The Need for a Life Cycle Approach on the Material Selection: a Case Study of an Automobile Fender

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Abstract— **The design stage of a product highly influences the products economic and environmental impacts throughout its life cycle. Therefore, decisions during this stage must be taken considering all possible information. The aim of this paper is to confirm the importance of analysing a product in an early stage of its development on a life cycle perspective. A case study was developed to outline this importance, considering the material selection of an automobile front fender. A set of candidate materials with different characteristics technologically suitable for an automobile fender were selected to analyse. The selection varied from mild steel to ultra strength steel and aluminium alloys. Starting from the most basic decision criterion, the material specific market cost, additional analysis were performed, including life cycle cost and environmental assessment, verifying that the "best material" considering different approaches is not always the same. The most economic material during production stage may not be the most economic one during the in-use stage and may also not be the most ecological one. Thus, life cycle approaches integrating the companies' strategies allow more conscious and informed decisions during product design stages.**

***Index Terms*— Material Selection, Life Cycle Cost, Life Cycle Assessment, Automobile fender.**

I. INTRODUCTION

To meet current markets needs, product design can not be focused only on design aesthetics, product performance and industrial costs. Decisions taken along product design stage largely influence the product's costs and environmental impacts for its entire life cycle [1]. Consequently, strategies and methods to promote the design of ecological and cost-effective products have been developed. In this context, life cycle approaches emerged in response to the need to develop products causing the lowest environmental impact, while still offering economic viability. Life Cycle Cost (LCC) evaluates economic issues while Life Cycle Assessment (LCA) considers environmental aspects, both for the entire life of a product or system. LCC refers to "all the costs associated with a product throughout the product's life" [2]. Its objective is to cover the assessment of costs for the succession of stages a product goes through in a cradle-to-grave analysis, including the costs not normally expressed in the product market price [3], 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 [2], [4]. Barringer et al [5] define that life cycle costs are summations of cost estimates from inception to disposal as determined by an analytical study and estimate of total costs experienced during their life. LCA is a structured method to quantify potential environmental impacts of products or services over their full life cycle [6], [7]. 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 - LCI), evaluation of the environmental relevance of inflows and outflows (Life Cycle Impacts Assessment - LCIA) and, finally, the interpretation of the results [8].

Within product design, material selection is an important area of application of life cycle methods. When selecting a material for a set of functionalities the relevant engineering properties of the material are identified and correlated to the design requirements. Normally, the selection is carried out considering the values of such properties altogether with economic considerations. For example, in mechanical design mechanical properties are the most important for material selection, but the influence of the material on the product final cost must be controlled to get a viable product as regards both technical and economical suitability. So, material selection is regarded as a multi-objective problem, being the optimal selection the best match between the available materials profiles and the requirements of the design [9], [10].

Material properties charts are probably the most common way of selecting materials for an application. They allow for the selection of a material, or set of candidate materials, by comparing two engineering properties at a time [11]. Cost is not a very realistic variable in this method. Even knowing that it is essential to evaluate the impact of the material in the product final cost, only a relative cost of each raw material is considered. As the relative cost of raw materials is only a parcel of such impact, the effect of materials, in a certain production volume, on manufacturing process and on its cost is naturally neglected. Considering that materials selection is a decision making process [12], another way of selecting materials is by using decision matrices. Several approaches, qualitative [13] and/or qualitative [14], are available. They are all very similar in their global methodology, based on a

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set of criteria and on some kind of criteria weighting to account for their different importance.

As mentioned by Field III, Clark and Ashby [15], all these approaches do not fully capture the entire materials selection framework, because no one covers the technological, economical, environmental, and current practice details needed to make an accurate and robust selection. This paper aims to contribute for a life cycle cost and assessment perspective of materials selection. A case study was developed, regarding the evaluation of a set of candidate materials technologically suitable for an automobile fender. A sequential approach of selection was followed based on material market price, fender material cost, fender production cost, and, finally based on the integration of the life cycle costs and environmental impacts. The importance of analysing on a life cycle perspective the design choices was confirmed.

II. Methodology

This paper aims to outline the importance of integrating information about the life cycle consequences of a material selection decision taken during the design of a product. With the rising public concern about environmental issues, the impacts of a design decision can not be focused only on conventional economic issues, being crucial to include life cycle costs and environmental aspects. The first step of any material choice is the pre-selection of some materials suitable for the application, based only on their technical performance. The pre-selection can be performed through Ashby material properties charts [10], concurrently with the expertise and experience of the design team. Within the pre-selected materials, the material specific market price (price per mass unit) is the basic decision criterion, also included in material properties charts. However, this approach is limited, as different materials can have a significant influence in the part dimensions, resulting in different amounts of materials. So the selection must take into account that materials with a higher specific performance may result in less material required to fulfil the same application. Moreover, even when similar materials are considered and the same production process is envisaged, those materials can induce particularities in the process that result in different production costs. Finally, when a life cycle approach is concerned the impact of the selected materials during the in-use and end-of-life phases, introduces even more variables in the selection decision.

In order to appraise the impact of life cycle issues in the effectiveness of material selection decisions a case study was developed, involving the selection of a metallic material for an automobile front fender, with an annual production volume of 100 000 units. The selection of the “best material” was made within a set of 6 candidate materials (3 aluminium alloys and 3 steels) all of them technologically suitable for the application. The question to answer in the case study is: when the design team considers only the material market price or the fender material cost as the only economic criteria is the selected “best material” different from the ones obtained when production costs and further life cycle issues are considered? Starting with a very basic comparison of the materials based only on their material unit cost, this study develops further approaches, ending in a life cycle cost and assessment that allow an informed decision.

III. Basic Approach: Material selection based on material specific market price

After defining a set of candidate materials technologically suitable for the application, the most basic approach is to compare them based on their specific market price. The material pre-selected and their specific market prices are presented in Table I. Aluminium is more expensive than steel in terms of cost per kg, while the mild steel (Steel-1) has the lower specific market price. So Steel-1 appears as the “best material”. However, as far as materials have different specific strengths and specific stiffness they induce different thicknesses to perform similarly in the application. Moreover, the density of aluminium is lower than the density of steel, pointing to different weights of the alternative fenders.

Table I – Specific market price of the candidate materials

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

IV. Material selection based on material cost

The candidate materials must assure the same technical/functional performance for the fender application. The aesthetics and the fender assembly conditions were considered to be frozen by the global automotive design, being the thickness the only possible design variation. Thus, the fender thickness for the six materials was determined, based on structural and frequency analysis, in order to guarantee the same and/ or a compatible technical behaviour of the alternatives. The objective was to guarantee that the alternative fenders have an equivalent level of strengths and strains when subjected to an equal load, and have natural frequencies far enough from the most relevant exciting ones. As far as the minimum required thickness for the fender made of each material is determined it is possible to refine the cost selection criteria, making an evolution from the material specific market price to the fender material cost. Results (Table II) 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 rejected fenders and material scraps inherent to the specific production processes.

Table II – Candidate materials and relevant design features (*Weight = Density x Surf. Area x Thickness)*

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

V. CONVENTIONAL APPROACH: MATERIAL SELECTION BASED ON MATERIAL AND PRODUCTION COSTS

So to refine the cost criteria the production process and its variations among the alternatives must be considered. To estimate the real material requirements and the production costs a technological cost model of the process was developed, in which several variations can be performed, including on the material, production volume, thickness and other relevant inputs.

In this model, the material cost includes the cost of the material input for the fender production, considering the rejects and scrap generated within the process, and the benefit of the scraps re-sold to the metal industry. The fabrication costs can be divided in two main cost groups: variable, which includes energy and labour, and fixed, which includes machine, tooling, building and fixed overhead cost. They are estimated based on process cost models, considering that the fenders of the candidate materials require the same process flow (blanking production, rinsing and stamping) and will be fabricated in a production line with the same organization. The costs associated with each step of the process flow are derived from a combination of engineering principles and empirical data considering the current manufacturing practice. Factor inputs include design specifications, material parameters, processing parameters (e.g., equipment parameters, space requirements, power consumption), production parameters (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. In the absence of accurate and site-specific data, which is the case for the new candidate materials, the machine and tooling costs were predicted based on the design specifications of the product using regressions derived from empirical data. 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 in a timeframe of 7 years.

Results (Table III) reveal that Steel-1 induces the lower production costs, 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, as ultra-high strength steel, requires a larger stamping force due to its high ultimate and yield strengths (high tonnage press machines and a more robust tooling set), and introduces a significant toughness in the guarantee the quality of the fender final surface (smaller production rate and higher reject rate). This aspect reveals the importance of estimating production costs during material selection stage.

Table III – 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**

VI. LIFE CYCLE APPROACH: MATERIAL SELECTION FOR LIFE CYCLE ECONOMIC AND ENVIRONMENTAL PERFORMANCE.

As previously exposed life cycle approaches were developed to reveal the importance of understanding the environmental and economical impacts of a decision over the life cycle of a product. Thus, life cycle cost and life cycle assessment models were developed and applied to the fender case.

A. Life Cycle Cost

Life Cycle Cost model (Fig. 1) allows the assessment of the product's life cycle cost. The fender life cycle considered included the material acquisition, production (labour, energy and fixed industrial facilities), fender use and dismantling stages. The first step of the model is to gather information from all processes for the entire life stages. With data related to the resources consumption along all these stages it is possible to quantify the different cost items involved, from labour and machine use to materials and energy spending, and correlate them to each life cycle stage. Table IV presents all these costs.

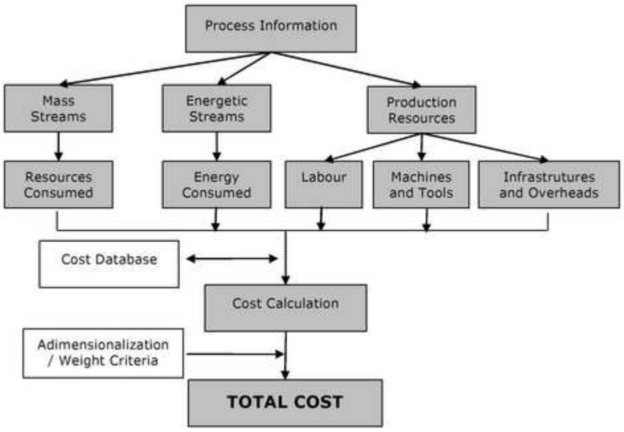

Fig. 1 – LCC Model

Table IV – Fenders Life Cycle Costs (100 000 fenders)

COSTS [€]	Steel-1	Steel-2	Steel-3	Al-1	Al-2	Al-3
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Total Production	**1 398 134**	**1 505 298**	**1 621 252**	**1 661 334**	**1 618 849**	**1 666 757**
Use	**1 844 444**	**1 411 590**	**988 750**	**979 607**	**894 659**	**990 451**
Dismantling	**5 905**	**4 519**	**3 165**	**3 136**	**2 864**	**3 171**

Along the fender life several costs are associated to different entities. For example, production costs are only supported by the industry in question, while the in-use costs are supported by the customers/users. Therefore, if the LCC analysis is being performed by the industry to support a material selection decision, these values can not be assumed as having the same importance. For the industry, a reduction in the production cost is normally perceived as more important than a reduction of the in-use costs. Therefore, as the results show, Steel-1 incurs in lower costs on the 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.

B. Life Cycle Assessment

At this stage an environmental impact assessment of all the candidate materials was performed. A cradle to grave approach was used, according to LCA standards [16] – [19]. The methodology for the impact assessment proposed (Fig. 2), considers eleven environmental impact categories, in the following three areas: Human Health (HH), Ecosystem Quality (EQ) and Resources (R). The methodology aggregates all the emissions and resources consumption cycle into these impact areas and, afterwards, weights the scores into a single value, called the “eco-indicator 99” (EI 99) [20]. The weighting coefficients were applied according to the hierarchic/average perspective (H/A), which is a moderate perspective generally accepted by the scientific community, attributing 40–40–20% of weight to the three considered impact areas, HH–EQ–R, respectively [21]. Detailed information can be found elsewhere [16] – [19], [20].

Table V presents the major consumptions and emissions over the fender life. Exhaustive results obtained in SimaPro7 software were incorporated in the environmental evaluation, but not presented in the table.

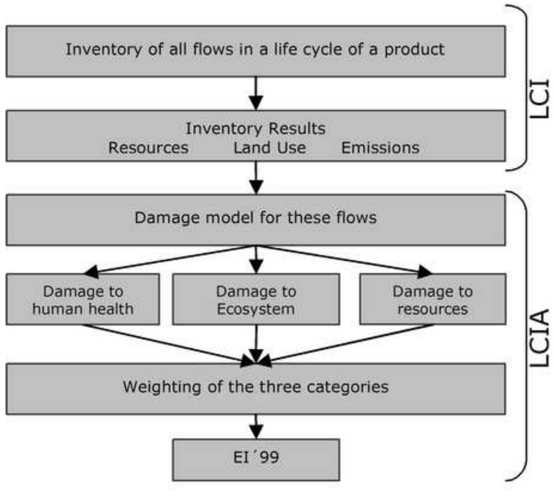

Fig. 2 - LCA Model

Table V - Consumptions and emissions over the fender life cycle (100 000 fenders)

	Consumption &Emissions	**Steel-1**	**Steel-2**	**Steel-3**	**Al-1**	**Al-2**	**Al-3**
Material Manufacture	Material [ton]	623	477	335	331	**302**	334
	Energy [TJ]	10.83	8.29	**5.83**	33.59	30.67	33.96
	CO_2e [ton]	1742	1333	**938**	3066	2800	3100
Fender Production	Energy [TJ]	**0.55**	0.60	0.72	0.55	0.55	0.55
	CO_2e [ton]	**6.22**	7.31	8.69	6.62	6.62	6.62
Fender Use	Fuel [m^3]	1346	1030	722	715	**653**	723
	CO_2e [ton]	3224	2467	1728	1712	**1564**	1731
Fender Dismantling	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

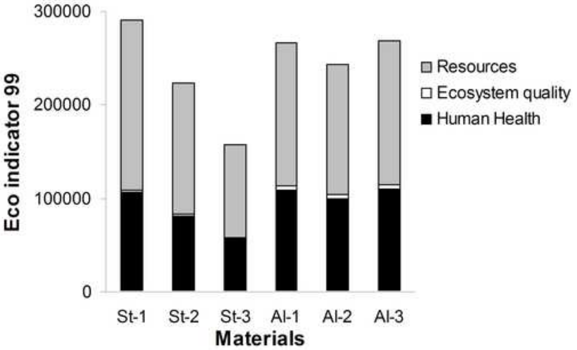

Fig. 3 – Environmental Evaluation of the fender life cycle (Eco indicator 99)

As the results achieved for the three major impact categories (Fig. 3) and the respective EI’ 99 show, 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, it performs better for the overall life cycle. Three major differences between the materials for the fender application establish their environmental evaluations: being steel or aluminium; their technical performance, which results in different thicknesses and fender weights; the recycling rate of the material is also an important issue, as different recycled material rates were considered: 30% for aluminium and 70% for steel [22], [23].

VII. CONCLUSIONS

This paper intents to reveal the importance of informed decisions regarding materials selection. The decisions should consider not only the production costs of the design alternatives, but also their economic and environmental impacts all over the product life cycle. To demonstrate the importance of these criteria a case study was presented based on an automotive front fender. The objective was to analyze a set of suitable candidate materials, from mild steel to ultra high strength steel or aluminium alloys, to redesign the fender accordingly, and to evaluate each material through several analyses. Results obtained revealed that a comparison based only on specific material market price or on the required material cost does not disclose the material that incurs in lower costs, as production costs are discarded in this decision criterion. The “best material” considering the required material cost (Steel-3) was not the same when considering also production costs, in which the “best material” is Steel-1. Moreover, the application of a cycle cost analysis shows that although Steel-1 remains the most economic material on the industry point of view, the in-use costs are lower using Steel-3. Finally, a LCA analysis was performed to compare alternatives on an environmental basis. The analysis revealed that economically the “best material” is not the environmental “best one”. The fender made of Steel-3 performs environmentally better than other alternatives mainly due to its low weight. Finally it should be noted that only metals were considered as alternatives. In fact, the screening of candidate materials, highly dependent on the expertise and experience of the design team, is a critical issue for any material selection.

Therefore, it was concluded that a comprehensive methodology is recommended when selecting a material for a product, as materials perform differently regarding different aspects of analysis. A choice considering only the material cost can lead to higher costs during production phase or during the in-use phase. Similarly, the most economic material regarding the life cycle cost can lead to higher environmental impacts. The knowledge of the product impacts, both economic and environmental, throughout its life cycle, can provide more informed decisions taken according to the companies’ strategies, as there is no “best material”; the choice relies on the “best material” for a certain goal. Moreover, a life cycle approach is recommended not only for material selection, but for all decisions taken during de design stage of a product, as early decisions taken during the development of a product highly influence its performance throughout its life cycle.

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