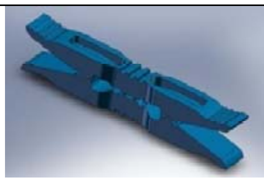
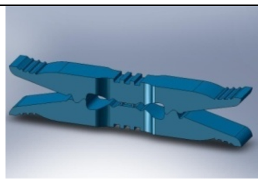


Fig 6.25 - Part and tool design alternatives – Impacts in the integrated life cycle

Regarding the part design, two design concepts were chosen to be studied and compared (see table 6.22). Design concept 1 (DC1) involves a significant reduction on the part volume (amount of material), with a slight reduction on the clamping force to hold the

cloths. Design concept 2 (DC2) is a compromise amid material reduction and clamping force. It must be noticed that using the same material of the current cloths peg, both DC 1 and DC 2 fulfil the technical requirements determined in the product specifications. Both design concepts are made of a polypropylene homopolymer (HMU 216).

Table 6.22 – Part design alternative concepts

Design Concept	Geometry	Material	Mass per part [g/part]
DC1		Polypropylene (PP)	3.00
DC2			3.26

Regarding the tool alternatives, two types of moulds were considered differentiated by their feeding system: mould with cold-runners and mould with hot-runners. The former are less expensive and easier to manufacture; the later allow lower cycle times and lower labour input after injection moulding.

Beside the type of mould, the number of cavities was also allowed to differ between 16, 32 and 96 cavities per mould. The number of cloths pegs (2 body parts per peg) obtained in each injection cycle is half of the number of cavities (parts). Figure 6.26 illustrates the feeding channels for the runner alternative systems regarding the 32 cavities per mould.

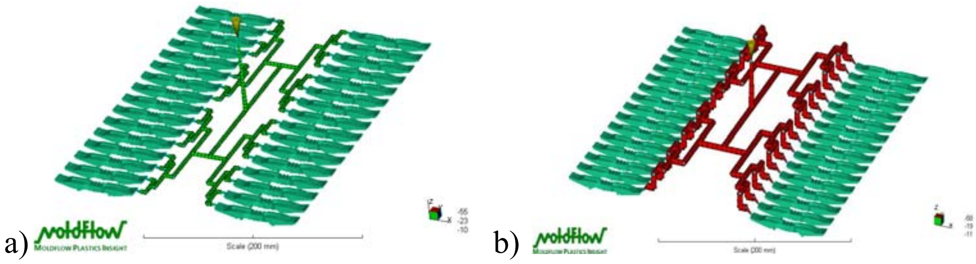


Fig.6.26 – Feeding channels designed for the a) 32 cavities / Cold runners / DC 1

and b) 32 cavities / Hot-runners / DC 1.

6.3.1 Comprehensive Life Cycle Cost

- *Tool Production Cost*

From the above, the number of mould design alternatives is then 6 for each part design solution, making 12 alternatives in total. The mould production cost depends mainly on the number of cavities and the runners system (the need for a manifold and sprues or valves for hot-runners, the number of cavities to be machined and the amount of steel and standard components comprehend the main cost drivers for differences among mould alternatives). However, there are also some cost differences between the two part designs. The moulding cavity for DC1 part that allows saving material requires an additional machined feature. Table 6.23 presents the mould production costs of each set of alternative part and mould designs.

Table 6.23 – Mould production cost of each set of alternative designs

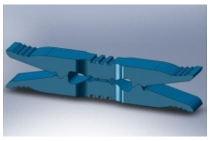
Mould type	Designation	DC 1 Mould Cost[€]	DC 2 Mould Cost [€]	Mould Volume [m^3]
16 cavities, hot runners	16H	18000	17500	0.035
16 cavities, cold runners	16C	10000	9500	0.035
32 cavities, hot runners	32H	31000	30250	0.070
32 cavities, cold runners	32C	15000	14250	0.070
96 cavities, hot runners	96H	65000	63000	0.210
96 cavities, cold runners	96C	40000	38000	0.210

- *Part Production/Mould Use Cost*

Specific process models were developed to this case study, allowing analysing the production costs of the part and accommodating the tool and part design alternatives. Regarding the part material cost, DC1 requests less plastic material and the use of hot-runners reduces the consumption of plastic material per cycle. Additionally, in the cold

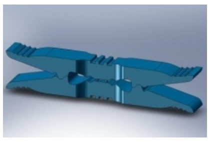
runners moulds the increase of the mould size causes the need for more channels and longer feedings, so the plastic mass required is higher. Table 6.24 presents the material consumption per cycle and the unit cost of the material for each set of part and mould design alternatives. The material consumption is in this case not only dependent on the runner system and part geometry, but also on the limit of recycled material in the injection process (in this particular case, 10%). As expectable, the DC1 with hot-runners is the most efficient option in terms of material consumption. Considering that there are no runners generated in all the hot-runner moulds, the number of cavities does not influence material consumption.

Table 6.24 – Part material consumption and material unit cost of each set of alternative designs

Design Concept	Mould type - Designation	Consumption [g/cycle]	Mass/part [g/part]	Unitary cost [€/kg]
Design Concept 1 DC 1 	16H	47.9	3.00	4.14
	16C	56.4	3.53	
	32H	95.9	3.00	
	32C	114.4	3.57	
	96H	287.6	3.00	
	96C	414.0	4.31	
Design Concept 2 DC 2 	16H	52.1	3.26	
	16C	60.6	3.79	
	32H	104.3	3.26	
	32C	122.9	3.84	
	96H	312.8	3.26	
	96C	439.3	4.58	

Cycle time is a main aspect to assess when computing costs of a process, as it influences all cost drivers except tooling and material consumption. In this case, depending on the part design and on the mould type, different cycle time can be achieved. Table 6.25 shows that DC1 permits a lower cycle time, which was obtained with Moldflow® software. When compared with cold runners, the use of hot-runners reduces also the cycle time and as the number of cavities increases the cycle time per part naturally reduces.

Table 6.25 – Cycle time estimated for each set of part and tool design.

	Reference	Cycle Time (s)	Cycle Time/part (s/part)
Design Concept 1 DC 1 	16H-DC1	16.3	1.019
	16C-DC1	20.9	1.306
	32H-DC1	17.1	0.534
	32C-DC1	22.8	0.713
	96H-DC1	19.5	0.203
	96C-DC1	25.4	0.265
Design Concept 2 DC 2 	16H-DC2	27.9	1.744
	16C-DC2	31.5	1.969
	32H-DC2	29.0	0.906
	32C-DC2	35.4	1.106
	96H-DC2	34.5	0.359
	96C-DC2	38.0	0.396

The analysis of the total injection moulding costs shows that the mould cost has an inverse trend with mould productivity (cycle time/part and mass/part), as hot-runners and a large number of cavities endorse the increase of the mould cost.

For a further understanding it is interesting to look at the cost parcels of the injection moulding phase for the production volume of 4 MPegs (Table 6.26). There is a trend for the higher mould cost to be balanced with a lower value of the other injection moulding cost parcels (material, labour, equipments, and energy). As observed in table 6.26, the alternatives with lower injection moulding cost are the ones involving moulds with a larger number of cavities and hot-runners. These two characteristics contribute for the mould higher productivity due to the lower number of injections cycles and lower cycle time (process time reduction with impact on associated time driven costs). Additionally, the use of hot-runner eliminates the need of post-injection operations related with the removing of feeding channels and the running of materials for recycling. So, it can be said that the lower cycle time of DC1 alternatives together with the lower cycle time per part of the moulds with a large number of cavities contribute for the low injection moulding costs of those alternatives. It is also important to notice that these results comprehend only the expected production volume, being the models developed able to accommodate all the variances in the part and tool design. Furthermore, as the further

analysis will show, it is also simple to compute the same results for a wider set of production scenarios.

Table 6.26 – Cost parcels of injection moulding for 4 Mpegs.

	16H-DC1	16C-DC1	32H-DC1	32C-DC1	96H-DC1	96C-DC1	16H-DC2	16C-DC2	32H-DC2	32C-DC2	96H-DC2	96C-DC2
Cost Drivers	Cost per year [€]											
Labour	685	874	365	483	146	187	1163	1312	610	742	249	273
Energy	312	398	166	220	67	85	530	597	278	338	113	125
Material	49527	58324	49527	59082	49529	71292	53857	62625	53862	63515	53861	75648
Total Variable	50524	59597	50058	59784	49742	71564	55550	64534	54750	64595	54223	76046
Main Machine	37478	48150	19670	26262	7499	9755	64197	72524	33387	40715	13395	14585
Mould	5926	3292	6240	3020	13085	8052	5762	3128	6089	2869	12682	7650
Overhead	68	87	36	48	15	19	116	131	61	74	25	27
Building	130	166	69	92	28	36	221	249	116	141	47	52
Maintenance	871	1032	520	587	412	357	1404	1518	792	874	522	446
Total Fixed	44473	52728	26536	30009	21039	18218	71700	77551	40445	44673	26672	22760
TOTAL FABRICATION	94997	112325	76594	89793	70780	89782	127250	142085	95196	109268	80895	98806

- *Mould and Part EOL Costs*

The mould and part EOL costs are also computed through the process models. However, in this case they are not relevant when compared with the injection costs. Considering landfill as the EOL scenario for the cloths pegs, the cost in the end of the use phase for each part is $2.2*10^{-4}$€/part for the DC1 and $2.4*10^{-4}$€/part for DC2. Considering the years of the product use, the present value of this cost, will be even lower.

Regarding the mould, the steel can be sold after 8 years, the life considered for the part. Table 6.27 presents the future and present values of the profit from the EOL of the mould for the different mould sizes (depending on the amount of cavities). In terms of a present decision, the present value of the revenue from the mould EOL is very low compared with the production cost.

Table 6.27 – Mould EOL Profit of each alternative regarding the number of cavities

Mould Type	Mould profit in EOL (Future Value)[€]	Mould Profit Present Value [€]
16C	-1325,11	-288,38
32C	-1987,67	-432,58
96C	-4472,26	-973,29

- Comprehensive Life Cycle Cost Results

Finally, with all costs computed following the proposed comprehensive life cycle methodology, the life cycle cost of the integrated life cycle was computed using the developed models for injection moulding. It should be noted that the use phase of the cloths peg was considered similar for all the alternative concepts under analysis and so it was not included for comparative purposes.

The results illustrated in Figure 6.26 evidence that DC1 based alternatives tend to exhibit a lower life cycle cost. The main reason is associated with lower injection moulding costs that are a consequence of the lower cycle time required for the DC1 alternatives. The importance of the injection moulding costs, for this production volume, is also revealed by the lower total costs driven by the alternative moulds with higher number of cavities (32 and 96). In fact, for the expected production volume of 4 million cloth pegs, the alternative with lower injection costs is the DC1 using the more expensive mould (96 cavities and hot-runners).

The consumption of material constitutes an important percentage of the total LCC. However, its variability is not as high as the other cost factors. The main differences in material consumption are observed between the hot and cold runners alternative moulds. Since the cold runners moulds consume (waste) more plastic material per cycle their use cost becomes higher than the hot-runners ones. Once again, for this production volume, the influence of the mould cost determines that alternatives with hot-runners (more expensive moulds) have always a higher LCC than the ones with cold runners.

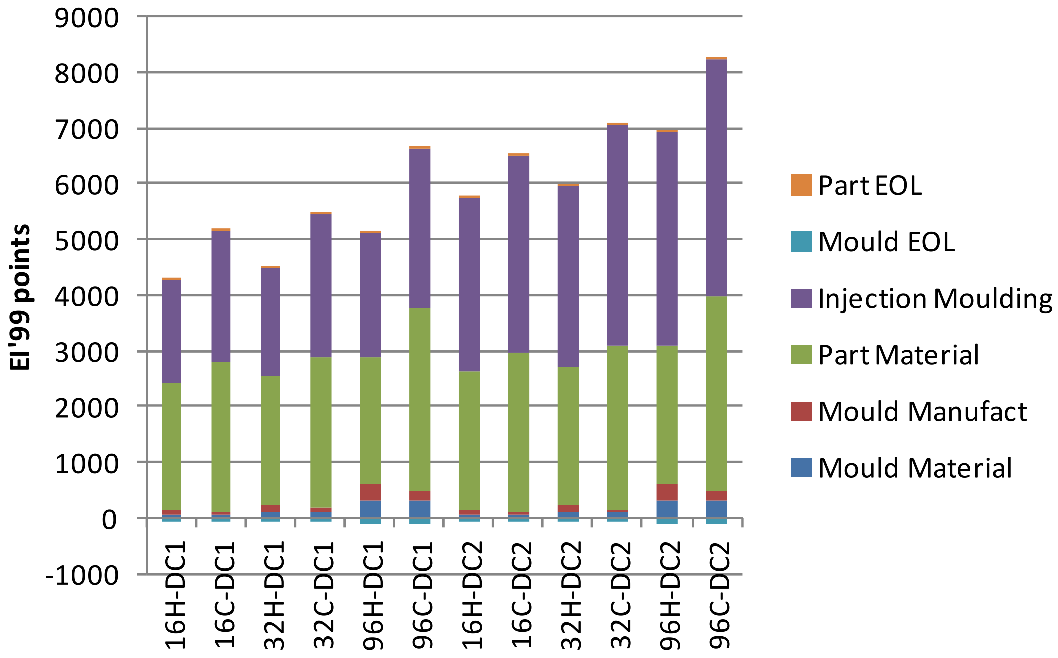


Fig.6.26 – Life Cycle Cost of the Design Concepts/Process alternatives for 4 Mpegs.

The influence of the production volume on the total LCC for the diferent alternatives can be assessed (figure 6.27) For the sake of interpretation only the alternatives with the lowest LCC for each production volume are represented. For high production volumes (more than 3.48 MPegs) the DC1 injected in 96 cavities moulds with hot-runners achieves the lower cost. It means that the lower cycle times allow lower injection moulding costs that together with lower material consumption (DC type and hot-runners) compensates the higher cost of the mould, which does not vary on the analyzed range of production volumes. For extremely low production volumes, until around 40.5 kPegs, the DC2 injected in 16 cavities moulds with cold-runners alternative is the best one, due mainly to the increasing importance of the mould cost. It should be remarked that the higher quantity of required material and mainly the higher injection costs (cycle time) of the DC2 type alternatives represent a drawback for this Design Concept when compared to the DC1 geometry. In that situation, the mould productivity largely reduces its impact and the LCC of the cloths peg becomes essentially driven by the mould cost. The other 3 alternatives appear as best choices for intermediate production volumes between these two extremes.

This analysis was, as explained, easily outputted from the developed models in chapter 5. Furthermore, other analyses could be performed if relevant to the case study regarding other productive scenarios, namely shifts, machine types, batches, etc.

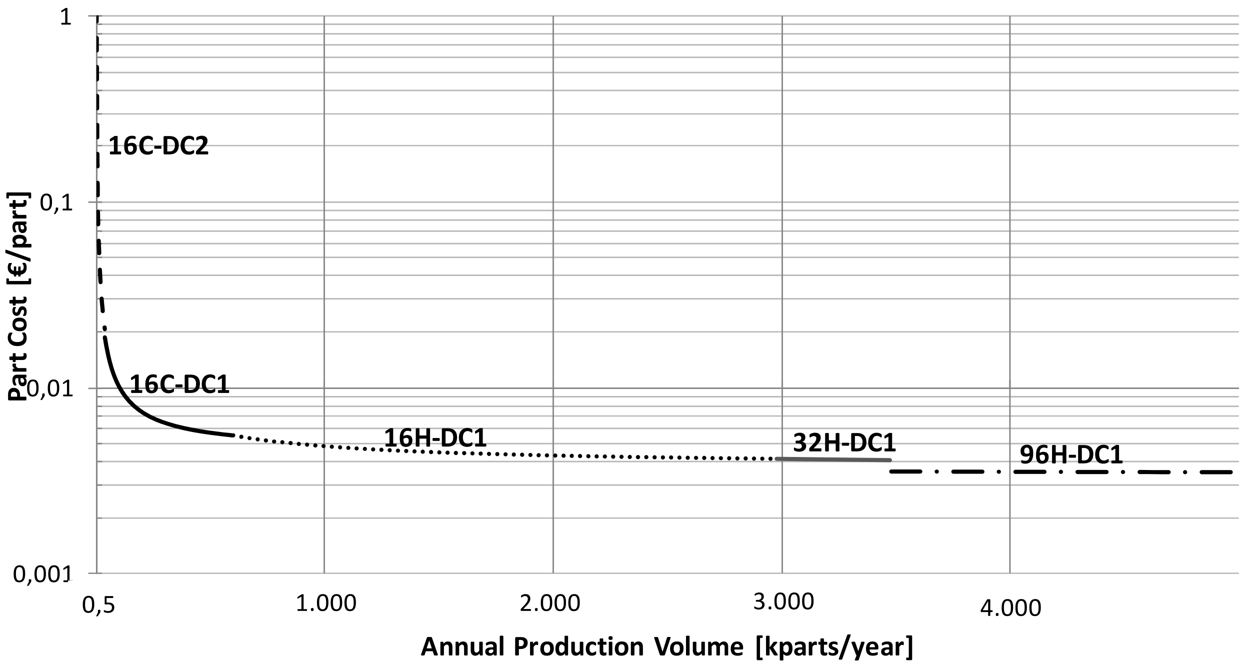


Fig.6.27 – Best (lowest LCC) alternatives for different production volumes.

6.3.2 Comprehensive Life Cycle Assessment

Following the proposed methodology, the environmental performance of the different alternatives was also evaluated, using all data previously collected and estimated for the product and mould specific conditions.

The analysed system was already described in the life cycle cost analysis and it refers to the processes involved in all the life cycle stages of the clothes pegs. In order to maintain coherence in the whole methodology, the functional unit is the same used in the LCC analysis and is the annual cloths pegs foreseen production, 4Mpegs.

Regarding the boundaries, the same boundaries defined in section 5 were considered. The use phase of the cloths peg was disregarded since it is neither responsible for significant impacts nor for significant differences among the alternatives. Regarding the materials impact all the stages of the plastic material from the raw materials extraction to the plastic production were considered. The injection moulding and the mould production were analysed separately, as more accurate and parcelled results can be obtained. Finally, the end of life of the plastic parts, were divided in two main streams: the used cloths pegs were considered to be deposited in landfill; the plastic material

required for the injection process but not included in the product (engineering waste) was considered to be recycled, in the company or by any recycling framework. The environmental streams of the clothes peg life cycle were weighed using EI'99 method permitting to compute the life cycle environmental impact.

- *Inventory Analysis and Impact Assessment*

Similarly to the previous case studies, the models developed for the cost analysis previously presented was used with the required adjustments to the LCA analysis to compute all the streams with an environmentally burden aspect.. The impact assessment of each stream was computed using the software SimaPró databases (see table 6.28).

Table 6.28 - Types of environmental impact drivers involved in the life cycle phases

Impact driver	Material	EI'99 [pts/kg]	Energy	EI'99 [pts/Mj]
Mould Material Production	H13 Steel	0.551 0.181	-	
Part Material Production	PP	0.380	-	
Mould Production	Dielectric Fluid Cutting Fluid	0.250 0.207	Portugal	
Part Production	-	-	Portugal	
Mould EOL Recycling	High Strength Steel Mild Steel	-0.070	Portugal	0.0136
Part EOL Landfill	PP	0,004/-0,294	-	

Figure 6.28 presents the environmental impact of the integrated life cycle for 4 Mpegs for the different alternatives under analysis. The first conclusion is the extremely reduced environmental impact of the mould. The plastic material has the major slice of impact, followed by the energy consumed during the injection moulding process. However, in the mould alternatives with higher number of cavities, the energy consumption represents a smaller part. The alternatives with lower performance are the ones that use cold runners, due to the extra material required for the feeding channels and the limit of 10% of recycled material in the injection process. When comparing the alternatives, the ones with lower cycle time per part (moulds with high number of cavities and hot-runners) have a lower environmental impact regarding energy

consumption in the part production phase. However, the higher impact of the mould production leads to higher life cycle impacts compared with the moulds with fewer cavities. Additionally, for the same type of runners and number of cavities the DC2 based alternatives result in a lower environmental performance. Unlike the economic analysis, the alternative with the best environmental performance considering the expected production scenario is the design concept 1 using the hot-runner mould with 32 cavities.

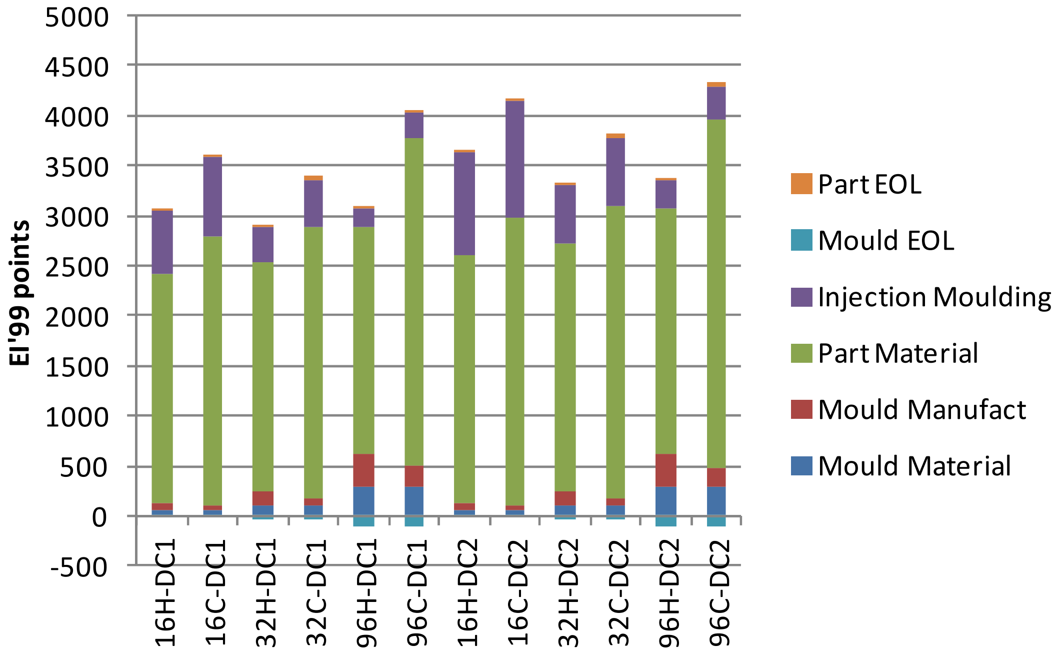


Fig.28 – Life Cycle Impact of the Design Concept/Process alternatives for 4 Mpegs.

Taking advantage of the model potential, it is important to understand the behaviour of the alternatives with different production volumes. The outputs of the sensitivity analysis to the production volume are illustrated in figure 6.29. The 32H-DC1 alternative has the lowest environmental impact for production volumes higher than 300.5 kPegs. In a scenario with extremely low production volumes, less than 25.5 kPegs, the best environmental alternative is 16C-DC2 due to the lower mould production impact. Between these two extremes the best alternative is 16C-DC1. Furthermore, out of the chart scope, for extremely high production volume scenarios (above 12.5MPegs produced per year) the best choice would be the DC1 using a mould

with 96 cavities and hot-runners due to the lower energy consumption and lower importance of the mould production impact.

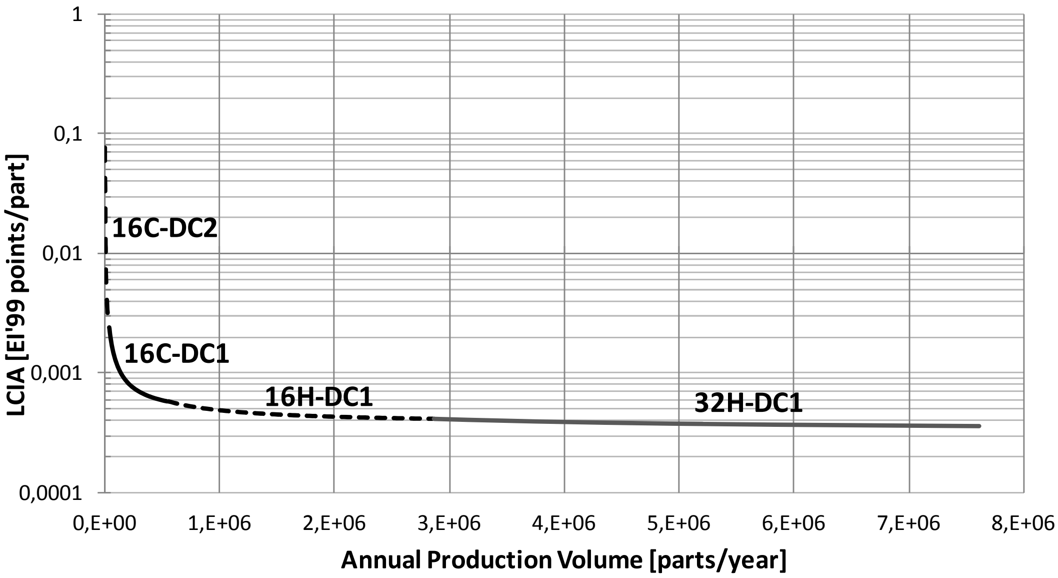


Fig.29 – Best (lowest environmental impacts) alternatives for different production volumes.

6.3.3. Integrated comparison of economic and environmental life cycle performance

The last step of this methodology supporting design decisions is to map the best alternatives according to the importance given both to the stakeholders involved (part production and EOL) and to the environmental impacts. Results of the integrated comparison are presented in figure 6.30 and consider the expected production volume of 4,000,000 pegs per year. In this case 4 domain areas for 5 alternatives appear as best alternatives, being the mould with higher production cost within the type U (user-based) category. The mould with 32H-DC1 alternative is a more balanced user-based category, as it also shares the low impact domain (category L) with the 16H-DC1 alternative. The last is also an environmentally based and balanced best alternative (categories B and E). This is due to the energy and material savings during part production with this alternative, along with a moderate mould production cost. Moving to the category C, cost based ones, two alternatives share this domain, both using the lower cost moulds. In the extreme of this category is the mould with 16 cavities and cold runners using part design concept 2 (16C-DC2). This is the alternative with the lower tool production cost

and higher material consumption due to the part design when compared with the same mould type (16 cavities and cold runners), but using the design concept optimizing part material consumption (DC1). However, this last one requires higher mould production cost and therefore is between the cost-based and environmental-based domains. It is also important to remind that for lower production volume scenarios the results would be different, namely with new best alternatives in the comparison map and the decrease of 96H-DC1 domain.

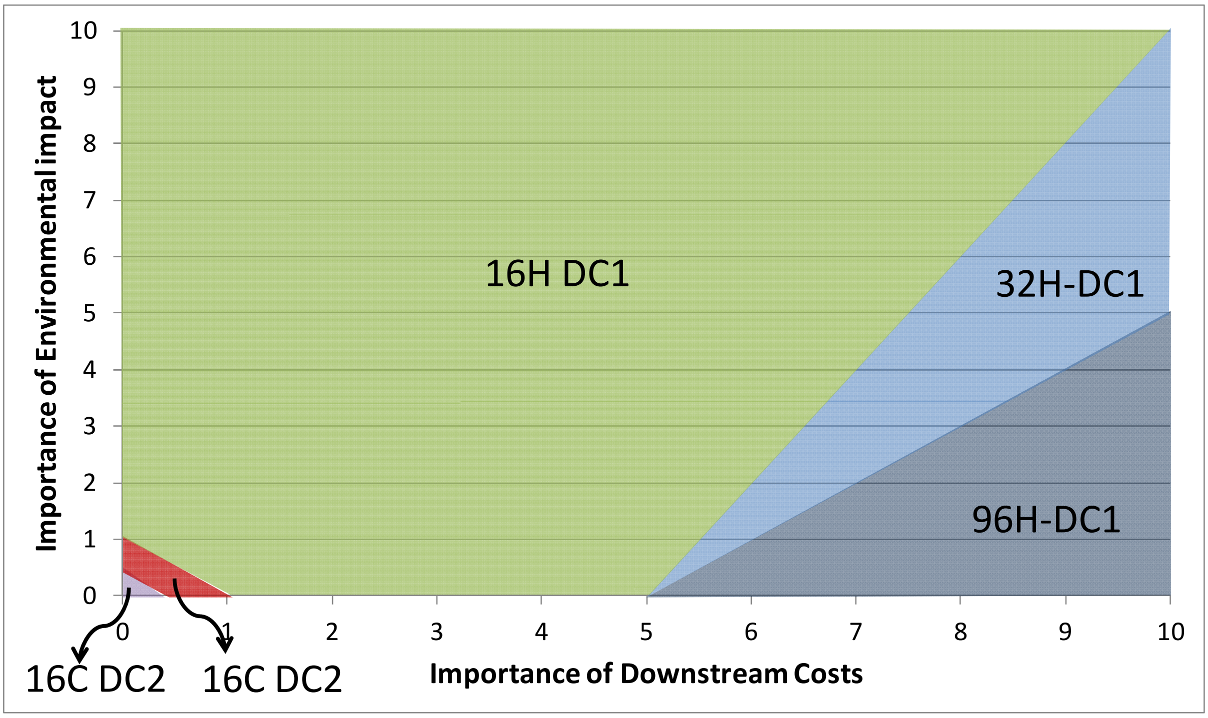


Figure 6.30. – Best-performing mapping of the alternatives

6.4 Discussion

In this chapter three types of case studies were developed following the comprehensive life cycle framework, within the scope of injection moulding parts and correspondent moulds.

The first type of case studies (section 6.1) only regarded analyses where several design alternatives of the tool (in this case an injection mould) were available keeping the part design frozen. Being the tool design alternatives the subject of the decision making, the tool design production and further impacts driven by the alternatives throughout the integrated life cycle were the primary focus of the analysis. This led to the need of exploring the mould probability of failure by gathering Weibull parameters for the critical mould elements sensitive to failure in each alternative design and computing the expected cost of failure for each alternative into the tooling use cost. The relevance of the proposed framework was illustrated by analysing the impact of the mould design alternatives in the part life cycle cost (part use phase was disregarded as being not affected). Results have shown that only considering mould maintenance and mould failure the most expensive mould alternative is identified as the best choice as regards the lower part cost. This is acknowledged by tooling making companies but not quantifiable in current decision making processes. In all case studies the end-of-life cost was negligible due to the low impact of both part and mould EOL costs in the overall life cycle cost.

The proposed methodology does not aim to translate into a model the current design decisions, but to go further in capturing the most relevant impacts of these design decisions, even if disregarded in the industrial current contexts. Therefore, despite the importance given to the environmental impact in nowadays design decisions by mould producers and users, LCA analysis was also included and the environmental impacts throughout the integrated life cycle computed for each alternative design. Results have shown that plastic material consumption is the major environmental driver in the life cycle of plastic injection moulds and injection moulded parts, being the moulds with hot-runners always the choice leading to lower environmental burdens.

Moreover, results have shown that these analyses are especially useful when dealing with new technologies and tool features, as the modelling of the process allows

estimating their future costs and other impacts without major investments. Hence, the proposed CLC framework can be used to support more informed decisions in the tool design phase, prior to the injection moulding phase. This aim fostered the need to gather the CLC results into a single decision framework, overcoming two critical aspects in analysing the outputs of the life cycle costs and environmental aspects – the importance given to each dimension and the fact that costs throughout the part and tool lie cycle are not supported by the same stakeholders. Integrated comparison of economic and environmental life cycle performance allowed mapping the best alternatives according to the importance given to the different producers and users stakeholders, , together with the importance given to the environmental impacts. Results have shown that generally hot-runners are the best options when the decision is based both on the best mould performance during injection moulding and on optimizing the environmental impacts. On the other hand low cost moulds, namely with cold-runners, are cost-based best alternatives for the mould producers.

Regarding the second type of case studies, presented in section 6.2, only the part design was considered, being the mould design kept static. This analysis comprised the use of several PLA-based BDPs and a common fossil based polymer, PP. Being the part a generic sample and nor a real product, the focus was given only to the impacts of the part material selection throughout the integrated life cycle. Moreover, being the EOL possible scenarios changing with the type of polymer used, this aspect was further explored when compared with the case studies presented in 6.1, were the only part EOL scenario was landfill. Results have outlined the importance of material selection in both economic and environmental performance throughout the part and mould life cycle, leading to significant differences in all phases, from part material production to EOL. Moving from the controversial issue of real EOL scenarios and analysing the extreme ones, this case study illustrated the potential of the proposed framework to estimate life cycle impacts and support more informed decisions in the part design phase, prior to the part production. Additionally, the integrated comparison of economic and environmental life cycle performance allowed the identification of the best alternatives according to the stakeholders and to the importance given to the environmental impacts in both EOL scenarios, showing PP as the best choice except if the choice is purely environmentally driven.

Section 6.3 explores the potential of the CLC framework to situations where both the part and tool are subject to design changes. With a very simple case study, but a complex and large process-model, the chain of impacts throughout the integrated part/mould life cycle were computed, comparing 16 sets of alternatives regarding the mould and part design parameters in terms of economic and environmental impacts. Several relations were analysed, from the impact of part design in mould design to the impacts of both part and mould design in the subsequent life cycle phases.

In the overall, all the case studies have shown that the best options are different according not only to the annual production volume, but they are also dependent on the analysis dimension, cost or environment. Additionally, the different types of case studies allowed understanding the possible connections and relations between the life cycle phases. This outlines the need to model the processes within the life cycle phases, linking them and developing the suitable analysis and models required to fully assess the impacts of design decisions. Moreover, the flexibility of these models allows the development of sensitivity analysis to production scenarios, process variations and even life cycle phase's options. The last step, the integrated comparison of economic and environmental life cycle performance mapping, showed the best alternative domains.

Although this thesis is focused on tool and part performance modelling for injection moulding based parts, the approach followed might be valid for other tool based manufacturing parts. However, appropriate adaptations are needed on the cycle time, energy and material consumption models to fit the physical mechanism of other technologies. The next section briefly illustrates the application of the CLC framework to two other case studies comprising different part production and dedicated tool use processes – stamping and die casting.

7 - CLC FRAMEWORK APPLIED TO OTHER PRODUCTION PROCESSES USING DEDICATED TOOLS

This chapter explores the application of the proposed CLC framework to other production processes using dedicated tools, namely stamping and die casting. Using case studies developed in past projects, these are now re-analysed with following the new approach. However, the models developed and presented in section 5 are not applicable, as are only suitable for the injection moulding process. In each case study the models developed for the specific processes are used, together with the available data. In the first case study presented in this chapter, Case Study 7, the life cycle of a stamping part and correspondent die is analysed through CLC framework, being the design decision focused on the part material. This case study was developed during MIT-Portugal Pilot Project, which final report is available for consultation [Pilot Project – EDAM 2008]. The author of this thesis took part in the project, being responsible for the development of the LCC and LCA analysis. However, the die was largely disregarded in the study, being available only its approximated cost. The Case Study 8, also a material selection problem, regards the use of copper vs. aluminium in the rotor bars of an induction motor. In this case tool material alternatives were also considered with the aim of prolonging the tool life. This case study was developed by the author of this thesis in a project for GM in Detroit, being the company's goal in this study understanding the cost difference between copper and aluminium rotors.

Both case studies were not developed at the time for the application of the CLC framework; however, it is expectable that this can be applied to other dedicated tools other than injection moulds. To test that hypothesis, the CLC framework is applied on the available data using the available models, intending more comprehensive results than the ones achieved at the time the projects took place.

7.1 Case Study 7 – Stamping of an Automobile Fender

The CLC framework is applied to a material selection problem regarding the use of different metallic materials in an automobile fender (Figure 7.1). The work was developed within the scope of the MIT-Portugal Pilot Project. Currently manufactured in mild steel using the stamping process, this study aimed to assess the impacts of

changing the part material to higher strength steels and several grades of aluminium alloys fostering weight reduction and consequently fuel savings.

Figure 7.1. – Picture of the automobile fender

The alternatives of this case study are mainly related with the material of the stamped part, although the die design also changes with the different part material alternatives. (see Figure 7.2). In these cases changes in the part material will influence not only the part production/tool use process, but also the die design (materials) and production, part use and EOL. Following the case study is described, with the material alternatives analysed in terms of economic and environmental impacts throughout the integrated life cycle.

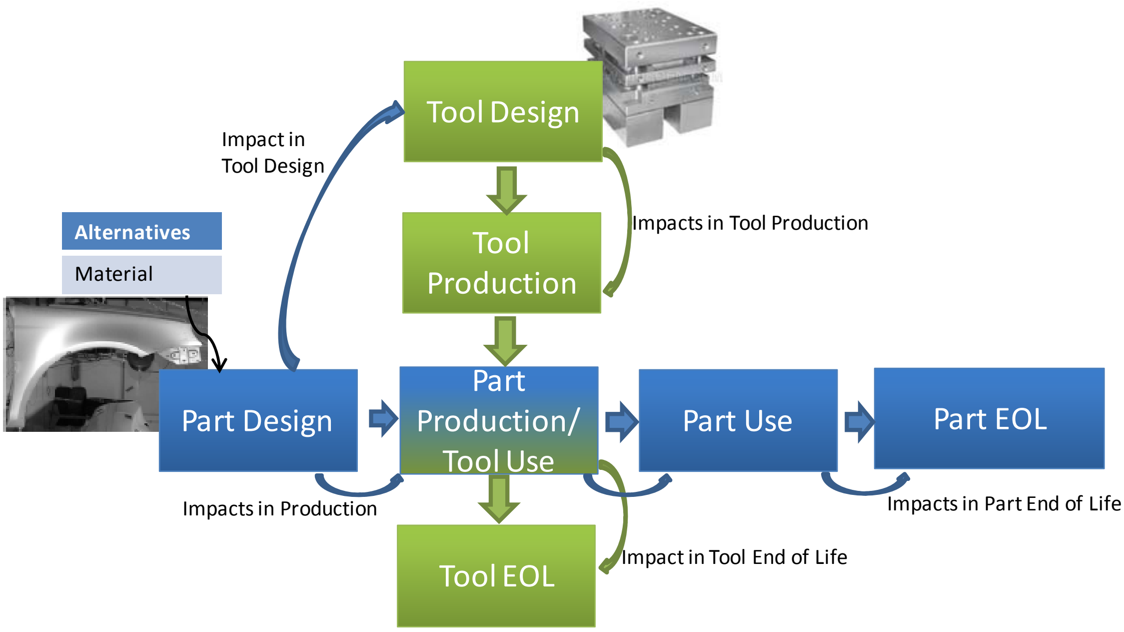


Figure 7.2. Part design alternatives – Impacts in the integrated life cycle

The candidate materials chosen in the project and their specific market prices are presented in Table 7.1, being their characterisation further presented in Annex 2. Aluminium is more expensive than steel in terms of cost per unit of mass, while the mild steel (Steel-1) has the lower specific market price. However, as far as materials have different specific strengths and specific stiffness they induce different thicknesses to perform similarly in the application.

Table 7.1. Set of materials pre-selected for the automobile fender

Materials	Material label	Price / kg [€/kg]
HX220YD+z100MCO	Steel-1	0.72
DOCOL 600DP	Steel-2	0.90
DOCOL 1000DP	Steel-3	1.04
Al 6010-T4	Al-1	2.52
Al 2036-T4	Al-2	2.52
GZ45/30-30	Al-3	2.52

7.1.1. Comprehensive Life Cycle-Costs

The Comprehensive Life Cycle comprises the scope already defined in chapter 4, being the processes involved presented in Figure 7.3. As fenders made of alternative materials might impact the automobile weight and fuel specific consumption, the part use phase was not disregarded in this case.

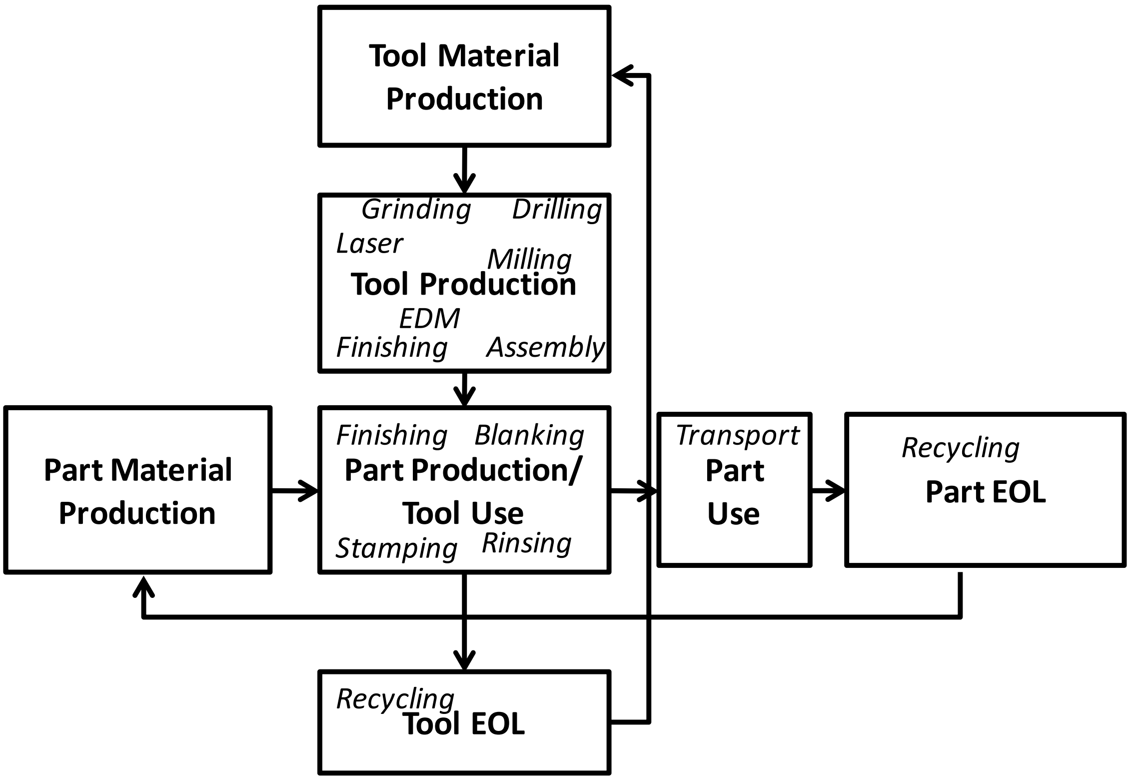


Figure 7.3 – Life Cycle Scope

7.1.1.1.Part Materials Cost

The candidate materials must assure the same technical/functional performance for the fender application. As the materials in focus have different engineering properties, each one might result in different design features. However, as the fender assembly system and aesthetics were frozen, the fender thickness was the only design feature that was allowed to change with different materials. The thickness was defined in the project for each alternative in order to guarantee the same level of strengths and strains when subjected to an equal load, and to have natural frequencies far enough from the most relevant exciting ones, with the current mild steel fender used as a baseline. Results (Table 7.2) show that while Steel-3 has a higher specific market price, the material effectively incorporated in the fender has a lower cost, which is the result of the smaller thickness required for an equivalent technical performance. Although the design data has been incorporated, the analysis still does not include the material scraps inherent to the specific production processes.

Table 7.2. - Candidate materials, relevant design features and material cost (Weight = Density x Surf. Area x Thickness).

Material	Yield Strength [MPa]	Cost [€/kg]	Thickness [mm]	Surf.Area [m2]	Weight [kg/part]	Material Cost [€/part]
Steel-1	220	0.72	0.65	0.34	1.73	1.25
Steel-2	350	0.90	0.50		1.33	1.19
Steel-3	700	1.04	0.35		0.93	0.97
Al-1	170	2.52	1.00		0.92	2.32
Al-2	190	2.52	0.90		0.84	2.12
Al-3	155	2.52	1.00		0.93	2.35

It is important to point out that the thickness required for the Steel-3 (0,35mm), resulting from the structural and frequency analysis, was not at the time of the project available in the market. In spite of this, as a methodological approach and because the steel supplier informally announced its availability in the near future, the minimum required value was used in the analysis. However in order to identify the life cycle impact obtained if the lower commercial available thickness at the time had been used, 0.50 mm, a sensitivity analysis will be presented.

7.1.1.2.Tool Material and Tool Production Cost

The tooling production cost was estimated through a relation based on the design specifications of the product using regressions derived from empirical data, obtained in the models developed for the Pilot Project (Equation 7.1) for transfer presses. The part material affects the tooling production cost, being the tools dependent not only on the part geometry, but also on the material strength. Results (table 7.3.) show that Steel-1 incurs in lower tooling material costs, followed by Steel-2, being Steel-3 the one that leads to higher tooling material costs and therefore higher tooling production costs. Regarding aluminium, the tooling production cost is between the lower strength steel (Steel-1) and the higher strength steel (Steel-3).

Table 7.3 – Tooling production cost for the different part material alternatives

Part Material	Tooling Production Cost [M€]

Steel-1	3.1464	$Tool\,Cost = Mat\_Invest\_Factor * 10^{A}$ $(Part\,Width \cdot Part\,Lenght)^{B}\,(Number of\ Stations)^{C}$ (7.1) with Part Length & Width in mm, A=1567, B=0.366, C=0.323 and D=0.342, Hits are the number of press hits required to stamp a part, Surf. Area is the part surface area and the Proj. Area is the part projected area. Material Investment Factor (Mat_Invest_Factor) is an empirical factor dependent on the tool material.
Steel-2	3.6183	
Steel-3	4.0903	
Al-1	3.7757	
Al-2	3.7757	
Al-3	3.7757	

7.1.1.3.Part Production/Tool Use Cost

Following the proposed framework, the part production/tool use costs were estimated using process-based cost models, allowing several variations on the material, production volume, thickness and other relevant inputs. The manufacturing processes are illustrated in figure 7.4. The fender production includes four technological processes. In the blanking stage the blanks are sheared from the metal coil, generating scraps and rejected parts as waste, consuming energy, labour, and production facilities resources and space. The blanks are then taken to a rinsing process, where they are washed and lubricated. In this process, production facilities are used and energy water and a washing solution are consumed. Afterwards, the blanks are stamped (stamping process), requiring energy, labour, production facilities, and stamping tools. In this process some parts are completed, others rejected, and some, with minor faults, are manually reworked in a finishing stage. If these faults cannot be eliminated, the part is rejected after finishing. Both in stamping and finishing, scraps are generated.

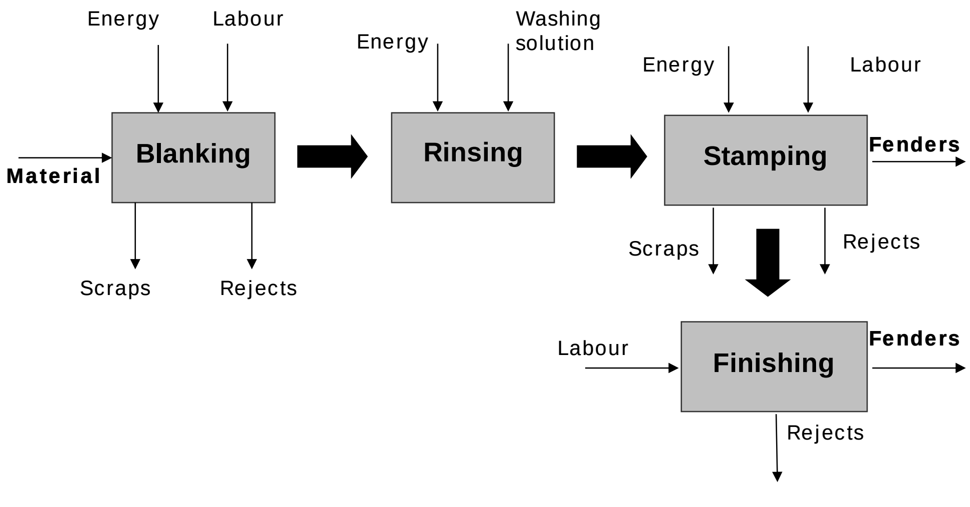


Figure 7.4 – Manufacturing process of the fender production

The costs associated with each step of the process flow are derived from a combination of engineering principles and empirical data gathered during the Pilot Project considering the current manufacturing practice. The inputs include design specifications, material parameters, processing (e.g., equipment characteristics, space requirements, power consumption), production (e.g., production volumes, production life, scrap rates, down times…), and economic parameters (e.g. cost factors, cost of capital associated with investments). Inputs are transformed into estimations of fixed and variable costs for each manufacturing step.

The machine and tooling costs were predicted based on the design specifications of the product using regressions derived from empirical data, being the estimation of the tool cost already presented in section 7.1.1.2. It should be noted that as far as production costs are concerned the fender unit cost was determined based on an annual production volume of 100 000 units (left and right fenders) in a timeframe of 7 years.

The maximum force required to stamp a part was estimated trough an empirical relation, developed for this specific case (equation 7.2), in which A_{surf} is the surface area, σ_{UTS} is the ultimate strength, σ_Y is the yield strength. Due to the empirical nature of this equation, a margin of 25% was added to the computed force.

$$F_{stamping} = A_{surf} \times \frac{\sigma_{UTS} + \sigma_Y}{2} \tag{7.2}$$

Knowing the required force to stamp a part, it is then possible to select a stamping machine able to produce the required force. Through the machine power and the required time to stamp a part is possible to compute the energy consumption.

The material cost included the cost of the material input for the fender production, considering the rejects and engineering scrap generated within the process, and the benefit of the scraps re-sold to the metal industry.

Results reveal that Steel-1 induces the lower production costs (Table 7.4), while Al-3 is the alternative with the higher ones. Despite the lower material cost, the fender made of Steel-3 incurs in higher production costs than the ones made of Steel-1, Steel-2 and Al-2. This is mainly because Steel-3, being an ultra-high strength steel, requires a larger stamping force due to its high ultimate and yield strengths (high tonnage press machines

and a much more robust tooling set), and introduces a significant toughness in the quality of the fender final surface (smaller production rate and higher reject rate).

Table 7.4 – Material and Production Costs (100 000 fenders)

COSTS [€]	Steel-1	Steel-2	Steel-3	Al-1	Al-2	Al-3
Material	375 485	363 948	304 374	489 926	447 441	495 349
Labour	39 120	39 128	39 130	39 130	39 130	39 130
Energy	8 749	9 666	11 497	8 752	8 752	8 752
Fixed Costs	974 780	1 092 556	1 266 251	1 123 526	1 123 526	1 123 526
Total Production	1 398 134	1 505 298	1 621 252	1 661 334	1 618 849	1 666 757

7.1.1.4.Part Use

The fender use stage considers the fuel consumption over the lifespan of 50000 vehicles (two fenders per vehicle) and 30,000 km per vehicle per year during 5 years. It was also considered a fuel consumption of 7.6l/100km for the whole vehicle, being then allocated to the weight of the fenders, which vary according to the alternatives. The unit cost of fuel was set to 1.7 €/l, Portugal price. Table 7.5 presents the use costs allocated to each alternative fender, showing that as expected, Steel-1, the fender with higher weight, is the one incurring in higher use costs. Al-2 is the fender material with lower use costs due to the lower weight. Notice that the use costs comprehend the present value (PV) of the annual costs throughout the 5 years of utilization of the vehicle. However other values are also easily changed in the process models, automatically computing new outputs.

Table 7.5 – Use costs considering an annual production volume of 100,000 fenders

Alternative	Use Costs [€/year]	PV –Use Costs [€]	Use Costs [€/part]
Steel-1	45,646	156,707	1.57 €
Steel-2	35,092	120,475	1.20 €
Steel-3	24,538	84,242	0.84 €
Al-1	24,274	83,336	0.83 €
Al-2	22,164	76,089	0.76 €
Al-3	24,538	84,242	0.84 €

7.1.1.5.Part and Tool EOL

To obtain values for the economic evaluation of the dismantling stage, an inquiry was made to a company involved in the management of the vehicles end of life. An average cost for dismantling one vehicle was obtained, 50 euros, and a proportional calculation was made considering the automobile weight and the weight of two fenders. The fenders can be then sold to be recycled, with a revenue of 0.26€/kg in the steel case and 2€/kg in the aluminium case. The tool material (steel) can be recycled with a revenue of 0.26€/kg. There were no specific data regarding the tooling weight, but considering the set of 6+6 stamping tools (left+right fender), an approximate calculation of 24 tons was considered. Therefore, the die can be sold for 6240€, with a correspondent present value of 1542€, only 0.044% of the tool production cost. Results for the EOL cost (negative costs or revenues in this case) of the alternative parts are presented in table 7.6. Notice that all EOL costs are transformed into present values (PV) in order to add them in the total LCC.

Table 7.6 – Part EOL costs considering the different alternative materials

Material	Dismantling Cost [€/part]	Scrap Cost, Credit from Recycling [€/part]	Total Credit Recycling-Dismantling [€/part]	PV - Total Credit Recycling-Dismantling [€/part]
Steel-1	0,029	-0,450	-0,420	-0,218
Steel-2	0,023	-0,346	-0,323	-0,168
Steel-3	0,016	-0,242	-0,226	-0,117
Al-1	0,016	-1,840	-1,824	-0,947
Al-2	0,014	-1,680	-1,666	-0,865
Al-3	0,016	-1,860	-1,844	-0,958

7.1.1.6.Comprehensive Life Cycle Cost Results

With the data collected from each life cycle stage, the costs of each stage regarding the annual production of 100,000 fenders for each alternative were calculated and are presented in table 7.7. Steel-1 incurs in lower costs from the automotive industry point of view, while Aluminium alloys and high and ultra-high strength steels, due to their

lower weight, induce a lower fuel consumption leading to lower in-use costs. Despite the lightness of aluminium alloys, their acquisition costs are higher. Globally, the Life Cycle Costs are lower with the use of Steel-1.

The results demonstrate the ability of the model in connecting different processes. Moreover, the model does not only allow variations in the process and production relevant parameters but goes further in adapting the productive configuration with the part design, namely material type in a complex net of influences.

Table 7.7– Comprehensive Life Cycle Costs (100 000 fenders)

COSTS [€]	**Steel-1**	**Steel-2**	**Steel-3**	**Al-1**	**Al-2**	**Al-3**
Material	375,485	363,948	304,374	489,926	447,441	495,349
Labour	39,120	39,128	39,130	39,130	39,130	39,130
Energy	8,749	9,666	11,497	8,752	8,752	8,752
Fixed Costs	974,780	1,092,556	1,266,251	1,123,526	1,123,526	1,123,526
Total Production	**1,398,134**	**1,505,298**	**1,621,252**	**1,661,334**	**1,618,849**	**1,666,757**
Use	**156,708**	**120,475**	**84,242**	**83,336**	**76,089**	**84,242**
EOL (Parts and Tool)	**-22,509**	**-17,471**	**-12,433**	**-95,428**	**-87,222**	**-96,467**
TOTAL LCC	**2,930,467**	**3,113,600**	**3,314,313**	**3,310,576**	**3,226,565**	**3,321,289**

7.1.2. Comprehensive Life Cycle – Environmental Impacts

At this stage, a cradle to grave approach to assess the environmental impacts of the fender made of the several candidate materials is performed, using all data previously computed though the process-based models. As previously explained, the proposed LCA methodology uses the EI'99 method and Simapro software. The boundaries of the LCA analysis were defined in chapter 4, and can be applied to this case study, being in this case the process in the use phase comprising transportation using an automobile. Again, the process-based models developed in Pilot Project were used, simplifying the assessment of all inputs and outputs of environmental impact drivers involved in the process.

7.1.2.1. Life Cycle Inventory and Assumptions

Regarding the inventory stage, most of the data was already determined in the cost dimension, in particular the material input for the annual production, the manufacturing processes consumptions and the fuel consumption. However, there is still the need of analysing other aspects such as emissions and EOL environmental flows.

Regarding the fender production, the energy consumed by the machines was considered, along with the emissions caused by this consumption.

In the fender use stage, the fuel consumed over the lifespan of 50,000 vehicles (two fenders per vehicle) was considered as an energetic resource. The consumption considered was 7.6l/100km, with a CO_2 emission rate of 182 g/km.

The average energy consumption at the dismantling end-of-life stage was estimated, considering the main machine power of a dismantling plant and its dismantling rate (values inquired at a management company of EOL vehicles). As a result, energy consumption and CO_2 emissions related to this energy could be obtained.

The major consumptions and emissions over the integrated life cycle are presented in Table 7.8. The exhaustive results obtained in SimaPro7 software were incorporated in the environmental evaluation, but they are not presented in the table. As expected, the energy consumption is lower in steel case for the first life cycle stages of the fender, but in the last stages (use and dismantling) is lower in Al-2 option.

Table 7.8 - Consumptions and emissions over the integrated life cycle

	Consumption &Emissions	**Steel-1**	**Steel-2**	**Steel-3**	**Al-1**	**Al-2**	**Al-3**
Material Manufacture	Material [ton]	622.54	476.58	335.35	330.77	302.09	334.43
	Energy [TJ]	10.83	8.29	5.83	33.59	30.67	33.96
Tool Production	Material [ton]	5.15	5.15	5.15	5.15	5.15	5.15
	Energy [MJ]	2.83	3.26	3.68	3.40	3.40	3.40
Part Production	Energy [TJ]	0.55	0.60	0.72	0.55	0.55	0.55
Part Use	Fuel [m^3]	1346.31	1030.36	721.72	715.04	653.04	722.96
	CO_2e [ton]	3224.06	2467.43	1728.32	1712.34	1563.85	1731.29
EOL (Parts and Tool)	Energy [TJ]	0.03	0.02	0.02	0.02	0.01	0.02
	CO_2e [ton]	0.35	0.27	0.19	0.18	0.17	0.19

7.1.2.2.Impact Assessment

The impact assessment was performed using the EI'99 method with a the hierarchic/average weighting perspective. The results achieved for the three major impact categories and the respective EI' 99 are presented in table 7.9.The steel currently used (Steel-1) and Steel-3 are the ones with higher and lower environmental impacts, respectively. Even though the fender production stage for Steel-3 results in larger environmental damages, the fender made of Steel-3 performs better for its overall life cycle.

Table 7.9 - Environmental Evaluation based on LCA Methodology

EI'99 pts	Steel-1	Steel-2	Steel-3	Al-1	Al-2	Al-3
Material Manufacture	160,608	122,984	86,448	508,344	464,152	513,936
Tool Production	41	47	53	49	49	49
Part Production	7,480	8,160	9,792	7,480	7,480	7,480
Part Use	189,157	144,766	101,402	100,463	91,752	101,576
EOL (Parts and Tool)	408	272	272	272	136	272
TOTAL	210,553	163,597	118,758	160,241	146,874	161,919

7.1.3. Integrated comparison of economic and environmental life cycle performance

The last analysis proposed is the integration of LCC and EI performance. The best materials are mapped in the (α, β) space, meaning that they are mapped as a function of different levels of importance attributed to the downstream life cycle phases and to the environmental performance. The decision maker is in this case the fender producer, being the tool cost imbibed in this cost and being the upstream phases the phases before the fender production. The downstream phases are use phase of the fender and the EOL phase. Fig.7.6 presents the visual representation of performance maps of all candidate materials, when Steel 3 with 0.35 mm option is considered. The low cost of Steel-1 on the material acquisition and production phases allow it to be the best choice when low importance is given to both use phases and EI performance. When more than 25% importance is given to the use phases and the importance of EI is kept low Al-2

becomes the best choice. The remaining materials selection space belongs to Steel-3 due to its good performance on EI mainly in the production phases.

Considering the proposed classification, one can conclude that HX220YD steel is a Cost-based type material for the fender application (Steel-1 option), AL 2036 is a User-based type material (Al-2 option) and DOCOL 1000P can be considered an Environment-, Balanced- and Low impact based type material for this particular application (Steel-3 option).

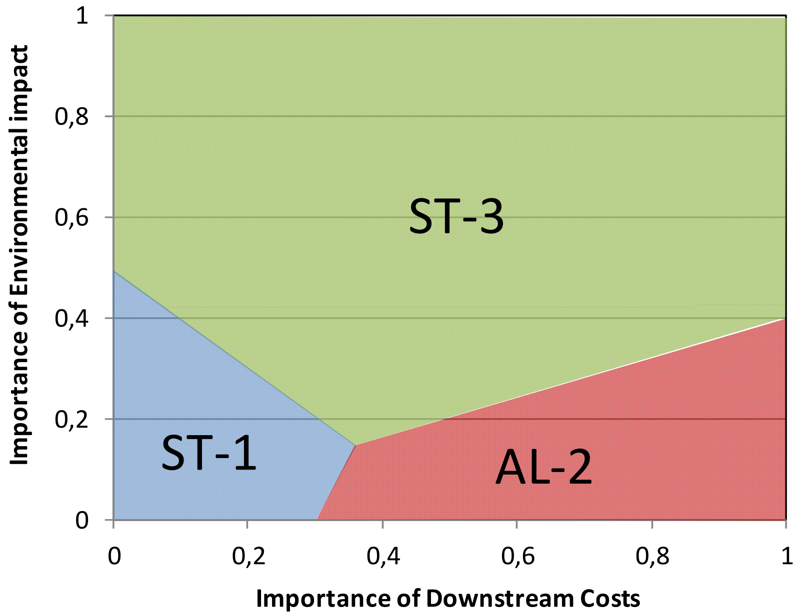


Figure 7.6. - Best-performing mapping of the candidate materials, considering the Steel-3 with 0.35 mm thickness

As previously explained, all the previous analysis considered the thickness required for the Steel-3 (0,35mm), resulting from the structural and frequency analysis. However, DOCOL 1000P coils were not commercially available in thicknesses smaller than 0.50mm. Fig.7.7. maps the integrated analysis considering this market constraint. It seems like DOCOL 1000P (Steel-3 option) is replaced in its best-performance mapping by the use of DOCOL 600P (Steel-2) and the aluminium fender (Al-2 option) increases significantly its best-performance area due to its very good performance on the Users-like phases (lower weight among this candidate materials).

Considering the proposed classification, for this set of materials the HX220YD steel remains the Cost-based type material for the fender application (Steel-1 option), but the aluminium alloy AL 2036 (Al-2) extends its domain and can be considered now a User- and Low impact-based material. In the Steel-2 option the DCOCOL 600P steel is clearly the Environmental-based type material. Furthermore, it would be also possible, due to the model flexibility, to perform sensitivity analysis to other parameters, namely regarding production scenarios.

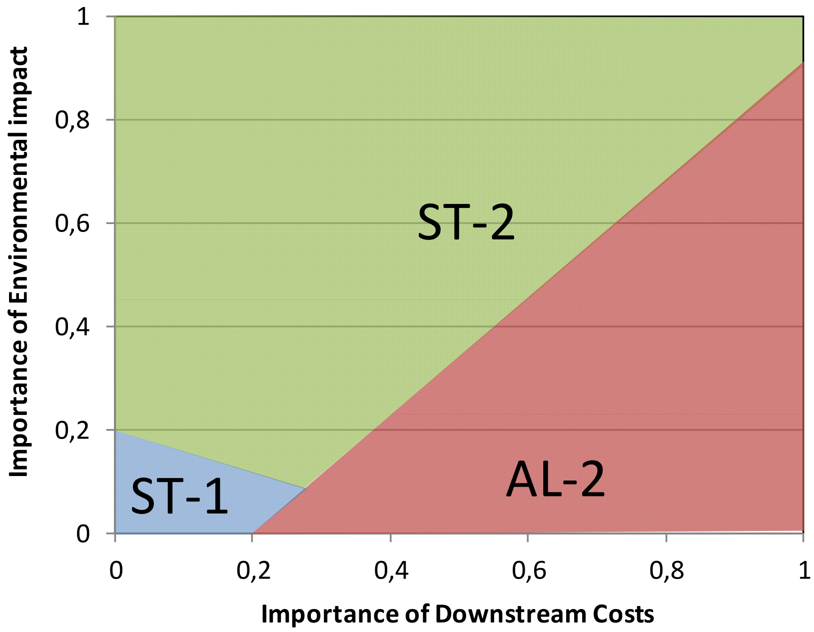


Figure 7.7 – Best-performing mapping of the candidate materials, considering the St-3 with 0.50 mm thickness.

7.2 Die Casting Case Study – Rotor Bars of an Automobile Induction Motor

This case study is explored using data from a study in General Motors - GM (Detroit, USA) and investigates the application of the CLC framework to understand the impacts in the part and tool life cycle of using aluminium or copper die cast induction motors for traction purposes. Induction motors for vehicle traction purposes have traditionally been manufactured using aluminium die casting as the conducting "squirrel cage" material, due to aluminium's light weight, low cost of processing, and relatively good electrical properties. However, copper offers an electrical conductivity of 160% that of aluminium, and as a result GM would like to investigate copper's feasibility as a replacement for aluminium. This change would lead to an increase in motor efficiency and eventually scale the motor down in size, thus decreasing the individual costs of many other steps in the manufacturing process and theoretically lowering motor cost as a whole. However, die casting copper involves many significant challenges compared to the processing of aluminium, which ultimately result in a higher cost to manufacture the induction motor. Many of these challenges include higher processing temperatures, the need for more complex and higher tonnage equipment, and more specialized and advanced tooling. Raw material cost is also significantly higher as well when compared with aluminum. The scope of this analysis is not the whole motor production, but only the rotor bars injected in the rotor laminations stack (see figure 7.8). Therefore, the part is in this case the rotor bars.

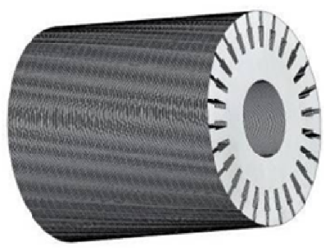


Figure 7.8 - Rotor stack comprising laminations

The scope of this case study is illustrated in Figure 7.9. Considering the analysis of the use of two different part materials, together with the use of two different tool material aiming to prolong the tool life. The different tool materials are fostered by the very short die life when cooper in the die casting process is used. Notice that only the bars in the lamination stack are considered as the product, being the die casting process the part

production phase. However, as the bars are used in the motor, the use phase is considered to be the motor production and the impacts in using copper vs. aluminium. These impacts are related with the possibility of downsizing the whole motor, possibly decreasing the whole production cost and environmental impacts despise the higher cost of copper and higher specific environmental impact compared with aluminium. The part EOL regards the dismantling and recycling the copper or aluminium rotor bars. The tool life cycle considerations are similar to the stamping case study, with the same boundaries.

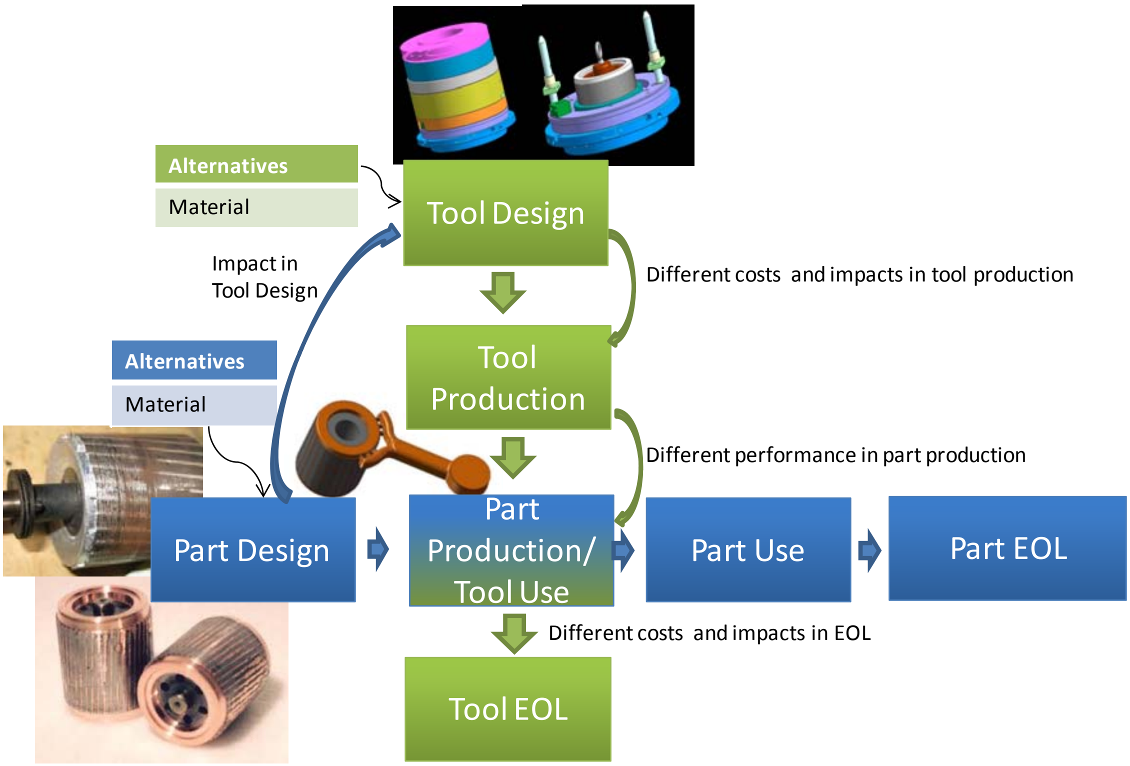


Figure 7.9. Part and tool design alternatives – Impacts in the integrated life cycle

Table 7.10 – Alternative materials regarding the part and tool

Rotor Bars Material	Tool Material
Aluminium	H13 Tool Steel
Copper	H13 Tool Steel Nickel Based Alloy

7.2.1. Comprehensive Life Cycle - Costs

The following sections describe the application of the CLC framework to the life cycle of this particular part produced by die casting. The processes related to each phase of the integrated tool and part life cycle were modelled in order to accommodate not only material changes, but also part design and tool material changes. The reason is that it was estimated that the copper rotor will allow downsizing the motor to 90% when compared with the aluminium rotor, maintaining the same efficiency. This obviously has also impacts not only in the part material consumption, but also in the die production, cycle time, energy consumption and machine requirements during part production, and amount of material in EOL processes.

Figure 7.10 presents the processes involved in the integrated life cycle, within the scope proposed in chapter 4. In this case study the use phase was considered to be the use of the die casted bars in the whole motor, being the induction motor production cost the use phase. The aim for this assumption was to assess the potential of downsizing the motor size using copper bars in the whole motor production cost. Although the structure of the model is similar to the previous one, following the CLC approach, the models need to be built to the specific processes involved in this life cycle.

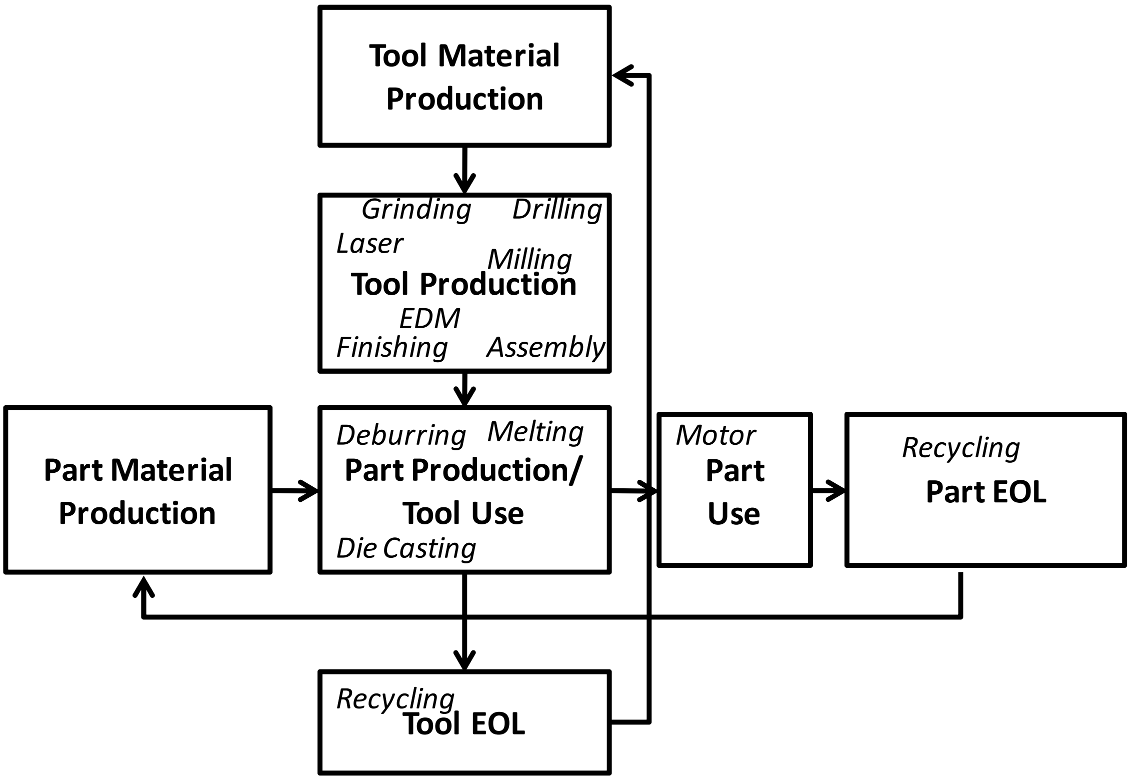


Figure 7.10 – Life Cycle Scope

7.2.1.1.. Part Material

The part material weight and cost is presented in table 7.11 considering a production volume of 75,000 parts per year. Although being possible to downsize the motor with the use of copper and therefore the rotor and the volume of the bars, the weight of the copper and extremely higher specific cost of this material leads to a significantly higher material cost. Notice that scraps generated in the process can be sold and recycled with n income to the die casting company.

Table 7.11 – Part Material Cost considering a production volume of 75,000 parts per year

	Aluminium		Copper	
	Density =2.7g/cm3 Price = 1.6 €/kg		Density=8.7g/cm3 Price=6.5€/kg	
	Cost per part [€/part]	Cost per year [€/year]	Cost per part [€/part]	Cost per year [€/year]
Incoming Material Cost	2.54	190,856	27.46	2,059,176
Process Scrap Cost (Credit)	(0.98)	(73,408)	(10.56)	(792,015)
Rejected Parts Scrap Cost (Credit)	(0.04)	(3,236)	(0.47)	(34,913)

TOTAL MATERIAL COST	1.52	114,211	16.43	1,232,248

7.2.1.2.. Tool Production

The tool production cost was defined by an empirical relation used in GM (equation 7.3) and by visits to GM suppliers. This cost depends mainly on the tool material used and on the surface area of the rotor bars. While in injecting aluminium bars the tool material used is H13 steel, allowing a tool life of 200,000 shots, in the copper die casting case the use of H13 steel allows a very limited tool life, between 4,000 and 10,000 shots. In order to extend the tool life another tool material is evaluated, a nickel based alloy, which allows extending the tool life to 100,000 shots. However, this type of material leads to higher tool material costs. Another aspect to consider is the number of cavities, which lower the cycle time during the part production phase but increase the tool production costs. Table 7.12 presents the results of the production costs for both types of tools.

Table 7.12 – Tool Production Costs considering different materials and number of cavities

	Production Cost [€]
H13 steel	48118
Nickel Based Alloy	90111

$$\text{Tool Cost} = \begin{cases} \text{Tool\_Coef}(N_{act}+1) + (A_{surf}(N_{act}+1))^{0.29} N_{cav} 1.6 & \text{if } N_{cav} > 1 \\ \text{Tool\_Coef}(N_{act}+1) + (A_{surf}(N_{act}+1))^{0.29} & \text{if } N_{cav} = 1 \end{cases} \tag{7.3}$$

Where N_{act} is the number of actions in tool, A_{surf} is the surface area of the injected part, N_{cav} is the number of cavities in the die. The Tool_Coef is the tool coefficient related with the tool material, with a value of 4000€ in the Nickel based alloy die and 2000€ in the H13 steel die.

7.2.1.3.Part Production/Tool Use

The die casting process related to the parts production were then modelled in order to accommodate part and tool design options, again using GM process-based models. The main differences between copper and aluminium die casting are summarized in table 7.13.

The part production comprises not only the die casting process, but also other complementary process, namely melting the metal and deburring the ejected rotor (see Figure 7.11). In summary, the loose rotor laminations are stacked in the die casting press. From here, the die is preheated and injected with molten die cast metal. Because

the rotor lamination stacking and heating can be done completely within the cycle time of the die casting, there is no need to model them as a separate step. The rotor cores then continue on to a deburring step. The following step of keyway broaching, which is necessary in order to install the hub through the axis of the rotor, is not covered in the scope of this analysis. Notice also the rotor laminations are also not included, as the part considered is only the metallic bars injected in the rotor laminations stack.

Table 7.13 - Main process trade-offs between copper and aluminium die casting

Cost Driver	Aluminium	Copper
Energy	Melting Temperature 660ºC No Pre-Heated Dies	Melting Temperature 1080ºC Pre-Heated Dies
Tool Life	200,000 shots with H13	4000-10,000 shots with H13 die 100,000 shots with Nickel based die
Auxiliary Equipment	Standard Die Casting	Temperature Control is required
Furnaces	Gas or electric resistance	Induction Single or double push-up furnaces

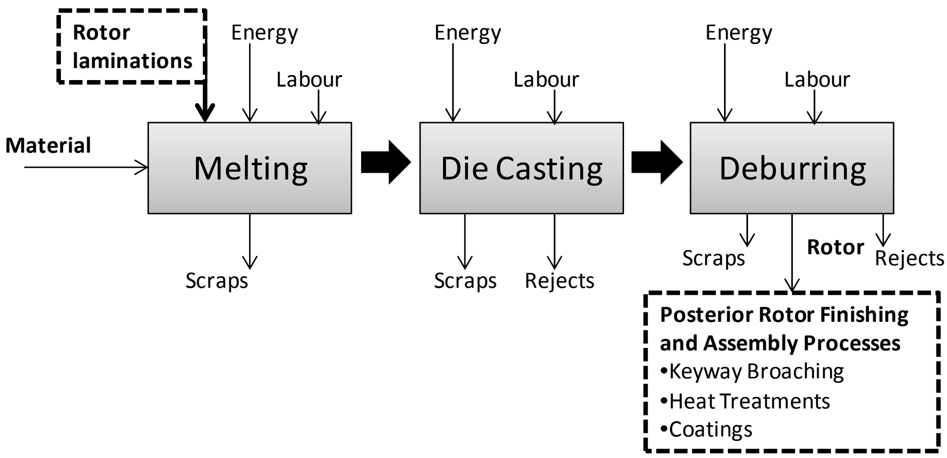


Figure 7.11 - Manufacturing process of the rotor die casting

The costs, similarly to the stamping case study, were developed following the cost structure proposed in chapter 4. The material cost was already computed in section 7.2.1.1, but is again presented here for better evaluation of the importance of the different cost drivers in the die casting process. Some correlations were developed in order to link part and tool design to the process outputs. Namely, the energy required per charge to melt material was estimated through a thermodynamic relation (equation 7.4) used in GM process based models, being dependent on several variables: the

amount of material per charge, material properties (heat capacity, c_p, latent heat of fusion, L_{fusion}, melt temperature, T_{melt}, material density (kg per available space in the furnace), furnace efficiency, Eff_{furn}, (higher in double push-up in the induction furnaces) and room temperature, T_{amb}. Finally, also the press required tonnage was linked to the part through relating the required clamping force with the part area, number of cavities and process pressure. This relation is based on the thermodynamic equation already used in section 5.2.2. (injection moulding process) adapted to accommodate also the furnace efficiency. This value was retrieved from historical data in die casting industries.

$$Energy_{melt} = Eff_{furn} \cdot Material_{Charge} (c_p (T_{melt} - T_{amb}) + L_{fusion}) \quad (7.4)$$

The part production costs are presented in Table 7.14 and show that copper die-casting leads to much higher costs, not only due to material cost but also in all other cost drivers, variable and fixed. Additionally, considering the expected production volume of 75,000 parts per year, the benefits of using Nickel based alloy dies in copper die casting are clear. Despite the higher tool investment cost (see tool production phase), the nickel based alloy allows a very significant extension of the die life and consequently lower the tool costs. However, this investment might not offset in lower production scenarios. Therefore, a sensitivity analysis was developed and results, illustrated in Figure 7.12, reveal the production volume (2000 parts/year) above which there is an economic worth in use the nickel based die. It is also clear that raw material is the main cost driver in the die casting process, followed by labour (tooling in the case of using H13 material tool in die casting copper), tooling and equipment.

Despite the higher die casting costs with the use of copper, the correspondent downsizing of the induction motor will certainly lead to lower subsequent costs in the whole motor, being required a smaller laminations stack and a smaller stator.

Table 7.14 –Material and Production Costs (75,000 rotors)

	Cost [€/part]			Cost [€]		
	Aluminum	Copper with H13	Copper with	Aluminum	Copper with H13	Copper with

			Nickel			Nickel
Raw Material Cost	1.52	16.43	16.43	114,211	1,232,248	1,232,248
Labor Cost	1.22	1.91	1.91	91,696	142,881	142,881
Energy Cost	0.05	0.11	0.11	3,893	7,897	7,897
Variable Costs	**2.80**	**18.44**	**18.44**	**209,803**	**1,383,028**	**1,383,028**
Equipment Cost	0.26	0.31	0.31	19,147	23,323	23,323
Tooling Cost	0.39	14.35	1.44	29,334	1,075,922	108,190
Building Cost	0.03	0.04	0.04	1,968	2,680	2,680
Overhead Labor Cost	1.26	1.86	1.86	94,566	139,205	139,205
Maintenance Cost	0.01	0.29	0.04	1,009	22,039	2,684
Working Capital Cost	0.19	1.17	1.17	14,288	88,094	88,094
Fixed Costs	**2.14**	**18.02**	**4.86**	**160,311**	**1,351,262**	**364,175**
TOTAL	**4.93**	**36.46**	**23.30**	**370,114**	**2,734,290**	**1,747,203**

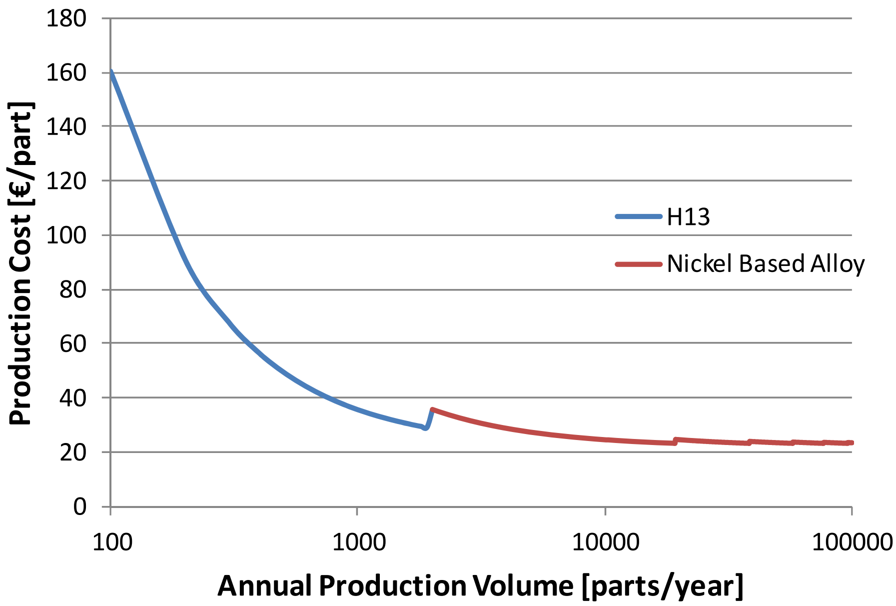


Figure 7.12 – Sensitivity analysis to the production volume considering copper die casting and two tool material alternatives (H13 and nickel based alloy). Only the alternatives of lower cost per part are represented

7.2.1.4.Part Use

The use phase of the die casted parts comprise the whole motor regarding the production costs. This study was part of a larger project, being the further motor production processes also computed considering the possibility to downsize the motor with the use of copper instead of aluminium. Being the other processes out of the scope of this thesis, only the total production costs are here presented for the sake of comparison. A work developed simultaneously during the study in GM and presented

on a Master Thesis [Mechler 2009] states that even optimizing the motor size with the use of copper, the overall production costs are still 4.5% higher that the induction motor produced with aluminium rotor bars (see Table 7.15). Furthermore, only 88.5% downsizing would yield equal costs, but at this point the motor efficiency is lower. All these values consider the use of nickel based die in the copper die casting. The use of H13 material in the die for injecting copper incurs in even higher costs.

This model was capable of accommodating changes in most variables, allowing new data to be incorporated or changes regarding new industrial and business scenarios.

Table 7.15. Motor Cost for each alternative considered [Mechler 2009], production volume of 75,000 parts per year

	Aluminium Rotor Motor (H13 Die)	Copper Rotor Motor (Nickel based die)	Copper Rotor Motor (H13 Die)
Die Cast Material [kg/rotor]	0.681	2.198	2.198
Amount of Steel [kg/motor]	8.116	7.297	7.297
Total Production Cost [€/motor]	303.008	316.635	326.505
Total Production Cost [€]	**22,355,486**	**19,991,310**	**20,978,397**

7.2.1.5.Part and Tool EOL

In this case both the part and tool can be recycled. However, being the rotor basically a composite after the bars die casting, it requires a separation process of the bars in aluminium or copper from the iron stack. In summary, the scrap rotor passes through a dry-type grinder and magnetic separator to break and separate the rotor and turn the rotor into copper (or aluminium) and iron. A pulse dust catcher is also allocated to the grinder to remove dust from the process. Table 7.16 presents the EOL costs of both alternative parts (copper or aluminium) and alternative tools (H13 or Nickel based), regarding the cost in the end of 5 years of utilization of the motor and the correspondent present value (PV). Results show that while copper has a higher value in EOL, the tool to produce the copper rotor die-casting has a smaller value due to the lower amount of tool material (90% reduction in the rotor size)

Table 7.16 – EOL costs of parts considering a production volume of 75,000 parts per

year and tool

		Amount of material [kg]	EOL Cost (Credit) [€]	PV - EOL Cost (Credit) [€]
Parts	Al Rotor	51,075	-68,951	-35,811
	Cu Rotor	164,850	-1,038,555	-539,393
Tool	H13 – Aluminium Rotor	96	-25	-13
	H13 – Copper Rotor	86	-23	-12
	Nickel based	86	-23	-12

7.2.1.6. Comprehensive Life Cycle Cost Results

From the costs of each life cycle stage computed (see table 7.17), it is possible to conclude that the copper rotor induces a lower production cost, although considering the whole life cycle, copper rotor using nickel based tool induces lower costs. This is due to the fact that despite the die casting costs are extremely higher with copper, the reduction of the motor size turns copper in to a competitive option in a life cycle cost perspective. It is also possible to assess that copper is only a competitive option if the tool is produced with a nickel based alloy. Finally, it is important to notice that this option is economically better only if the analysis considers the credit from the copper EOL.

Table 7.17 – Life Cycle Cost results considering an annual production volume of 75,000 parts/year

	Cost [€]			Cost per part [€/part]		
COSTS [€]	Aluminium	Copper with H13 Tool	Copper with Nickel based Tool	Aluminium	Copper with H13 Tool	Copper with Nickel based Tool
Material	114,211	1,232,248	1,232,248	1.523	16.430	16.430
Labour	91,696	142,881	142,881	1.223	1.905	1.905
Energy	3,893	7,897	7,897	0.052	0.105	0.105
Fixed Costs	160,311	1,351,262	364,175	2.137	18.017	4.856
Total Production	**370,114**	**2,734,290**	**1,747,203**	**4,935**	**36,457**	**23,296**
Use	**22,355,486**	**20,978,397**	20,978,397	**298,073**	**279,712**	**279,712**
EOL (Parts and Tool)	**-35,824**	**-539,405**	**-539,405**	**-0,478**	**-7,192**	**-7,192**
TOTAL LCC	**22,689,776**	**23,173,282**	**22,186,195**	**302,530**	**308,977**	**295,816**

7.2.2. Comprehensive Life Cycle – Environmental Impacts

Then the analysis can go further through the environmental aspects along the integrated life cycle. The processes and boundaries considered were already illustrated in figure 7.10. Notice that in this case study the production of the whole motor was considered as the use phase of the parts (the die casted bars). Again, a cradle to grave approach to assess the environmental impacts of the several candidate alternatives is performed, using all data previously computed through the process based models.

7.2.2.1.Life Cycle Inventory and Assumptions

Regarding the inventory stage, data was already determined in the cost dimension, in particular the material input for the annual production and the consumptions in the manufacturing processes, being the results presented in table 7.18.

In order to assess input and output streams in the material production for the several alternatives, the SimaPro7 software was used.

Regarding the die casting process, the energy consumed by the machines was considered, along with the emissions caused by this consumption. As previously explained, the analysis of the manufacturing processes supports the identification of the material wastes during the production. The tool material and energy to produce the required tools are estimated for one year of production, that is, 75,000 parts. In the Aluminium die casting and Copper die casting with Nickel based tool, one tool is enough to cast the yearly production.

In the use stage the production of the whole motor was considered. However, only the material used was included, being the production processes disregarded. This can be explained by the fact that the steps and processes required to produce the whole motor are the same for all the alternatives, being in terms of comparison not significant. However, the amount of material differs due to the downsizing of the motor for the copper-based alternatives.

Table 7.18 - Consumptions and emissions over the integrated life cycle

	Consumption &Emissions	Aluminium	Copper with H13 Tool	Copper with Nickel based Tool
Material Manufacture	Material [ton]	51,075	164,850	164,850
Tool Production	Material [ton]	97	695	89
	Energy [MJ]	880	32,277	3,246
Part Production	Energy [MJ]	234	474	474
Part Use	Material [kg]	8	7	7
EOL (Parts and Tool)	Material [kg]	AL - 51,075 Steel - 96	Cu - 164,850 Steel - 86	Cu - 164,850 Steel - 86

7.2.2.2.Impact Assessment

The impact assessment was performed using the EI'99 method with a hierarchic/average weighting perspective. The results achieved for the three major impact categories and the respective EI' 99 are presented in Table 7.19. Aluminium die casting incurs in lower environmental impacts, despite the motor downsizing with copper use. This is due to the lower tool life and higher impact of the nickel based alloy, along with the higher environmental impact per mass of copper when compared to aluminium. In fact, the differences between the two materials are higher looking in an environmental perspective, as copper, even using the nickel based alloy, represents environmental impacts in the overall integrated life cycle 215% higher that the aluminium alternative.

Table 7.19 - Environmental Evaluation based on LCA Methodology

EI'99 pts	Aluminium	Copper with H13 Tool	Copper with Nickel based Tool
Material Manufacture	42,136.88	440,149.50	440,149.50
Tool Production	29.53	564.77	84.20
Part Production	3.18	6.45	6.45
Part Use	1.60	1.40	1.40
EOL (Parts and Tool)	-36,789.07	-428,646.55	-428,646.55
TOTAL	**5382.11**	**12075.56**	**11594.99**

7.2.3. Integrated comparison of economic and environmental life cycle performance

Finally, the proposed analysis integrating the life cycle cost and environmental performance of the design alternatives is presented in Figure 7.13. The best materials are mapped as a function of different levels of importance attributed to the upstream and downstream life cycle phases. In this case study the decision maker is the part producer, being the tool part of the part production cost, similarly to the previous case study. The downstream phases, the user-like phases, comprehend the part use and part EOL processes, in order to incorporate the effects of motor downsizing with the use of copper and the income of part EOL.

Considering the proposed classification, one can conclude that aluminium rotor is both a Cost-based and Environmental-based type alternative, while copper is a User-based and Low-impact type alternative. This is due mainly to the lower environmental impact and lower part production cost with the use of aluminium and to the lower motor production cost and higher EOL income with the use of copper. Other analysis would be possible regarding production scenarios and the tool number of cavities, which would have significant impacts in the process productivity.

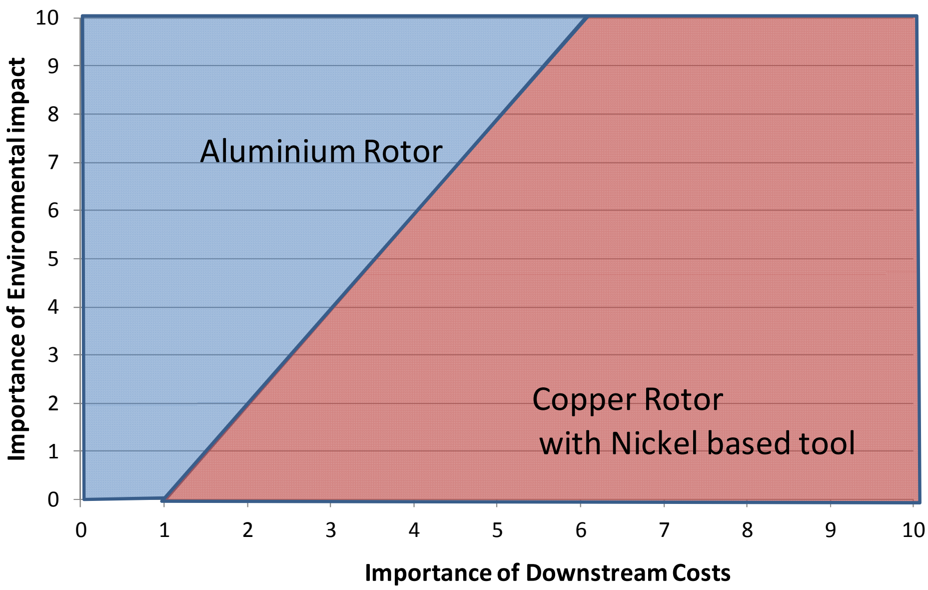


Figure 7.13 - Best-performing mapping of the candidate materials

7.3 Discussion

This chapter illustrates the possibility of expanding the Comprehensive Life Cycle framework to other processes using dedicated, tailored tools. The case studies regarding two different processes showed that CLC framework is also applicable to other processes beyond injection moulding, despite being required to develop appropriate correlations between the processes parameters integrating the tool and part life cycle (the processes are themselves different). However, following the methodology described in chapter 4 it is possible to expand the approach outside injection moulding parts and tools.

Regarding the particular case studies, the first is focused on the impacts of material selection in the overall life cycle of a metallic part produced by stamping and the correspondent tool. The case study was presented based on an automotive front fender, currently made of mild. The global objective was to analyse the possibility of using a different metallic material for the fender, as high strength steel or aluminium alloys, to redesign it accordingly (if necessary), and to evaluate the global performance of each material following the CLC dimensions of analysis. This application showed that by modelling the design changes (material and geometry) and the processes involved in the whole life cycle it is possible to assess the alternatives in both economic and environmental dimensions. The second case study explored the potential of the framework proposed in analysing another type of production process using dedicated tools, die casting. The case study comprised the life cycle of the rotor bars of an induction motor and the dedicated tool to cast the bars. The main goal was to assess the economic and environmental impacts of the rotor bars material selection. In this case study was clear the importance of incorporating the tool in the analysis. In fact, what seems a simple material change highly affects the tool, being determinant in the final decision.

Ultimately, the CLC framework and the models that embodied it are valuable engineering decision making instrument in a design and technology selection context. In the set of alternatives it was possible to identify the ones with lower LCC values. However, in each life cycle phase the best choice is not always the same. Additionally,

the best choice environmentally may not be the best in terms of costs. The decision rely on the importance given to the life cycle phases and to the cost/environmental dimensions. Therefore depending on who decides and when, supporting this framework informed decisions. Particularly relevant is its applicability to any dedicated tooling based manufacturing process, its flexibility of accommodating a wider range of sensitivity analysis (more than the ones presented in this document) and its potential to adapt the modelled processes to product and technological innovations.

8 CONCLUSIONS

Dedicated tools are a major issue in most products' life cycle; their design and production are in the critical path of a new product development and greatly affect the manufacturing process in which they are used. Despite being acknowledged by the industry, there is still a lack in the quantification of these impacts due to the "one of a kind" nature of these tools. This is especially critical when moving forward through the tool life cycle. In the tool design stage several relevant issues are not in a formal way, especially regarding aspects as reliability, material wastes, energy consumption, expected downtime, among others. However, there is generally sufficient theoretical knowledge and historical data and, most of all, tacit knowledge based on the experience of senior tool designers that can be gathered, treated and structured into formal relations and rules to support "good" design decisions. Another factor sensitive to the tool design is the environmental impact. Increasingly important nowadays, it is normally disregarded in tool design, as the tool itself usually represents low environmental burdens. Yet, when analysing the impacts of design changes in material and energy consumption, the environmental impacts can be very sensitive to it.

It is widely established the need to analyse a new part or product through a life cycle perspective. Tools can be acknowledged as products, although life cycle approaches to tool design are not common practice nowadays. Most analyses found analyse tool performance assessment and improvement restricted to the manufacturing processes. Furthermore, traditional product life cycle does not incorporate the tool, or when it does, the tool is only an input of "black box" nature. This thesis was a contribution to the life cycle research area by proposing a wider framework to product life cycle design, incorporating also the tool life cycle.

The proposed CLC framework integrates the part and the tool life cycles and combines process-based models of all life cycle phases involved, introducing relations of dependencies and impacts between them. These process-based models regard cost as a function of technical factors, such as cycle time, downtime, reject rate, equipment and tooling requirements, or the material used. As a dedicated tool is a critical element of the part manufacturing phase, the performance of the tool in its use phase (part production phase from the part point of view) was modelled as regards the part

production cycle time, the part material waste, the energy consumption, and the expected tools maintenance and failure cost, all according to the tool and part design specifications. While process-based models are traditionally cost models, in this framework we propose their use to assess also environmental impacts. They were found extremely suitable for environmental assessment when combined with an impact assessment method, in this case the EI'99. Given their mechanism of linking design parameters to process requirements most resources consumption are defined for costs and can be also translated into environmental impacts.

In order to understand the importance of the proposed integrated framework, it was applied to plastic parts produced by injection moulding. By integrating the plastic injection mould into the plastic part life cycle, it was possible to analyse all the processes within the integrated life cycle and investigate the relations between the part and tool life cycle phases. Several internships in injection mould and plastic injection parts producers allowed the development of two phases; the first, the development of the models required to fill the proposed framework; the second, the application of this framework developed for injection moulds and plastic parts life cycle to real case studies.

Several case studies were presented regarding plastic part produced by injection moulding. The case studies were separated in three types of analysis; regarding only tool design alternatives, only part design alternatives and both. This allowed understanding the type of models required for different design problems. For example, tool reliability depends mainly on the tool design, although the mould design is obviously connected with the part complexity. The relevance of the failure model was illustrated by analysing the impact of the mould design alternatives in the part life cycle cost (part use phase was disregarded as being not affected). Results have shown that only considering mould maintenance and mould failure models it is possible to capture the benefits of choosing the mould alternative with higher production cost, but with better performance in the use phase (injection moulding process). This is acknowledged by tooling companies but not quantifiable in current decision making processes. On the other hand, maintenance, material and energy outputs are related with both part and mould design decisions. Energy is also dependent on the injection machine power, which is also related with both mould and part design.

When looking at the environmental analyses performed, it was also visible the impact of both part and tool design in this dimension of analysis. The best choice economically is not always the best environmentally, despite both being sensitive to material and energy consumption. Cost drivers like labour are not environmental drivers, being clear the need to analyse both dimensions. Finally, an integrated approach for results outputs was proposed to address two decision problems; the question of adding costs allocated to the different stakeholders involved in the whole life cycle and the separation between costs and environmental impacts (EI). It was proposed to map the performance of the design alternatives for the two performance dimensions: cost and EI. Results of this graphic proposal shown different tool and part "best" design alternatives when different sets of weights regarding environmental impacts and downstream costs are chosen.

Ultimately, this research showed the importance of incorporating the tool design in traditional product life cycle design approaches, not only as an input but considering also tool alternatives that may improve the overall performance in the integrated life cycle.

One more question arose in the course of the research; would this framework be applicable and useful in other dedicated tools case? Although the modelling was developed for injection moulding based parts, the approach followed might be valid for other tool based manufacturing parts. However, appropriate adaptations are needed on the cycle time, maintenance, reliability, and energy and material consumption models to fit the physical mechanism of other technologies. For this, case studies from past projects were re-analysed and the process-based models for the specific production processes used. Two were chosen to cover the main production processes regarding dedicated tools, the stamping and die casting process. Despite some punctual lack of data, interesting results were obtained, showing in particular in the die casting case the importance of also considering the die design. The entire framework was "filled" with the available design relations found in the process models and data and further analysis were developed over a life cycle perspective. It was possible to conclude the suitability of this framework for the generality of dedicated tools and products, despite the need to further investigate in the future these design relations and more case studies.

Finally, this approach is not aiming to translate into a model the current design decisions, but aims to go further in capturing the most relevant impacts of these design

decisions, even if disregarded in the process. Moreover, it is especially useful when dealing with new technologies and tool features, as the modelling of the process allows estimating their future costs and other impacts without major investments. Hence, it can be used to support more informed decisions in the tool design phase, prior to the part production.

9 FUTURE WORK

The moulding industry is one of the most relevant in Portugal context. Moreover, nearly all plastic parts production employs moulds, affecting therefore the economics of producing a very large number of products. This places moulds reliability as a critical aspect regarding not only mould producers, but also plastic parts manufacturing industry. In particular, the failure of an injection mould may cause not only the machine downtime, but also other costs associated to the tool repair, penalties and safety stock. In this thesis the problem was addressed by decomposing the tool in sub-systems/components and profiling the failure probability of each using the Weibull distribution. However, the profiling is performed relying on experts' knowhow and disregarding the failure modes and mechanisms. An interesting research path to follow is to understand the tool sub-systems/components failure modes and mechanisms using a learning method based on real data. The proposal is to develop an Artificial Neural Network (ANN) in order to predict the probability of failure of each component, trained with extensive historical data collected in injection moulding industries. Although this method was never used in assessing reliability of dedicated tools, several studies have been successfully developed on products, structures and on the optimization of life and reliability of some tools. When input attributes are carefully chosen and sufficient data is available for training and testing the network, ANN proves to be a powerful predictive tool to apply in this area. ANN models are likely suitable to deal with mould failure data due to the high number of variables involved and the empirical historical data (and knowledge) available in Portuguese industry. Specifically, the following methodology is proposed:

1. Decompose plastic injection moulds into components, covering a wide range of mould types. To define the components and features critical to failure, along with the injected part specification and process parameters affecting mould reliability. This will be possible through extensive interviews and historical data collection in injection moulding and mould making industries.
2. Develop an Artificial Neural Network (ANN) using a multilayer perceptron with a feed forward learning model, in which the network inputs are attributes regarding the selected mould components and features, process parameters and

part specifications. The outputs regard the failure modes and correspondent time to failure statistics (mean, median and shape parameters).

3. Train and test the ANN with extensive historical data collected in injection moulding industries, covering the range of mould types defined in the first phase of the project. The database will be partitioned into training (90%) and testing (10%).
4. Develop a decision support tool using the ANN developed, trained and tested to support injection mould designers to predict in the design phase the failure profile of mould components and features according to the part and process specifications and parameters.
5. Develop this tool to be not only integrated in the design phase of plastic injection moulds, but also used in the definition of maintenance plans and spare parts, optimizing also the machine uptime, and therefore adding value to the moulds. Ultimately, the methodology can be replicated in other dedicated tooling industries, namely stamping and casting.

The development of a predictive tool to profile the failure modes of plastic injection mould sub-systems/components will allow predicting in a design phase the failure profile of a decision, fostering the optimization of maintenance plans, spare parts, machine uptime and therefore promoting added value to this industry.

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10 REFERENCES

Abernethy, R. B., 2006. The new Weibull Handbook, 5th edition. North Palm Beach: Robert B. Abernethy Publishing.

Ahsan, K., Gunawan, I., 2010. Analysis of cost and schedule performance of international development projects. International Journal of Project Management, 28(1), 68-78.

Almeida, D., Peças, P., Ribeiro, I., Teixeira P., Henriques, E. (2010). Application of Life Cycle Engineering for the Comparison of Biodegradable Polymers Injection Moulding Performance. Proceedings of the 18th International CIRP Conference on Life Cycle Engineering 2011. Braunschweig, Germany.

Altan, T., Lilly, B., Yen, Y.C., 2001. Manufacturing of Dies and Moulds. CIRP Annals – Manufacturing Technology, 50(2), 404-422.

Alting, L., Legarth, J. B., 1995. Life Cycle Engineering and Design. Annals of CIRP, 44(2), 569–580.

Andersson, K., Ohlsson, T., Olsson, P., 1998. Screening life cycle assessment (LCA) of tomato ketchup : a case study. Journal of Cleaner Production, 6(3-4), 277-288.

Aoe, T., 2007. Eco-efficiency and ecodesign in electrical and electronic products. Journal of Cleaner Production, 15(15) 1406-1414

Artto, K. A., Lehtonen, J.-M., Saranen, J., 2001. Managing projects front-end: incorporating a strategic early view to project management with simulation. International Journal of Project Management, 19(5), 255-264

Asiedu, Y., Gu, P., 1998. Product life cycle cost analysis: State of the art review. International Journal of Production Research, 36 (4), 883–908.

Aurich, J. C., Fuchs, C., & Wagenknecht, C., 2006. Life cycle oriented design of technical Product-Service Systems. Journal of Cleaner Production, 14, 1480–1494.

Azari-N, R., Kim, Y.-W., 2012. Comparative assessment of life cycle impacts of curtain walls mullions. Building and Environment, 48, 135-145.

Barringer, H. P., Weber, D. P., 1996. Life Cycle Cost Tutorial. Fifth International Conference on Process Plant Reliability, Houston, Texas.

Bay, N., Azushima, A., Groche, P., Ishibashi, I., Merklein, M., Morishita, M., Nakamura, T, Schimidt, S., Yoshida, M., 2010. Environmentally benign tribo-systems for metal forming. CIRP Annals – Manufacturing Technology, 59(2), 760-780.

Bento, C., Peças, P., Henriques, E., & Silva, A., 2008. Product Development guided by Value Analysis through Collaborative R&D. In Gonçalves, R. (Ed.), 14th International Conference on Concurrent Enterprising – ICE 2008 (pp.751-758). Lisboa: ESoCE-NET.

Berkout, F., Howes, R., 1997. The adoption of life cycle approaches by industry patterns and impacts. Resources, Conservation and Recycling, 20(2), 71-94.

Betz, M., Schuckert, M., Herrman, C., 1998. Life Cycle Engineering as Decision Making Support in the Electronics Industry. Proceedings of the Custom Integrated Circuits Conference, IEEE.

Bras, B., Emblemsvag, J., 1996. Designing for the Life Cycle: Activity Based Costing and Uncertainty, in Design for X, Concurrent ImperativesChapman & Hall, UK

Bribián, I.Z.; Usón, A.A.; Scarpellini, S., 2009. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification, in: Building and Environment, 44(12), 2510-2520.

Brissaud, D., Tichkiewitch, S., 2001. Product Models for Life-Cycle. Annals of the CIRP, 50(1), 105-108.

Chen, S., Keys, L. K., 2009. A cost analysis model for heavy equipment. Computers & Industrial Engineering, 56 (4), 1276-1288.

Chien, Y.-H., 2010. Optimal age for preventive replacement under a combined fully renewable free replacement with a pro-rata warranty. International Journal of Production Economics, 124 (1), 198-205.

Cho, H.-N., Frangopol, D. M., Ang, A. H.-S., 2007. Life-Cycle Cost and Performance of Civil Infrastructure Systems. Cooper, J. S., Vigon, B., 2001. Life Cycle Engineering Guidelines. (Report 600/R-01/101). Washington, DC: Environmental Protection Agency.

Chou, J.-S., 2011. Cost simulation in an item-based project involving construction engineering and management. International Journal of Project Management, 29(6), 706-717.

Cobas, E., Hendnckson, L., Lave, L., McMchael, F., 1995. Economic Input/Output Analysis to Aid Life Cycle Assessment of Electronics Products .Proceedings of the IEEE International Symposium on Electronics and the Environment. Orlando, Florida, 273-278.

Cooper, J. S., & Vigon, B., 2001. Life Cycle Engineering Guidelines. (Report 600/R-01/101). Washington, DC: Environmental Protection Agency.

Dahlén, P., Bolmsjö, G. S., 1996. Life Cycle Cost analysis of the labour factor. International Journal of Production Economics, 46-47, 459-467.

Dahmus, J., Gutowski, T., 2004. An Environmental Analysis of Machining, in: Proceedings of the 2004 ASME International Mechanical Engineering Congress and RD&D Exposition, California, USA.

Datta, P., Roy, R., 2010. Cost modelling techniques for availability type service support contracts: A literature review and empirical study. CIRP Journal of Manufacturing Science and Technology, 3(2), 142-157.

Dey, P. K., 2010. Managing project risk using combined analytic hierarchy process and risk map. Applied Soft Computing, 10(4), 990-1000

Dhillon, B. S., 1989. Life Cycle Costing. Gordon and Breach Science Publishers.

Dhillon, B. S., 1996. Optimum life cycle and labour costs estimation of repairable equipment. Microelectronics and Reliability, 36 (2), 227-229.

Duflou, J., Dewulf, W., Sas, P., Vanherck, P., 2003. Pro-active Life Cycle Engineering Support Tools. Annals of the CIRP, 52(1), 29-32.

Dunk, A. S., 2004. Product life cycle cost analysis: the impact of customer profiling, competitive advantage, and quality of IS information. Management Accounting Research, 15 (4), 401-414.

Duque Ciceri, N.; Gutowski, T.G.; Garetti, M. (2010): 'A Tool to Estimate Materials and Manufacturing Energy for a Product, in: IEEE/International Symposium on Sustainable Systems and Technology, Washington USA

Ermolaeva, S., Castro, G., Kandachar, V., 2004. Materials selection for an automotive structure by integrating structural optimization with environmental impact assessment. Materials and Design, 25(8), 689–698.

Eversheim, W., Neuhausen, J., Sesterhenn, M., 1998. Design to Cost for Production Systems. Annals of the CIRP, 47, 357-360.

Fabrycky, W.J., Blanchard, B.S., 1991. Life Cycle Cost and Economic AnalysisPrentice Hall, Englewood Cliffs, N.J.

Fava, J. A., Brady, K., Young, S. B., & Saur, K., 2000. Sustainable Strategies Using Life Cycle Approaches. Environment and Progress, 19(2),61–64.

Field, F., Kirchain, R., Roth, R., 2007. Process cost modeling. Strategic engineering and economic evaluation of materials technologies. JOM, 59 (19), 21-32.

Finnveden, G., Hauschild, M., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. Journal of Environmental Management, 91(1), 1-21.

Fixson, K., 2005. Product architecture assessment: a tool to link product, process, and supply chain design decisions. Journal of Operations Management, 23 (3-4), 345–369.

Folgado, R., Peças, P., Henriques, E., 2010. Life cycle cost for technology selection: A Case study in the manufacturing of injection moulds. International Journal of Production Economics, 128 (1), 368-378.

Fabrycky, W. J., Blanchard, B.S., 1991. Life Cycle Cost and Economic Analysis. Prentice Hall, Englewood Cliffs, N.J.

Fizsel, J., 1993. Design for the Environment: an Integrated Systems Approach. Proceedings of IEEE International Symposium on Electronics and the Environment. Arlington, VA, USA, 126-131.

Frangopol, D. M., Maute, K., 2003. Life-cycle reliability-based optimization of civil and aerospace structures. Computers & Structures, 81 (7), 397-410.

Fratila, D., 2010. Macro-level environmental comparison of near-dry machining and flood machining, in: Journal of Cleaner Production, 18(10/11), 1031–1039.

Fuchs, E. R. H., Field, F. R., Roth, R., Kirchain, R. E., 2008: Strategic materials selection in the automobile body: economic opportunities for polymer composite design. Composites Science and Technology, 68 (9), 1989–2002.

Goedkoop, M., Effting, S., Collignon, M., 2000. The Eco-indicator 99 - A damage oriented method for Life Cycle Impact Assessment Manual for Designers. PRé Consultants. http://www.pre.nl/

Goedkoop, M., Schryver, A., Oele, M., 2007. Introduction to LCA with SimaPro 7. PRé Consultants. http://www.pre.nl/

Guilong, W.; Guoqun, Z.; Huiping, L.; Yanjin, G. (2010): Analysis of thermal cycling efficiency and optimal design of heating/cooling systems for rapid heat cycle injection molding process, in: Materials and Design, Vol. 31, No. 7, pp. 3426-3441.

Guinée, J., Udo de Haes, H., Huppes, G., 1993a). Quantitative life cycle assessment of products: 1. Goal definition and inventory. Journal of Cleaner Production, 1(1), 3-13.

Guinée, J., Heijungs, R., Udo de Haes, H., Huppes, G., 1993b). Quantitative life cycle assessment of products: 2. Classification, valuation and improvement analysis. Journal of Cleaner Production, 1(2), 81-91.

Gutowski, T.G. (2010): The efficiency and eco-efficiency of manufacturing, in: International Journal of Nanomanufacturing, Vol. 6, No. 1/4, pp. 38-45

Gutowski, T.G.; Branham, M.; Dahmus, J.; Jones, A.J.; Thiriez, A.; Sekulic, D.P. (2009): Thermodynamic analysis of resources used in manufacturing processes, in: Environmental Science and Technology, Vol. 43, pp. 1584–1590.

Gutowski, T., Dahmus, J., Thiriez, A., 2006. Electrical Energy Requirements for Manufacturing Processes, in: 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium.

Hahn, T., Figge, F., Liesen, A., Barkemeyer, R., 2010. Opportunity cost based analysis of corporate eco-efficiency: A methodology and its application to the CO2-efficiency of German companies. Journal of Environmental Management, 91(10), 1997-2007

Hannsgen, G., 2008. The welfare economics of macroeconomics and chooser-dependent, non-expected utility preferences: A Senian critique with an application to the costs of the business cycle. Journal of Socio-Economics, 37 (5), 1980-1993.

Hanssen, O. J., 1998. Environmental impacts of product systems in a life cycle perspective: a survey of five product types based on life cycle assessments studies. Journal of Cleaner Production, 6(3/4), 299-311.

Hauschild, M.; Jeswiet, L.; Alting, L., 2005. From Life Cycle Assessment to Sustainable Production: Status and Perspectives, in: CIRP Annals - Manufacturing Technology, 54(2), 1-21.

Huang, J.-M., Jou, Y.-T., Zhang, L.-C., Wang, S.-T., Huang, C.-X., 2009. A web-based model for developing: A mold base design system. Expert Systems with Applications, 36(4), 8356-8367.

IES, 2010. ILCD Handbook: Analysing of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment. Institute for Environment and Sustainability, Joint Research Centre, European Commission.

ISO, 2006a. ISO 14040 International Standard. Environmental Management – Life Cycle Assessment – Principles and FrameworkInternational Organisation for Standardization, Geneva, Switzerland.

ISO, 2006b. ISO 14044 International Standard Environmental Management – Life Cycle Assessment – Requirements and GuidelinesInternational Organisation for Standardisation, Geneva, Switzerland.

Ishii, K., 1995. Life-Cycle Engineering Design. ASME Journal of Vibration and Acoustics, 117(B), 42-47.

Jagger, P., Bertsche, B., 2004. A new approach to gathering Failure behaviour information about mechanical components based on expert knowledge. Proceedings of the Annual Reliability and Maintainability Symposium, 90-95.

Jambulingam, N., Jardine, A. K. S., 2009. Life cycle costing considerations in reliability centered maintenance: An application to maritime equipment. Reliability Engineering, 15 (4), 307-317.

Jeswani, H.K.; Azapagic, A.; Schepelmann, P.; Ritthoff, M., 2010. Options for broadening and deepening the LCA approaches, in: Journal of Cleaner Production, 18(2), 120-127.

Jeswiet, J. A., 2003. Definition of life cycle engineering. In Bley H. (Ed.), Proceedings of the 36th CIRP international seminar on manufacturing systems (pp. 17-20). Saarbrücken: CIRP.

Jeswiet, J., Hauschild, M, 2005. EcoDesign and future environmental impacts. Journal of Materials and Design, 26(7), 629-634.

Jeswiet, J., Kara, S., 2008. Carbon emissions and CES™ in manufacturing, in: CIRP Annals Manufacturing Technology, 57(1), 17-20.

Johansson, K., Perzon, M., Fröling, M., Mossakowska, A, 2007. Sewage sludge handling with phosphorus utilization e life cycle assessment of four alternatives. Journal of Cleaner Production, 16(1), 135-151.

Johnson, M. D., Kirchain, R. E., 2009. Quantifying the effects of parts consolidation and development costs on material selection decisions: a process-based costing approach. International Journal of Production Economics, 119 (1), 174–186.

Kaebernick, H., Sun, M., Kara, S., 2003 Simplified Lifecycle Assessment for the Early Design Stages of Industrial Products. Annals of the CIRP, 52(1), 25-28.

Keoleian, G.A. and D. Menerey, 1992. Life Cycle Design Guidance Manual: Environmental Requirements and the Product System (Washington: DC: Risk Reduction Engineering Laboratory, Office of Research and Development, U.S. Environmental Protection Agency) EPA 600/R-92/226.

Keoleian, G.A., 1993. The application of life cycle assessment to design. Journal of Cleaner Production 1(3/4), 143-149.

Keys, L. K., 1990. System Life Cycle Engineering and DF”X”. IEEE Transactions on Components. Hybrids, and Manufacturing Technology, 13, 83–93.

Kharel, G.P., Charmondusit, P., 2008. Eco-efficiency evaluation of iron rod industry in Nepal. Journal of Cleaner Production, 16(13), 1379-1387

Kim, G.-T., Kim, K.-T., Lee, D.-H., Han, C.-H., Kim, H.-B., Jun, J.-T., 2010. Development of a life cycle cost estimate system for structures of light rail transit infrastructure. Automation in Construction, 19 (3), 308-325.

Kirchain, R. E. (2001): Cost Modeling of Materials and Manufacturing Processes, in: Encyclopedia of Materials, Science and Technology, , K.H.J. Buschow, et al., Eds. Oxford, England: Elsevier, pp. 1718-1727

Kordonowy, D.N. (2002): A Power Assessment of Machining, Undergraduate Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology

Krause, F.-L., Kind, Chr., 1996. Potentials of information technology for life cycle oriented product and process development. Proceedings of the IFIP WG5.3 international conference on life cycle modeling for innovative products and processes. H. Jansen and F.-L. Krause, Eds., Chapman & Hall: Berlin, 14-27.

Krozer, Y., 2006. Life cycle costing for innovations in product chains. Journal of Cleaner Production, 16(3), 310-321.

Kwak, Y.-H., Anbari, F. T., 2009. Analyzing project management research: perspectives from top management journals. International Journal of Project Management, 27(5), 435–446.

Nam, K., Chang, D., Chang, K., Rhee, T., Lee, I.-B., 2011. Methodology of life cycle cost with risk expenditure for offshore process at conceptual design stage. Energy, 36 (3), 1554-1563.

Lanza, G., Niggeschmidt, S., Werner, P., 2009. Optimization of preventive maintenance and spare part provision for machine tools based on variable operational conditions. CIRP Annals - Manufacturing Technology, 58 (1), 429-432

Lanza, G., Rühl, J., 2009. Simulation of service costs throughout the life cycle of production facilities. CIRP Journal of Manufacturing Science and Technology, 1 (4),. 247-253.

Lanza, G., Werner, P., Appel, D., Behmann, B., 2011. Increased trustability if reliability prognoses for machine tools. Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Germany, 225-228.

Lee, K.-M., Cho, H.-N., Choi, Y.-M., 2004. Life-cycle cost-effective optimum design of steel bridges. Journal of Constructional Steel Research, 60 (11), 1585-1613.

Lee, R.-S., Chen, Y.-M., Lee, C.-Z., 1997. Development of a concurrent mold design system: a knowledge based approach. Computer Integrated Manufacturing Systems, 10(4), 287-307.

Li, C.G., Li, C.L., 2008. Plastic injection mould cooling system design by the configuration space method. Computer-Aided Design, 40(3), 334-349.

Lundquist , L., Leterrier , Y., Sunderland , P., Månson , J-A. E., 2000. Life Cycle Engineering in Product Development. Life Cycle Engineering of Plastics, chapter 5, 101-127.

Nadeau, M. C., Kar, A., Roth, R., Kirchain, R., 2010. A dynamic process-based cost modeling approach to understand learning effects in manufacturing. International Journal of Production Economics, 128 (1), 223-234.

Nakao, M., Yamada, S., Kuwabara, M., Otubo, M., Hatamura, Y., 2002. Decision-based process design for shortening the lead time for mold design and production. CIRP Annals – Manufacturing and Technology, 51(1), 127-130.

Nam, K., Chang, D., Chang, K., Rhee, T., Lee, I.-B., 2011. Methodology of life cycle cost with risk expenditure for offshore process at conceptual design stage. Energy, 36(3), 1554-1563.

Osswald, T., Turning, L. S., Gramann, P., 2001. Injection Molding Handbook. Hanser.

Pacific NW Pollution Prevention Resource Center (PPRC), 1997. Report on the Analysis of Pollution Prevention and Waste Minimization Opportunities using Total Cost Assessment: A case study in the Electronics Industry, Seattle, WA.

Park, J.-H., Seo, K.-K., Wallace, D., Lee, K.-I., 2002. Approximate Product Life Cycle Costing Method for the Conceptual Product Design. CIRP Annals - Manufacturing Technology, 51 (1), 421-424.

Peças, P., Henriques, E., 2011. New Business Models for the Tooling Industry. Advances in Business and Management, 4, 1-33. Nova Science Publishers, Inc.

Peças, P., Ribeiro, I., Folgado, R., Henriques, E., 2009. A Life Cycle Engineering Model for Technology Selection: a Case Study on Plastic Injection Moulds for Low Production Volumes. Journal of Cleaner Production, 17 (9), 846-856.

Peças, P., Henriques, E., Ribeiro, I., 2010. Integrated approach to product and process design based on Life Cycle Engineering. Handbook of Research on Trends in Product Design and Development: Technological & Organizational Perspectives, Business Science Reference. IGI Global.

Peças, P., Ribeiro, I., Silva, A., Henriques, E., 2013. Comprehensive approach for informed life cycle-based materials selection. Materials and Design, 43, 220–232.

Pieragostini, C.; Mussati, M-C, Aguirre, P. (2011): On process optimization considering LCA methodology, in: Journal of Environmental Management, Vol. 96, No. 1, pp. 43-54

Pilot Project EDAM, 2008. Pilot Project Final Report, EDAM, MIT-Portugal Program.

Pousa, C., Ribeiro, I., Folgado, R., Peças, P., Henriques, E., 2009. LCC and LCA Simplified Models to Foster the Design of Sustainable Plastic Injection Moulds. In Waguih ElMaraghy (Ed.), 16th CIRP International Conference on Life Cycle Engineering – LCE 2009 (pp. 99-104). Cairo, Eqypt: University of Windsor.

Pusavec, F., Krajnik, P., Kopac, J., 2010a. Transitioning to sustainable production – Part I: application of machining technologies. Journal of Cleaner Production, 18(2), 174-184.

Pusavec, F., Krajnik, P., Kopac, J., 2010b. Transitioning to sustainable production – Part II: evaluation os sustainable machining technologies. Journal of Cleaner Production, 18(12), 1211-1221.

Ramesh, T.; Prakash, R.; Shukla K.K., 2010. Life cycle energy analysis of buildings: An overview, in: Energy and Buildings, 42(10), 1592-1600.

Rebitzer, G.; Hunkeler, D., 2003. Life Cycle Costing in LCM: Ambitions, Opportunities, and Limitations. International Journal of Life Cycle Assessment, 8(5), 253-256.

Ribeiro, I., Peças, P., Silva, A., Henriques, E., 2008. Life cycle engineering methodology applied to material selection, a fender case study. Journal of Cleaner Production, 16 (17), 1887-1899.

Ribeiro, I., Peças, P., Henriques, E., 2011. Life Cycle Approach to Support Tooling Design Decisions. Proceedings of the 11th International Conference on Engineering Design. Copenhagen, Denmark.

Ribeiro I., Peças P., Henriques E. (2008). Environmental Impact of Plastic Injection Moulds. Proceedings of the 3rd International Conference PMI. Ghent, Belgium.

Ribeiro I., Peças P., Henriques E. Life Cycle Engineering applied to design decisions, a case study. Proceedings of the 16th International CIRP Conference on Life Cycle Engineering 2009. Cairo, Egipt.

Rodriguez, C. E. P., Souza, G. F. M., 2010. Reliability concepts applied to cutting tool change time. Reliability Engineering & System Safety, 95(8), 886-873.

Rosato, D.V.; Rosato, M. G. (2000): Injection Molding Handbook, Springer – Verlag, 3rd Edition

Roy, P., Nei, D., Orikasa, T., Xu Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. Journal of Food Engineering, 90(1), 1-10.

Santos, J.P.; Oliveira, M.; Almeida, F.G.; Pereira, J.P.; Reis, A. (2011): Improving the environmental performance of machine-tools: influence of technology and throughput on the electrical energy consumption of a press-brake, in: Journal of Cleaner Production, Vol. 19, No. 4, pp. 356-364.

Senthil, K. D., Ong, S. K., Nee, A. Y. C., Tan, R. B. H., 2003. A proposed tool to integrate environmental and economical assessments of products. Environmental Impact Assessment Review, 23 (1), 51-72.

Sheriff, Y.-S., Kolarik, W.-J., 1981. Life cycle costing: Concept and practice. Omega, 9 (3), 287-296.

Shtub, A.; Bard, J. F.; Globerson, S., 2005. Project Management - Processes, Methodologies and Economics, Pearson Prentice Hall.

Song, R., Hanaki, S., Yamashita, M., Uchida, H., 2008. Reliability evaluation of a laser repair die-casting die. Materials science and Engineering, A(483-484), 343-345.

Sousa, I., Wallace, D., 2006. Product classification to support approximate life cycle assessment of design concepts. Technology Forecasting and Social Change, 73(3), 228-240.

Takata, S., Kimura, T., 2003, Life Cycle Simulation System for Life Cycle Process Planning, Annals of the CIRP, 52/1:37-30.

Takata, S., Kimura, F., van Houten, F.J.A.M., Westkämper, E., Shpitalni, M., Ceglarek, D., Lee, J., 2004. Maintenance: Changing Role in Life Cycle Management. Annals of the CIRP, 53(2), 643–655.

Tang, S.H., Kong, Y.M., Sapuan, S.M., Samin, R., Sulaiman, S., 2006. Design and thermal analysis of plastic injection mould. Journal of Processing technology, 171(2), 259-267.

Thiriez, A. (2006): An Environmental Analysis of Injection Molding, Master's Thesis at Massachussetts Institute of Technology, Cambridge.

Thieriez, A., Gutowsky, T., 2006. An Environmental Analysis of Injection Molding. Proceedings of the 2006 IEEE International Symposium on Electronics and Environment. Scottsdale, AZ.

Tillman, A. M., 2000. Significance of decision-making for LCA methodology. Environmental Impact Assessment Review, 20(1), 113-123.

Tipnis, V.A., 1991. Product life cycle economic models. Annals of the CIRP, 40(1), 463-466.

Tseng, H. E., Chang, C. C., Li, J. D., 2008. Modular design to support green life-cycle engineering. Expert Systems with Applications, 34, 2524–2537.

Tummala, V. M. R., Burchett, J. F., 1999. Applying a Risk Management Process (RMP) to manage cost risk for an EHV transmission line project. International Journal of Project Management, 17(4), 223-235.

Tysseland, B. E., 2008. Life Cycle cost procurement decisions: A case study of Norwegian Defence Procurement projects. International Journal od Project management, 26(4), 366.375.

Udo de Haes, H. A., Heijungs, R., 2007. Life-cycle assessment for energy analysis and management. Applied Energy, 84(7-8), 817-827.

Van den Heede, P., De Belie, N., 2012. Environmental impact and life cycle assessment (LCA) of tradicional and 'green' concretes: Literature review and theoretical calculations. Cement and Concrete Composites, 34(4), 431-442.

Vezzoli, C., Sciama, D., 2006. Life Cycle Design: from general methods to product type specific guidelines and checklists: a method adopted to develop a set of guidelines/checklist handbook for the eco-efficient design of NECTA vending machines. Journal of Cleaner Production 14(15/16), 1319-1325.

Vogtländer, J. G., Bijma, A., Brezet, H. C., 2002. Communicating the eco-efficiency of products and services by means of the eco-costs/value model, Journal of Cleaner Production, 10 (1), 57-67.

Wanyama, W., Ertas, A., Zhang, H.-C., Ekwaro-Osire, S., 2003. Life-cycle engineering: issues, tools and research. International Journal of Computer Integrated Manufacturing, 16(4), 307 – 316.

Warren, J. L., Weitz, K. A., 1994. Development of an Integrated Life-Cycle Cost Assessment Model. Proceedings of the IEEE International Symposium on Electronics and the Environment; IEEE: San Francisco, CA, 155-163.

Westkämper, E., Osten-Sacken, D., 1998. Product Life Cycle Costing Applied to Manufacturing Systems. CIRP Annals - Manufacturing Technology, 47 (1), 353-356.

Westkämper, E., 2002, Platform for the Integration of Assembly, Disassembly and Life Cycle Management. Annals of the CIRP, 51(1), 33-36.

Woodward, D. G., 1997. Life cycle costing—Theory, information acquisition and application. International Journal of Project Management, 15 (6), 335-344.

Wu, S., Longhurst, P., 2011. Optimising age-replacement and extended non-renewing warranty policies in lifecycle costing. International Journal of Production Economics, 130 (2), 262-267.

Yang, G., 2007. Life Cycle Reliability Engineering. John Wiley & Sons, New Jersey, USA.

Xie, L.-J., Schmidt, J., Schmidt, C., Biesinger, F., 2005. 2D FEM estimate of tool wear in turning operation. Wear, 258(10), 1479-1490.

Zhang, H.C., Li, J., Shrivastava, P., Whitley, A., Merchant, M.E., 2004. Web-Based System for Reverse Manufacturing and Product Environmental Impact Assessment Considering End-of-Life Dispositions. Annals of the CIRP, 53(1), 5-8.

Zhu, J. Y., Deshmukh, A., 2003. Application of Bayesian decision networks to life cycle engineering in Green design and manufacturing. Engineering Applications of Artificial Inteligence, 16(2), 91-103.

Züst, R., Caduff, G., Schumacher, B., 1997. Life-Cycle Modelling as an Instrument for Life Cycle Engineering. CIRP Annals – Manufacturing Technology, 46(1), 351-354.

Annexes

ANNEX 1 – MOULD FAILURE DATA

Table A1a) - Expert 1 – Mould maintenance manager

	Fmax	Fmin	tmax	tmin	tmod	**t0**	**T**	**b**
Swinging gear	0,980	0,012	1000000	24000	400000	24000	534230	2,108
Ejector pins	0,998	0,002	500000	24000	200000	24000	246100	2,364
Nozzles	0,972	0,028	1000000	200000	500000	200000	623054	2,007
Thin core pins	0,999	0,001	200000	5000	50000	5000	73204	1,858
Manifold	0,870	0,130	2000000	1000000	1500000	1000000	1701841	2,018
	0,870	0,130	2000000	1000000	1900000	1000000	1914986	8,041
Stop block	0,977	0,023	1000000	300000	500000	300000	626613	1,741
Slides	0,977	0,023	1500000	100000	1000000	100000	1079309	3,714
Mould cavity/core–abrasive material	0,977	0,023	500000	150000	300000	150000	344395	2,257
Mould cavity/core–non abrasive material	0,933	0,067	1000000	400000	600000	400000	735352	1,706
Corepins/ abrasive material	0,995	0,005	500000	150000	300000	150000	331819	2,566
Corepins/non abrasive material	0,991	0,009	1000000	400000	600000	400000	679010	2,033

Table A1b) - Expert 2 – Experienced mould maintenance technician

	Fmax	Fmin	tmax	tmin	tmod	t0	T	b
Swinging gear	0,933	0,067	1000000	12000	240000	12000	513113	1,462
Ejector pins	0,977	0,023	1000000	12000	100000	12000	349269	1,235
Nozzles	0,998	0,002	1000000	6000	300000	6000	415941	2,034
Thin core pins	0,999	0,001	480000	960	24000	960	101323	1,205
Manifold	0,977	0,023	1000000	12000	500000	12000	602373	2,578
Slides	0,966	0,034	1000000	60000	900000	60000	906544	11,608
Mould cavity/core–abrasive material	0,993	0,007	500000	60000	200000	60000	257712	2,003
Mould cavity/core–non abrasive material	0,997	0,003	1000000	360000	400000	360000	516411	1,230
Sliding block	0,966	0,034	1000000	24000	900000	24000	906324	12,047
latch	0,891	0,109	1000000	24000	750000	24000	813100	3,737

ANNEX 2 – COST RELATIONS OF BOUGHT COMPONENTS – PLASTIC INJECTION MOULDS

Table A2 – Mould structure cost according to its dimensions [data from Hasco catalogue]

Height (mm)	Length (mm)	Thickness (mm)	Cavity Plates	Clamping Plates	Backing Pates	Risers	Ejector Assemblies	Ejector Plates	Thermal insulating sheet
246	246	116	375 €	140 €	150 €	50 €	50 €	120 €	58 €
246	296	116	440 €	150 €	160 €	60 €	60 €	130 €	71 €
246	346	116	490 €	160 €	180 €	70 €	80 €	160 €	81 €
246	396	116	538 €	180 €	200 €	80 €	90 €	175 €	92 €
246	446	116	571 €	200 €	220 €	90 €	90 €	190 €	104 €
296	296	116	474 €	180 €	185 €	80 €	70 €	140 €	83 €
296	346	116	527 €	190 €	200 €	90 €	80 €	175 €	98 €
296	396	116	574 €	200 €	220 €	90 €	88 €	200 €	112 €
296	446	116	620 €	215 €	220 €	90 €	95 €	200 €	124 €
346	346	116	571 €	200 €	220 €	90 €	95 €	200 €	115 €
346	396	116	622 €	230 €	240 €	130 €	100 €	200 €	130 €
346	446	116	682 €	250 €	260 €	150 €	100 €	220 €	179 €
396	396	116	692 €	260 €	270 €	170 €	200 €	180 €	150 €
396	446	116	757 €	300 €	330 €	230 €	250 €	220 €	170 €
446	446	116	813 €	300 €	730 €	400 €	330 €	330 €	230 €

Regarding the hot runners system, its cost depends on the type of manifold, responsible for deliver melt to a mould cavity through a hot runner nozzle (see fig.A2 and equation A2), the number of nozzles and the existence or not of valves.

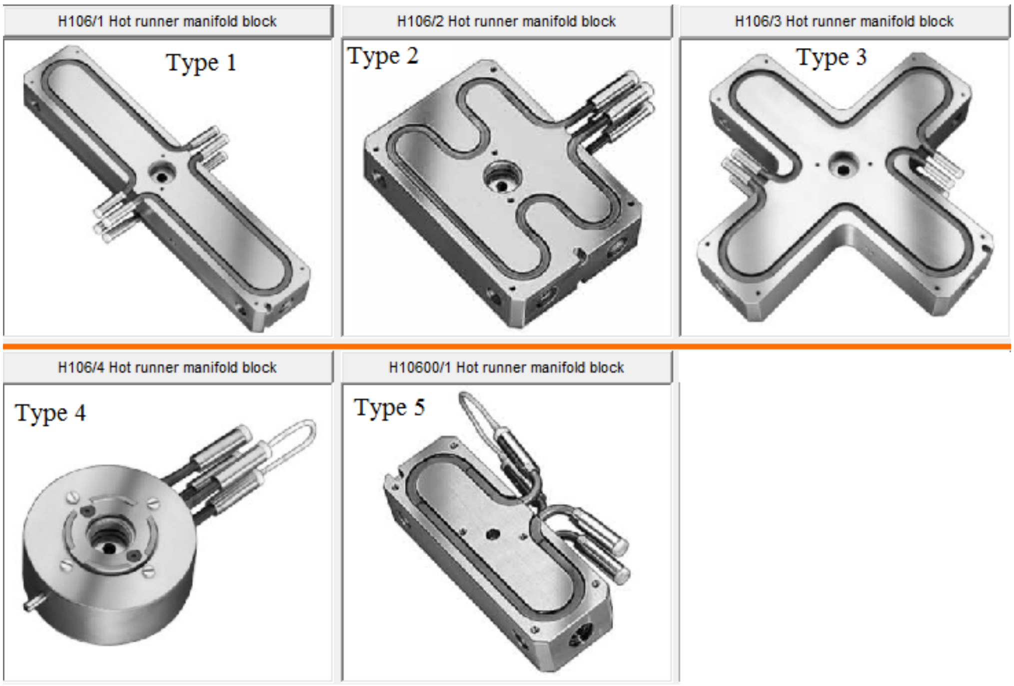

Figure A2 – Manifold types available

$$C_{hot\ run} = \begin{cases} \text{if with valve(s)}, & b * 2000 \\ \text{if without valve(s)}, & b * 1100 \end{cases} + \begin{cases} \text{if manifold type } 1, & 2.574 * l + 280.2 \\ \text{if manifold type } 2, & 5.773 * l + 116.5 \\ \text{if manifold type } 3, & 5.999 * l + 172.7 \\ \text{if manifold type } 4, & 793 \\ \text{if manifold type } 5, & 650 \end{cases}$$

[A2]

Where b is the number of nozzles and l is the length

ANNEX 3 - CASE STUDY 7 – MATERIAL PROPERTIES

Table A3 presents the main properties used in MIT-Portugal Pilot Project for defining the thicknes required for the fender in each material.

Table A3 - Material Properties of candidate materials [Pilot Project – EDAM]

MATERIAL ->		STEEL	STEEL	STEEL	ALUMINIUM	ALUMINIUM	ALUMINIUM
Property Name	Units	HX220YD	DOCOL 600P	DOCOL 1000P	AL6010	AL2036	GZ45/30
Yield Stress	MPa	220	350	700	170	193	155
Young Modulus E	GPa	200	200	200	69	71	70
Density	Kg/dm3	7.85	7.85	7.85	2.71	2.75	2.74
Coef. Poisson		0.29	0.29	0.29	0.33	0.33	0.33
Ultimate Stress	MPa	410	700	1200	290	338	
Thickness	mm	0.65	0.49	0.33	0.96	0.87	1.03
Von Mises Stress	MPa	221.1	289.1	587.5	142.3	161.5	129.3
Element Number	--	31869	25659	25659	31869	31869	31869
Max.Displecement	mm	5.87	10.39	22.75	7.46	8.92	6.33
Node Number	--	9866	9866	9866	9866	9866	9866
Factor Of Safety	--	1	1.21	1.19	1.19	1.2	1.2
1st Frequency	HZ	14.3	12.2	9.7	18	17.2	18.8
2nd Frequency	HZ	29.1	24.5	19.3	36.8	35	38.5
3rd Frequency	HZ	36.9	31.3	24.8	46.8	44.3	48.9
1st Frequency (fixed)	HZ	87.2	73.9	58.6	109.7	104.4	114.5
2nd Frequency (fixed)	HZ	98.3	85.1	70.5	122.4	116.7	127.7
3rd Frequency (fixed)	HZ	125.7	103.4	78.8	165.9	156.1	174.5