LCE: a framework for an informed and sustainable decision-making process

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Abstract

Life cycle engineering can be understood as an umbrella framework that covers all the engineering activities and engineering decision-making processes addressing technical/functional performance of products and systems together with the environmental and economic requirements for all their life duration. The integrated analysis of technical, economic and environmental dimensions of performance provides a solid foundation for engineers to understand the trade-offs and implications of their decisions since the early phases of the design process. This paper provides an overview of a life cycle engineering approach that contributes to a more informed decision-making process on the early development of products and systems, particularly as regards the analysis and selection of alternative design options, materials, technologies and manufacturing processes. The alternatives are analysed and, more than retrieving the best option, the results, as regards the dimensions of performance are mapped in a decision space diagram.

Keywords:

life cycle engineering, injection molding, multi-dimensional assessment

1 Introduction

During the last decade of the 20th Century several paradigmatic organisations of the manufacturing world began to consistently implement the life cycle concepts, fostering competitive and sustainable products and systems. For a trustworthy exploration of a life cycle based analysis three fundamental dimensions must be acknowledged: *functional* and/or *technical* performance, *economic* performance (cost) and *environmental* performance. These dimensions must be present on the decision-

R. Neugebauer, U. Götze, W.-G. Drossel (eds.), Energy-related and economic balancing and evaluation of technical systems – insights of the Cluster of Excellence eniPROD, Proceedings of the1st and 2nd workshop of the cross-sectional group 1 "Energy related technologic and economic evaluation" of the Cluster of Excellence eniPROD, Wissenschaftliche Scripten, Auerbach, 2013.
URN: http://nbn-resolving.de/urn:nbn:de:bsz:ch1-qucosa-105232

making processes of 1) competitive product design and manufacturing process planning or systems development and 2) sustainable technology/materials evaluation and selection.

The mentioned Functional/Technical and Economic dimensions are well established and have been used recurrently. However, to effectively promote competitiveness and sustainability they need to be enlarged for an integrative analysis on a life cycle perspective of products and systems. In other words, functional and technical performance should be assessed for all life cycle phases the product or system goes through. Accordingly, the assessment of the Economic performance should consider the integral costs incurred in a cradle-to-grave perspective, which is commonly referred to as Life Cycle Cost (LCC).

The environmental performance dimension, translated in the Environmental Impact (EI) is the dimension that somehow constitutes a novelty in this triangle of dimensions of analysis. In fact, the importance of Design for Environment (DfE) and Life Cycle Assessment (LCA) is a market push issue currently present in every sector of activity involved in the consumption and transformation of the planet earth resources [1-3]. Another driver for this dimension is the European legislative framework [4] that seeks to minimize the environmental impact of products by looking at their life cycle stages and taking action where appropriate. In the near future some obligations will arise for specific products to be placed on the market, namely the application of a form of life cycle assessment and the fulfilment of a setting of eco-design requirements [5, 6].

Despite these needs there are some barriers for the integration of the environmental dimension with the other two [7]. There are several tools available to support DfE and to perform an entire LCA to define the life cycle EI of the product [4, 8]. Regardless of all the existing methodologies their integration with the design process is difficult, time consuming and requires the availability of information related with the different materials and processes involved and data processing [7, 8]. To deal with these problems some authors advocate the permanent integration of an environmental expert (or even team) in the design process [9]. Another barrier is related with the inability of the available tools to incorporate economic aspects, product hierarchy levels and technical performance with EI [1, 5]. Some works have been published proposing methodologies to integrate these essential aspects in decision-making [10, 11] but it is still too early for them to be considered mature enough to be available as a toolkit for the product designer..

In this paper the use of Life Cycle Engineering (LCE) framework is proposed as an integrating approach of the three performance dimensions. This framework contributes to a more informed decision-making process on the early development of products and systems; and also on the evaluation and selection of materials, technologies, features and manufacturing processes. The LCE framework must be tuned to these two decision-making situations. In the next sections the general LCE approach is described and the LCE framework is proposed. The required tools are also described as well as the kind of results and assessments the LCE framework permits to obtain for the two types of decision context.

2 Life Cycle Engineering

On the trend of design for sustainability and competitiveness several authors have published relevant work related with the *Design for Life Cycle* topic. Aiming to distinguish these progresses from the more design-focused developments on *Design for X,* prominent institutions and researchers propose "Life Cycle Engineering" [12, 13] as an umbrella framework process to coherently organize the engineering and research developments in assessing the environmental impacts in conjunction with the economic impacts, taking into consideration the technical performances along the life cycle of products and systems. Three main research branches under the scope of LCE can be identified in the literature [14]: 1) Definition of guidelines and frameworks fostering the application of LCE philosophy in the early design phase of products, services and social policies [15-20]; 2) Development of strategies and approaches aiming at the implementation of LCE principles in the product's reliability and serviceability design and modelling [16-18]; 3) Development of tools and models that apply the LCE principles to compare alternatives during the product or process design phase [14].

The third branch is the most related with the research presented in this paper, so more emphasis will be given to it. Nevertheless, some important remarks must be stated related with the other branches. As Keys [15] points out the research in LCE challenges the academic world because it is problem focused and requires a multidisciplinary approach. In fact, the similarity of the LCE philosophy with Designing for the Life Cycle, emphasizes 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 [15-17]. As different authors pointed out [17, 18], the development of increasingly sophisticated products (systems or facilities) in shorter timeframes can be better achieved by a holistic understanding of products and processes life cycle. Additionally, a change in the whole concept of industrial production and in the consumer society behaviour is mandated by profound demographic and economic evolutions and by a growing awareness of environmental issues [17, 19]. So, to support LCE philosophy in early design phases, implementation guidelines were published, considering LCE an on-going process to develop specifications to meet a set of requirements and goals that span the product life cycle [20]. Additionally, LCE should be integrated into existing corporate structures and be based on pre-formed product teams rather than on new LCE teams [21, 22]. In this context, as the third research branch states, to take full advantage of LCE philosophy, a strong effort is required to develop models and tools for the application of LCE principles.

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 [16, 19]. Having in mind that decisions made at the design stage influence between 70 and 85 % of the total cost of the product [16, 18, 22] as well as the total environmental impact and its technical performance [13, 19], several tools have been developed to support effective and informed decisions at that stage. The aim of these tools is to fulfil total or partially the LCE goal as defined by Jeswiet [12]: “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”.

One of the first LCE models was presented by Ishi [18]. He proposes a tool based on a hierarchical semantic network to support early design decisions. Despite allowing a quick evaluation of the life cycle costs of a layout design, this tool does not support comparisons of alternatives and does not include environmental impacts of all life cycle. Betz et al. [23] proposed a LCE model integrating relevant information, regarding economic, environmental and functional/technological dimensions, in a single decision supporting tool. For results interpretation he proposed a 3D-portfolio method that allows a graphical reading of the outcomes. In spite of recommending one evaluation key for each dimension, the interpretation of the 3D-graphics is difficult and requires post-computing to identify the intersections points and the best-domains limits. Yan et al. [24] developed an integrated product and process development methodology based on a generic LCE framework, in which trade-offs on life cycle costs, environmental impacts and benefits are expressed formally as constrained optimization problems. An objective function is set with a fixed weighting for each dimension and the optimal alternative is found. However, the methodology is only demonstrated for products with a fully modular architecture, built from a set of alternative components. Also, the use of pre-determined weighting in the objective function limits the analysis of the alternatives.

Other models and tools to support design decisions that claim to follow an LCE approach can be found in literature [25-28]. Although their clear utility and scientific accuracy, they hardly can be considered as LCE tools since they do not embrace in an integrated way the three dimensions formerly mentioned: economical, environmental and functional/technical.

The models proposed by Ribeiro et al. [29] and Peças et al. [14] follow the LCE principles, using LCC, LCA and Multi Attributes Decision-Making (MADM) for the three dimensions of the analysis. The integrated analysis is performed through the use of ternary diagrams. A similar approach was already proposed by Betz [23] using 3D-graphics. However, ternary diagrams allow a clear visualisation and easier interpretation of the performance in each dimension as well as the identification of the “best domains” of each alternative. This innovative way of presenting the results facilitates the decision making in the design process and promotes the discussion. In fact, the decision making in engineering design is also a negotiation process among numerous perspectives of the involved team [27]. These models have been applied in the automotive sector [29] and in the plastic injection moulding sector [14, 30].

In a recent paper [31] an evolution of that model was proposed by the same authors adapting and proposing its application for the materials selection process. For the specific case of materials selection, the authors refer that the analysis of the functional/technical performance dimension is somewhat redundant. In fact, any candidate material has to meet necessarily the technical specifications of the product being designed. Furthermore, for the sake of minimum cost, designers are used to look for materials that just meet the requirements, avoiding those whose technical properties exceed significantly the minimum requirements. Of course, well selected high performance materials might result in products that exceed their minimum requirements. But, if it is a benefit indeed it should be reflected on the economic and/or environmental performances. The result is the development of a Materials Selection Engine (MSE) intending to contribute to a more informed decision-making process in materials selection [31]. Starting from a large set of materials that seems to fit the application, the materials selection procedure reduces the number of candidate materials based on technical performance requirements and follows through the analysis of their cost and EIs along the different life cycle phases. At the end, more than retrieving the best material, the results, as regards total life cycle EIs and costs, are mapped in a 2D decision space.

In the following section of this paper the LCE framework on the basis of these two application models is presented together with the illustration of the nature of results that can be obtained from these innovative approaches.

3 The proposed LCE framework

The proposed LCE framework integrates all relevant information that must be available within the design phase in a single decision supporting tool, regarding the technical, economic and environmental dimensions, and considers all the life cycle stages of the product. So, besides the obvious comparison of the alternatives in terms of product manufacturing time and cost, the model includes their economic performance in the following life cycle phases, namely product use and dismantling. Also, the environmental impact of each alternative during its life cycle can be quite different since different materials are used, distinct levels of energy are consumed, different maintenance levels are required and distinct disposal approaches are involved. The inclusion of the functional/technical performance aims to quantify the different levels of technical and production know-how incorporation, as well as different performances on technology and consumables availability, processes capabilities and product time-to-customer, which are often difficult (if not impossible) to translate into costs or EI measures. So, these characteristics, which might differentiate each alternative, must not be included in the other two dimensions of analysis.

The proposed LCE framework relies on the integrated analysis of these three dimensions in the two types of decision making-process. For supporting the product and process development the three dimensions are used in the same stage of the decision-making process. For supporting more focused decisions, like the selection of materials and technologies, the functional/technical dimension is exploited in a first stage for screening the candidate alternatives, and the economical and EI dimensions are the ones present on the final decision-making process.

The following sections are dedicated to present the information and tools required for the proposed approach to the life cycle engineering analysis as well as the mapping of the decision space inherent to both analysis contexts. In the first section are detailed the requirements related with product life cycle characterization and the need to define the main aims of the analysis. In section 3.2 the tools to assess the functional/technical performance are described, following the next section with the description of the tools to assess the economic and environmental performance. In section 3.5 the representation of the integrated analysis is presented giving some examples of its application.

3.1 Study aims and boundaries definition

In the proposed framework it is crucial to clearly identify the aims and boundaries of the study. This will permit to focus the analysis scope and limit the data volume requirements. The product life cycle phases must be identified and all the process involved should be characterized in a detail that depends on the study aim. It means that the inputs/outputs of each life cycle phase and their relation with the product/process design alternatives need to be identified. If dedicated engineering tools are involved in the product manufacturing (e.g. injection moulds, stamping dies, etc.) their related manufacturing process should also be considered. Additionally, there are some life cycle stages that may occur outside an industrial context, as for example the product use or some end-of-life (EOL) scenarios such as landfill or recycling. As these stages involve stakeholders outside the design and manufacturing context and often occur in a later timeframe, they should be evaluated individually. It should be noted that some phases may be disregarded if no costs or environmental impacts are entailed or if they do not change among the alternatives under analysis (for example the cost and the EI of the use phase of some household plastic products can be ignored).

Figure 1 presents a simple example of an automotive fender life cycle, with the reference on the type of information required for each life cycle phase. Another example of a plastic part life cycle and study boundaries (including the dedicated injection mould) is presented in Figure 2.

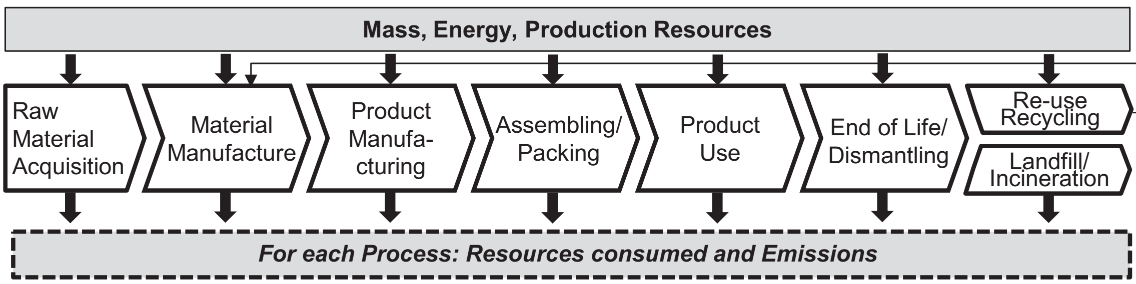

Fig. 1: Life cycle phases of an automotive fender [29, 31].

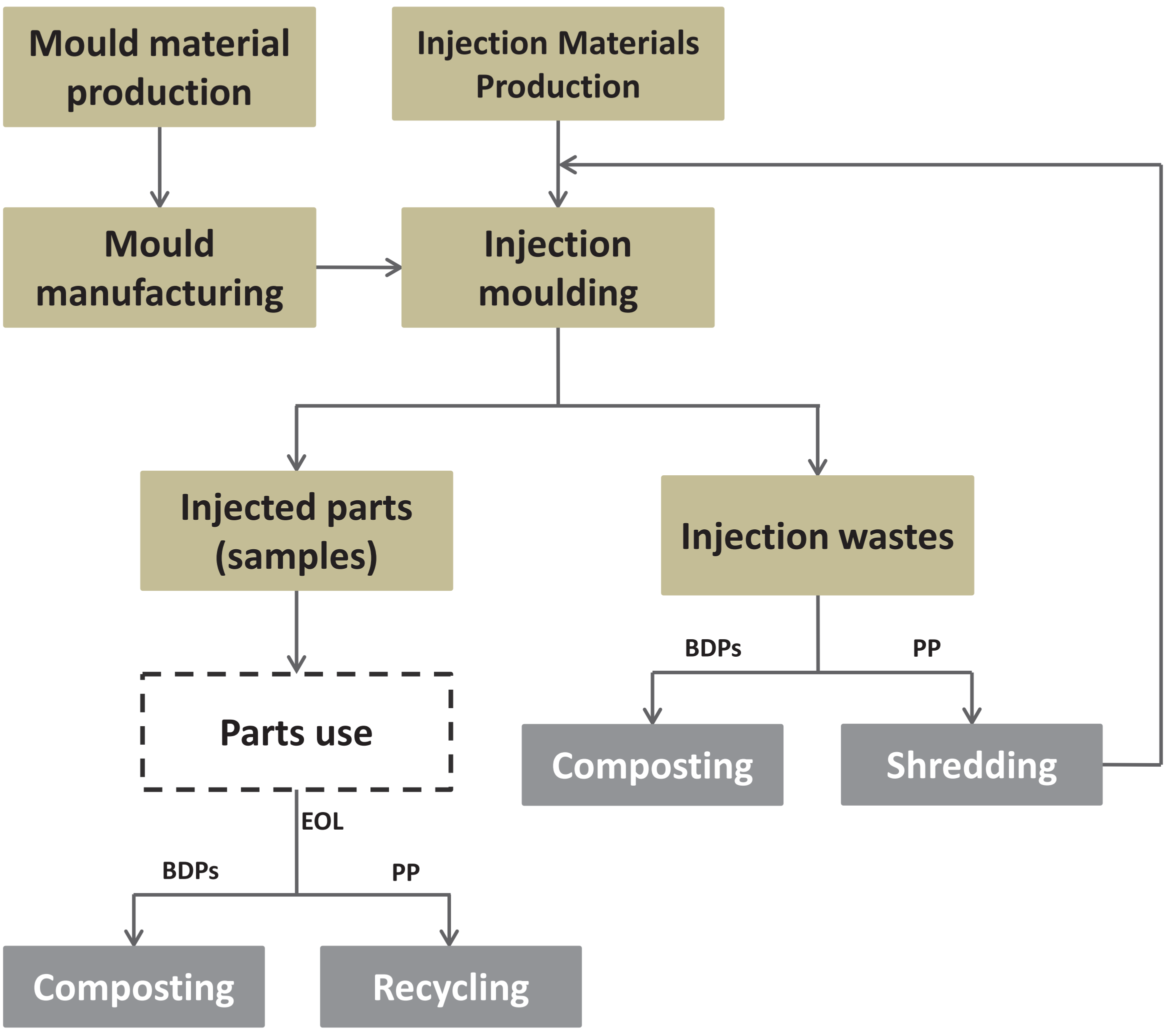

Fig. 2: Life cycle of plastic parts. In this study the LCE framework is applied on a household product manufactured by injection moulding where two types of materials are compared: a common polymer (polypropylene-PP); and several sub-types of renewable-biodegradable polymers (R-BDP) [32].

3.2 Functional/Technical dimension

The analysis of functional/technical performance of the product (system, tooling or technology) is performed using a multiple attribute decision method. The analysis relies mostly on the know-how of professionals (and users) to choose the relevant attributes to technically evaluate the different product alternatives (Figure 3). Several decision making methods can be applied on this kind of comparisons, such as graphic theory and matrix approach and fuzzy multiple attribute decision-making methods (MADM). In common, all of them rely on the know-how and expertise of professionals and users to determine the relevant functional attributes for the application, and, on a comparison basis, assess the performance of the alternatives within this set of attributes.

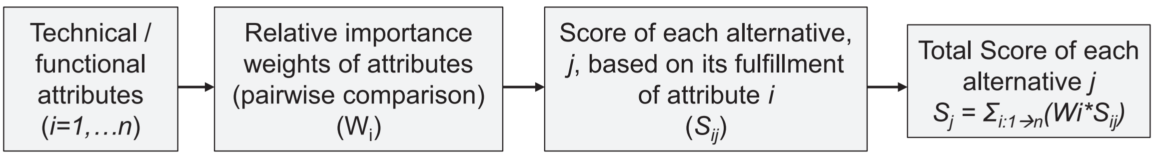

Fig. 3 Basic methodology used for the functional assessment. More complex methods can be used.

An example of functional assessment results based on MADM analysis method is presented in Table 1. The assessment functions were not included in the other two dimensions and can be used to relatively assess the alternatives. Table 2 presents an example of the functional assessment of pre-candidate materials for the manufacturing of an automotive fender.

Table 1: Example of Functional dimension assessment based on the methodology presented in Figure 3 (S_{ij}: 1-lowest; 10-highest performance based on moulds cavities characteristics). Study comparing three technological alternatives of injection moulds (steel and aluminium machining based moulds and mould formed by a spray metal shell backfilled with resin and aluminium powder) to produce very low volumes of a plastic part [32].

Functions (i)	***Weights (W_i)***	***Score of alternatives j in each function i (S_{ij})***		
		Steel; Machining	***Aluminium; Machining***	***Resin loaded with aluminium powder + metal shell; Spray Metal (SMT)***
Mould prod. technology reliability	*17%*	*10*	*7*	*1*
Number of mould production steps	*14%*	*10*	*8*	*1*
Time to plastic part production	*22%*	*1*	*5*	*10*
Mould capability in injection	*47%*	*10*	*7*	*1*
Score of alternatives (S_j)		***8.02***	***6.7***	***3.0***

Table 2: Example of final scores of the functional dimension assessment. Study comparing several alternative materials (different steels and aluminium alloys) for an automotive fender. After determining the relative importance of each technical attribute *i* (W_{ji}), the score of each *j* material alternative in each technical attribute (S_{ij}) is calculated having the product requirements as reference (S_{ij} =10*A_{ij}/R_i (A_{ij} - alternative specific attribute; R_i - product requirement attribute; if S_{ij} = E_{ij}/A_i > 1 → S_{ij} =10.. The total score of each alternative (S_j) is computed by the sum of the W_i*S_{ij} for each *j* material. The materials with the highest scores were identified as candidate materials for further detailed analysis [31]

Technical Attribute	*W_i*	*S_{ij}* St-1	*St-2*	*St-3*	*Al-1*	*Al-2*	*Al-3*
Yield Strength	*23%*	*10*	*10*	*10*	*7.8*	*8.7*	*7.0*
Young's Modulus	*23%*	*10*	*10*	*10*	*3.5*	*3.5*	*3.5*
Strain hardening exponent	*17%*	*10*	*8.8*	*8.2*	*10*	*10*	*10*
Density	*14%*	*3.6*	*3.6*	*3.6*	*10*	*10*	*10*
Ductility (strain at rupture)	*9%*	*10*	*5.6*	*1.1*	*7.8*	*7.8*	*8.9*
Coefficient of anisotropy	*8%*	*10*	*10*	*10*	*10*	*10*	*10*
Hardness	*6%*	*10*	*10*	*10*	*6.7*	*8.3*	*8.3*
	S_j	***90.8***	***83.8***	***79.7***	***75.4***	***78.5***	***76.0***

3.3 Economic dimension

The economic performance assessment is developed according to LCC methodology. 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. The general proposed LCC model with its general inputs and structure is presented in Figure 4.

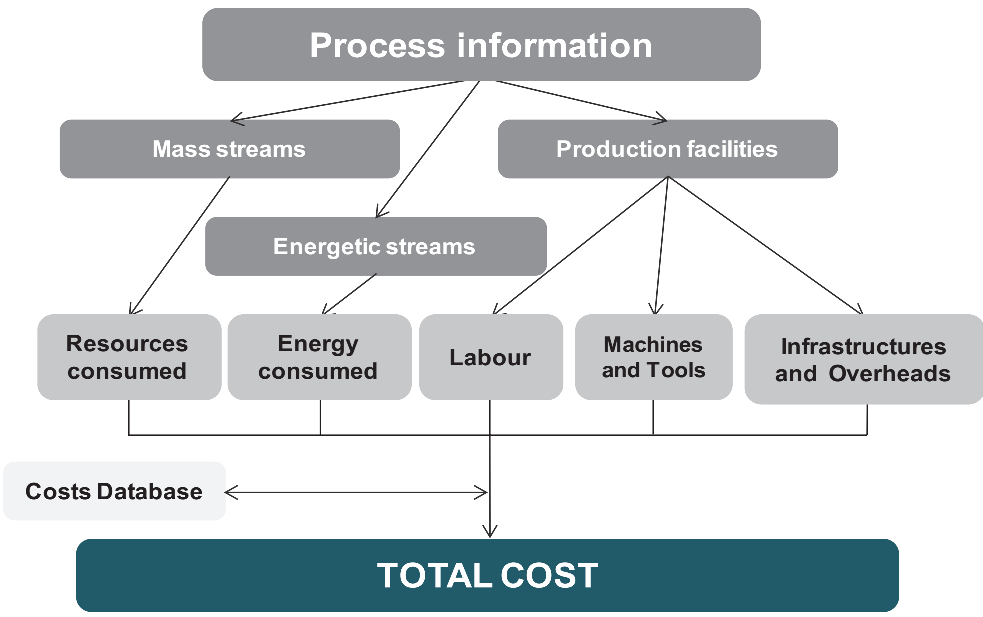

Fig. 4: LCC model structure.

This methodology is integrated with the process-based cost models which regard cost as a function of technical, operational and financial factors. This type of models has been applied by researchers to several processes within different scopes, always with the intent to compare alternatives – either in materials, processes or product architectures. Process-based cost models start from the description of the intended product (part material and geometry). The process(es) required for its production is(are) then modelled regarding the cycle time, resources (equipment and labour) specifications, materials and energy consumption, etc. This can be obtained with theoretical and empirical relations correlating the properties of the part and the requirements of the technologies involved in the process(es). 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, its time consumption). Having modelled all the processes and the required resources to produce the part, and introducing the price factors to each cost driver, the economic model is completed and the part cost computed (Figure 5). An example of an output for two injection mould alternatives is given in Table 3.

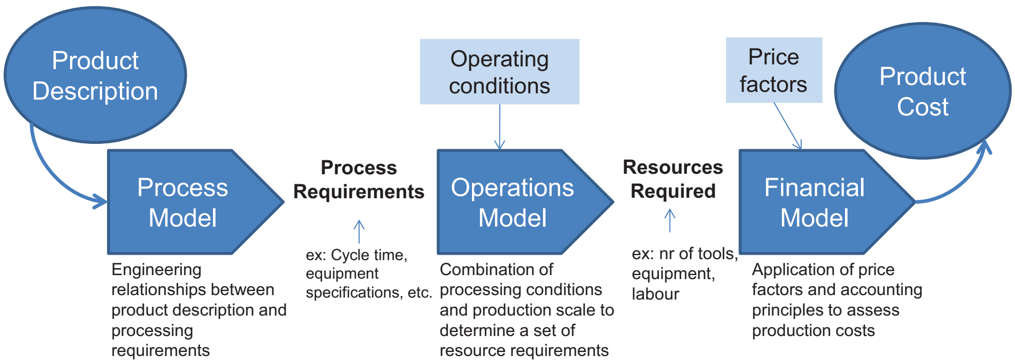

Fig. 5: Process-based cost models.

Table 3: Example of a LCC model results for two injection mould alternatives (Table 1) [14].

Life Cycle Phases	***Cost types***	***Aluminium Mould***		***SMT Mould***	
Mould Production	*Process*	*36.1%*	*92.0%*	*26.3%*	*87.8%*
	Materials	*53.1%*		*61.0%*	
	Energy	*2.9%*		*0.5%*	
Use of the Mould	*Process*	*1.1%*	*7.0%*	*3.3%*	*11.0%*
	Materials	*5.7%*		*7.3 %*	
	Energy	*0.1%*		*0.5%*	
End of Life	*Process*	*0.9%*	*0.9%*	*1.2%*	*1.2%*
Cost category	*Processes Costs*	*38.2%*		*30.8%*	
	Materials Costs	*58.8%*		*68.2%*	
	Energy Costs	*3.0%*		*1.0%*	

3.4 Environmental Impact dimension

The environmental performance analysis is performed using LCA, which is a structured method to quantify potential environmental impacts of products or services over their entire life cycle. Although LCA had emerged in the early 1970s, in the 1990s a standard terminology and methodology was established. Presently, LCA consists of four steps: definition of the goal and scope of the study, construction of the product life cycle model with all environmentally relevant 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. The LCA methodology is also integrated with process-based cost models. In fact, the mass, energy and emissions determined for the cost computing are used as input on the LCA model, representing the LCI phase [33, 34]. For the LCIA phase, 11 environmental impact categories are considered, in the following three areas: Human Health, Ecosystem Quality and Resources. The methodology aggregates all the emissions and resources consumption from the life cycle into these impact categories and, afterwards, weights the scores into a single value, called the "eco-indicator 99". The general proposed model is presented in Figure 6 and an example of the results achieved in Figure 7.

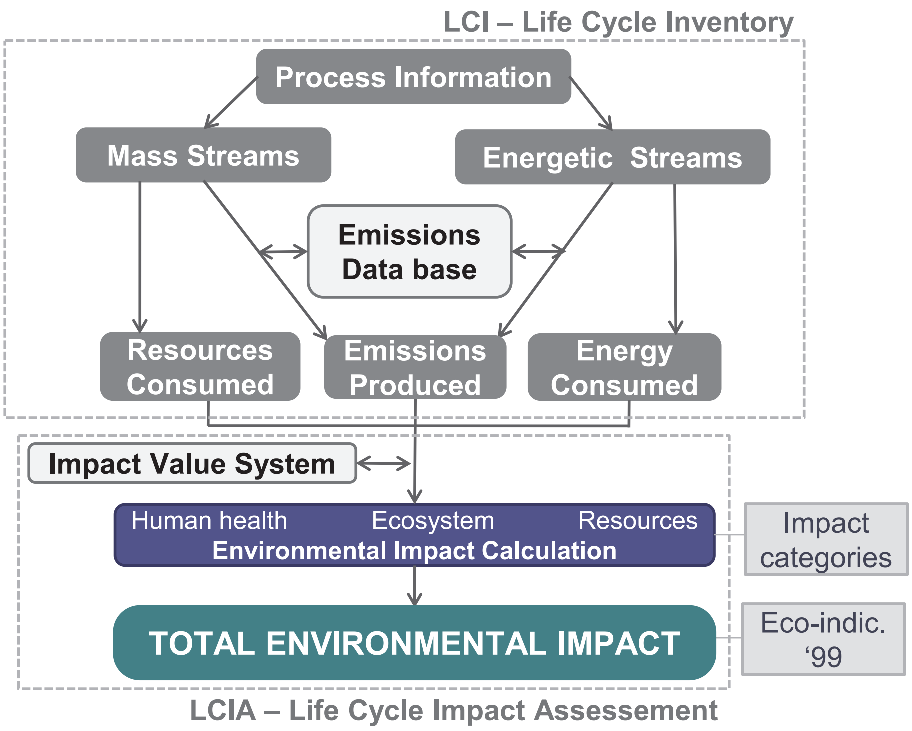

Fig. 6: LCA model structure.

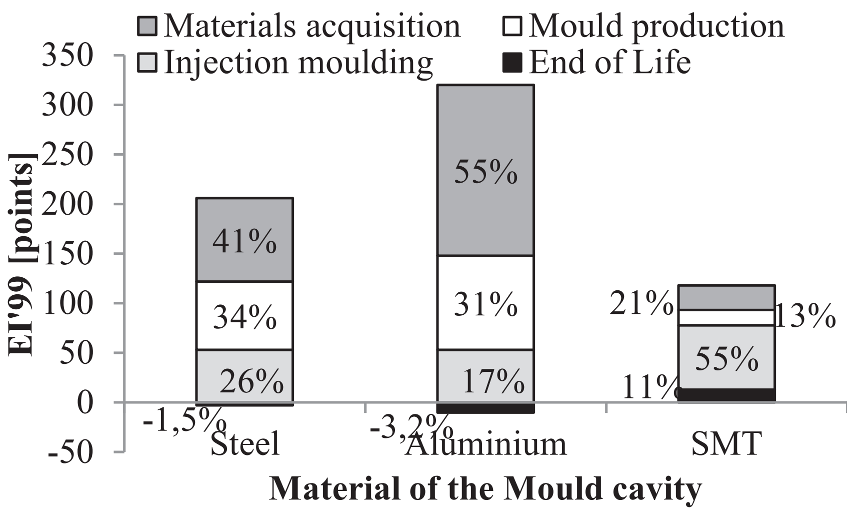

Fig. 7: Example of a LCA model results for three injection moulds alternatives (Table 1) [14].

3.5 Life cycle integrated performance

The analysis framework depends on the type of decision-making process required. In the cases the functional/technical dimension has a variable performance among the alternatives, the three dimensions must be analysed simultaneously. This is the case in most of product or process development projects and also on some technology evaluation undertakings. In other type of decision-making processes the functional and/or technical attributes are mostly requirements that must be achieved but higher values than the must be ones are not translated into a higher recognized performance. It means a preliminary screening process can be undertaken based on the technical/functional dimension to select the most adequate alternatives as potential candidates among a larger set. These candidate alternatives must then be assessed in the economic and environmental dimension. These two dimension analysis framework is proper to apply in most of materials selection processes and also on some technology evaluations (when the ultimate aim is to achieve a fix performance target).

The LCE analysis framework proposed is based on “best alternative performance mapping” rather than in common, fixed or pre-recommended importance weights. The major drawbacks normally pointed to a global evaluation based on fixed weights attribution are the difficulty to give importance weights to the dimensions of analysis that closely reflects the real corporation strategy and the sensibility of the results achieved to such weights. The use of performance mapping permits a clear and non-forced view of the possible “best alternatives” correlated to their domain of importance (weights). It should be noticed that there is an intermediate step before mapping the three or the two dimensions. This step is the normalisation of the performance of the alternatives in each dimension. The final values in each dimension are normalised for the value of the best alternative. The scores obtained for each alternative in each dimensions are then used to build-up the best alternative performance mapping.

So, the life cycle integrated performance evaluation is implemented through ternary diagrams where each axis represents one dimension of analysis in the case the three dimensions performance varies among the alternatives (Figure 8a). It becomes clear that the performance of an alternative is a relative quantity and that it depends on the set of alternatives being considered. Therefore there is no universally best alternative for a given application, which reinforces the need for tools to support decision making (Figure 8b).

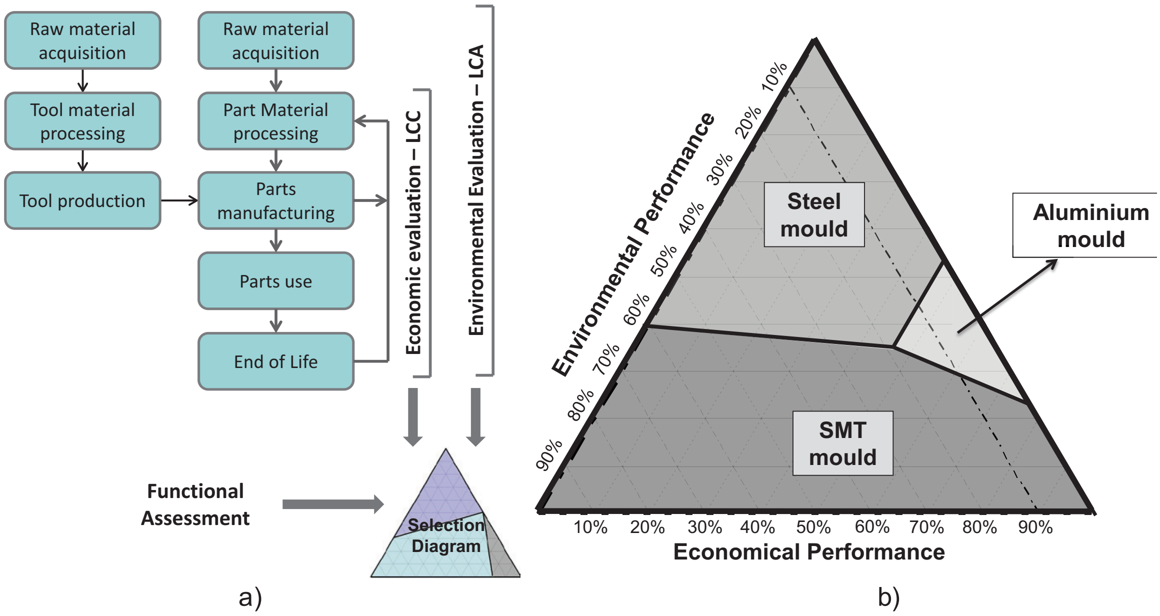

Fig. 8: a) LCE framework using ternary diagram for a decision-making process involving the product and dedicated tools life cycles; b) Life cycle integrating performance evaluation of three alternative mould designs for injection moulding of a plastic part [32].

In the cases, in which the analysis of the technical/functional performance is preliminary done just to identify the apparently best alternatives that deserve further evaluation, the diagrams are based on two axes. One axis represents the space of importance (between 0 and 1, zero and full importance, respectively) the decision makers give to EI. The other axis relates to the importance space of the downstream life cycle phases cost (use and EOL). It is assumed that the materials acquisition cost and production cost (the upstream phases) have a frozen importance, normally a full one if the analysis and decision takes place in a product development and manufacturing context. The best performing alternatives (e.g. materials) can then be mapped in this decision space allowing their classification as Cost-, Low impact-, User-, Balanced- and Environment-based type alternatives for the envisaged application (CLUBE classification), keeping the final decision for the design team (Figure 9a). This type of best-performing maps enrich the product design team with an integrated comparison of fitness-to-purpose alternatives along the product life cycle (Figure 9b). The separation of the maps in regions gives a kind of personality to the alternative that occupies each of the regions. Although this does not help in technical terms, it provides an interesting and new way of classifying the design options in relative terms. This in turn can be used to infer on feelings and emotions that each design option, material or technology elicits from users.

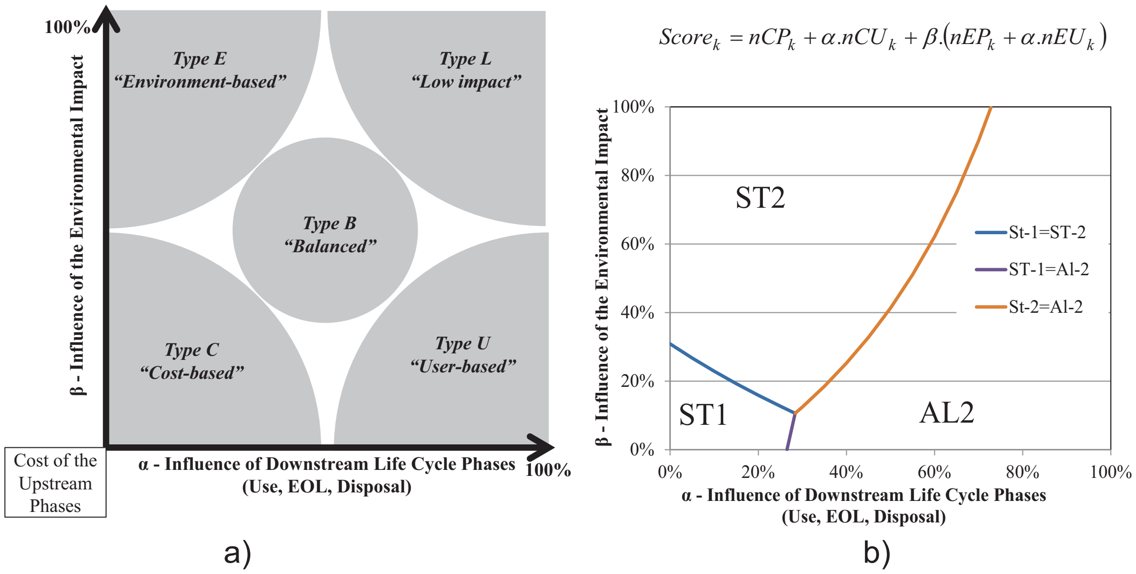

Fig. 9: a) Typical zones for each type of best materials based on CLUBE classification. b) Best-performing mapping of the candidate materials for an automotive fender. Where *k* refers to each alternative; *nCP* is the normalised cost for the life cycle phases prior to the Use phase; *nCU* is the normalised cost for the Use, EOL and disposal phases; *nEP* and *nEU* follow the same logic for the EI; α is the importance of the downstream life cycle phases and β is the importance of the EI performance [31].

4 Conclusions

The proposed LCE framework regards a comprehensive analysis of design alternatives in terms of the life cycle environmental and economic impacts, and also in terms of their functional performance. These analyses are assembled in a single framework, in which the mapping of the best alternatives becomes possible. The comparison of the alternatives in each case study is visually represented, providing a common communication tool to support the discussion and the decision among the design team members. Each point in the mapping diagrams is representative of a set of importance weights given to the different dimensions of analysis. So, depending on the companies' strategies the best alternative selection can be done in an informed way.

The best alternative maps should be represented in ternary diagrams when the technical/functional performance is different among alternatives and this difference gives to the alternatives a distinct perceived value not quantifiable in cost or EI measures. This is usually the case in the product and process development projects. Binary diagrams can be used when the functional performance is mainly a set of technical requirements that must be fulfilled to deserve consideration (and better technical performances do not reflect a higher value). In this case the functional dimension is applied as a screening of the candidate alternatives, as usually occurs in materials and technology selection.

Most of manufacturing sectors are very intense in introducing continuously new technologies and new ways of products and parts manufacturing. So, the framework presented is a valuable tool to assess, for several production and life cycle scenarios, the performance of those innovations even in stages where the existing information is limited.

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