Application of Design for Environment principles combined with LCA methodology on automotive product process development: the case study of a crossmember

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Abstract. The existing Community regulation pushes the carmakers to design eco-sustainability of the vehicle over its life cycle to limit the consequences of the current state and the expected growth of the sector. In this sense, one of the primary aim is reducing raw materials consumption and emissions through the adoption of innovative materials and technologies. This implies the need for the carmakers to integrate Design for Environment (DfE) principles at the early Research and Development (R&D) stage. The article presents a concreate example of integration of DfE and LCA methodology application in the R&D process of a vehicle component produced by Magneti Marelli. The study allowed drawing a balance between the advantages of a lightweight solution with respect to the standard one both from performance and environmental point of view.

Keywords: Automotive sector, Sustainable Manufacturing, Design for Environment, Lightweighting, Life Cycle Assessment.

1 Introduction

The motivators that have pushed the Governments to focus their attention on sustainability activities are mainly due to the alarming data recorded on non-renewable resources depletion and global climate change. The transportation sector accounts for two-thirds of total crude oil consumption, and, one third for GHG emissions [1, 2]. Vehicles are extremely resource intensive products, especially during their use phase (particularly for internal combustion engines vehicles), causing a relevant amount of fuel consumption and CO_2 emissions generation. Another matter is originated by vehicle disposal; every year, in Europe, End-of-Life Vehicles (ELVs) constitute about 8-9 million tonnes of waste [3]; hence European Directive 2000/53/EC fixed new targets for vehicle recovery and specific standards (i.e. ISO 22628) exist for calculating the recyclability and recoverability rate of a vehicle [4, 5]. To tackle these prob-

adfa, p. 1, 2011.

lems, the automotive sector has started to focus the attention on environmental impact reduction initiatives, by getting involved into sustainability programs, incorporating policy regulations from the organization to the product level.

In order to meet environmental impact reduction, it is important to integrate environmental friendly principles and solutions in the R&D process, paving the way for the introduction of Design for Environment (DfE). The overall characteristics of DfE approach are the application at the early design phase and the perspective of the whole product life-cycle [6]. The Life Cycle Assessment (LCA) represents one of the most spread methodology providing useful set of environmental indicators for the DfE process and a clear procedure to compare and select the most favorable scenario; few case study application regards the automotive sector [7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. On the one hand, the use of LCA to drive DfE choice could provide in the LCA result interpretation since the environmental consequences are addressed by means of indicators which are distant from the designer comprehension (i.e. Abiotic Depletion Potential) [17, 18]. Moreover, an intensive data collection is required to obtain reliable results and, in most cases, the LCA analysis necessary relies on a number of assumptions [19]. On the other hand, LCA is a comprehensive methodology that, despite its inherent challenges in terms of data availability and impact indicators improvements [11, 20], is still considered a useful and practicable approach for designers.

This article presents a concrete example in which these challenges are addressed in the context of vehicle component lightweight design. First, an overview of the R&D workflow integrating DfE principles and LCA is shown. Then, a case study is presented concerning a part of the suspension system designed by Magneti Marelli$^{©}$. In this study, two important environmental issues have been focused, as relevant for the automotive sector: the mitigation of GHG emissions and the raw material reduction. Particular attention is given to the relationship between the lightweight strategy and these specific environmental objectives along the product life cycle, furthermore outcomes are discussed in terms of DfE strategies.

2 Method

Figure 1 shows the R&D workflow in which DfE principles are integrated with the LCA. First, the *DfE Conceptual Study* is defined, in particular the DfE approaches guiding the procedure [6] and the design strategy (i.e. lightweighting, power efficiency).

Then, the *feasibility analysis* compels the product functional requirements definition (i.e. corrosion resistance) which is preparatory for the design phase. This step is followed by the *prototype realization*. Finally, *Test Validation* is carried out to check if the innovative design satisfies the technical performance, accordingly to the specific component function. If the prototype is validated then its environmental performances are evaluated and compared to the standard design by means of LCA. Developing the environmental assessment after the prototype step would guarantee more reliable

LCA results since they could be based on detailed data collection about geometry, materials, technologies etc.

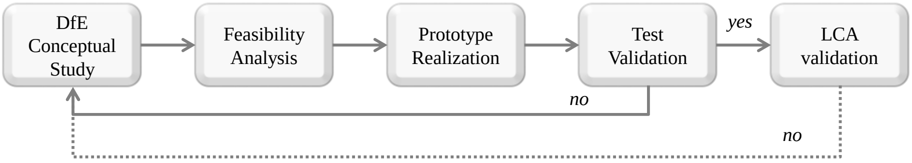

Fig. 1. R&D workflow which integrates Design for Environment principles and LCA

3 Case study

3.1 Component description

The method has been applied for a new design concept of an existing automotive component of the suspension system: a front crossmember, hereafter CM, made of stainless steel. The main reason guiding the CM selection is its mass (19 kg), so significant results could be expected through the implementation of a lightweighting strategy. Among the several DfE approaches [6], four of them can be considered particularly relevant for the sector: i) design to minimize material use; ii) design for manufacturing; iii) design for energy efficiency; iv) design for recycling. Lightweighting is obtained through the raw material substitution using an aluminum alloy. Moreover, additional changes are expected also in the production technology, the supply chain management and the recovery process during End-of-Life cycle.

The CM is a structural component that takes part either in the suspension system and transmissions connected to the body at different points and linked to the lower arms through elastic bushings. CMs design solutions are depicted in Figure 2; the standard design is stainless steel (19 kg) constituted by several sub-components (highlighted in difference colors), whereas the innovative design is one-piece unitary structure of aluminum (15.65 kg) allowing an overall reduction of about 22%.

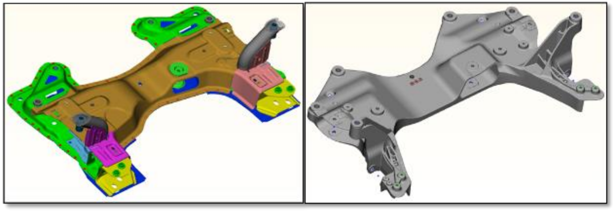

Fig. 2. CM standard design (left) and innovative design proposal (right)

Previous works have addressed the economic and environmental convenience of using cast aluminum in the design of an automotive crossmember [21, 22].

The substitution of the material did not lead to a geometry variation of the reference crossmember design; nevertheless specific tests were carried out in order to verify the aluminium conformity for crossmember functionality. Based on crossmember technological requirements, structural, static and dynamic stiffness, frequencies and corrosion resistance (CM is located under vehicle chassis and so exposed to a corrosive environment) have been accomplished. Results demonstrated that the innovative aluminum-component satisfy the functional requirements; in addition better corrosion-resistance can be provided.

3.2 LCA goal and scope, inventory and impact categories

The LCA analysis is performed according to ISO 14040 standard, following a "cradle-to-grave" approach. The functional unit of the assessment is the CM mounted on an Alfa Romeo Giulietta 1.4 Turbo 105 CV gasoline for an operational lifetime mileage of 150 000 km. Figure 3 shows CM life cycle phases for the two alternatives, which differ for the initial phases of production and manufacturing, affected by the employment of different materials and therefore manufacturing. For the End-of-Life (EoL) phase it was assumed the worst case scenario, where the component is not previously disassembled from the vehicle and the material recovery occurs during downstream treatments. To environmentally characterize all processes an analytical model reproducing real CM life cycle for each scenario has been developed by means of the software GaBi 6.5.

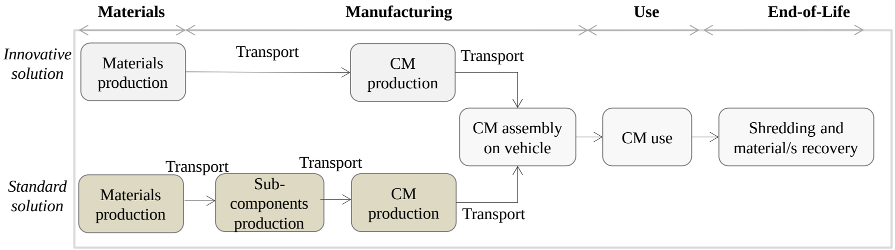

Fig. 3. CM life cycle breakdown for the two solutions of analysis according to the system boundaries considered

Primary data, concerning energy consumption of the machineries, auxiliary materials (i.e. process water) and scraps rate, have been collected for manufacturing and EoL phase, whereas raw materials and energy production eco-profile have been retrieved from the GaBi database. The raw material production category includes all stages from their extraction to the final state. The standard CM is produced with two different raw materials: austenitic stainless steel FEE 430 and ferritic stainless steel FEE 316, instead the innovative design with secondary aluminum 6061 - T6. In the modelling of the raw materials and auxiliary materials, GaBi6.5 database has been used.

The production technology of the standard design compels sub-components production, welding and painting process (pre-treatment and cataphoresis). Such processes are critical since involve several auxiliary materials and the production of sludge and waste water that need to be properly treated. The innovative CM includes one-piece unitary structure of secondary aluminum through die casting and machining processes. The scraps generated during steel-based sub-components and aluminum machining process were considered as steel and aluminum recycling credit of 22% and 32%[1] respectively. Process parameters (materials and energy flows) were obtained by direct measurements on industrial processes on site during the production period of one week dividing the energy expenditure and auxiliary materials consumption for the relative productivity; an extract is provided in Table 1. The logistic analysis takes into account all supply-chain actors from the raw materials extraction to the final phase of component assembly on vehicle suspension system. Logistic data on itinerary, transport typology and distance travel were collected (Table 1); the differences of the two supply-chain scenarios are in the up-streaming phase; in fact, for the steel based solution three different suppliers are involved whereas for the innovative solution only one supplier is present, while the means of transport is equal (Trucks 28 - 34t gross weight, 22t payload capacity, diesel driven, Euro 5 - cargo consumption mix, Gabi software modelling parameter). To calculate the environmental impact imputable to the CM mass during the use phase it was used an analytical model based on the approach of Koffler [23], taking into account the technical data referred to the specific vehicle (i.e. vehicle mass, type, fuel consumption, driving cycle) (see eq. 1). The amount of CO_2 and SO_2 are directly dependent from the fuel consumed during the operation life time of the vehicle equipped with the CM (see eq. 2).

$$Fuel\ component = Fuel\ vehicle \left({}^{Mcomponent}/_{Mvehicle} \right) * FRV \tag{1}$$

- $Fuel_{component}$, $Fuel_{vehicle}$ = fuel consumption of the reference component and the reference vehicle, (l/100 km);
- $M_{component}$, $M_{vehicle}$ = mass of the reference component and the reference vehicle, (kg);
- FRV_{NEDC} = Fuel Reduction Value for the NEDC driving cycle (0.12) [12]

$$emiss\ i = emiss\ i\ km * use\ km * ({}^{100 * fuel\ component}/_{fuel\ vehicle * use\ km}) \tag{2}$$

- emiss i = emissions of pollutant i during the entire component life-time (g);
- emiss i km = vehicle per-kilometre emission of pollutant i (g/km);
- fuel vehicle = vehicle per- kilometre fuel consumption (l/100 km).

During the EoL phase, it is assumed that the CM remains on the vehicle which is shredded and then material flows are sorted and recycled. Overall, the EoL management system is characterized by a high heterogeneity since different technologies and processes exist, moreover they are frequently developed in different plants [24]. In this study, it has been assumed a typical Italian craft-type Authorized Treatment Facilities where two main stages targeted to ferrous and non-ferrous metals sorting. The first stage includes shredding, aeraulic separation and magnetic separation for ferrous metals separation. The remaining waste flows are then treated by means of magnetic separation, eddy current, inductive resonance and ballistic separation for the non-ferrous metals separation. To model the initial phase of vehicle shredding was considered the *car drained* process within Gabi 6.5 database, then for the further processes

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[1] Based on GaBi 6.5 steel rebar world steel data and aluminium credit data.

and energy consumption, primary data were collected from an EoL plant during one day of operation (Table 1). To perform the recovery process, it has been considered the *sorted automotive casting scrap credit* process for steel solution and *aluminum auto fragments scrap credit* process for aluminum, already modeled in Gabi software.

	Standard	**Innovative**
Manufacturing		
the Electricity consumption manufacturing phase	Sub-component production = 9.5 MJ/FU Welding = 2000 MJ/FU Painting = 88 MJ/FU	Machining = 7.42 MJ/FU
Electricity consumption EoL treatments	Shredding → Aeraulic separation → Magnetic separation = 2.76 MJ/FU	Shredding → Aeraulic separation → Magnetic separation → Eddy current → Inductive resonance → Ballistic separation = 3.66 MJ/FU
Logistic		
Total distance travelled (km)	2700	1129

Table 1. Manufacturing processes, EoL treatment electricity consumptions (CM standard with ferrous recovery and CM innovative with Al non-ferrous recovery) and logistic data (distance for the delivery of goods across CMs supply chain within manufacturing gate)

The impact categories selected aim at evaluating the aforementioned environmental issues (GHG emissions and resource depletion) which the new design strategy intends to decrease. In particular the Global Warming Potential (100 years) (GWP), the Abiotic Depletion Potential Elements ($ADP_{elements}$) and Primary Energy Demand (PED) from the CML method are calculated.

4 Results and discussions

The material and technology variation mainly influenced the emissions generated during vehicle operation and the recoverability portion of the material at the component disposing stage, in Table 2 are summed up the results.

	Standard	**Innovative**
CO_2 emissions (kg/FU 150 000 km)	92	75
SO_2 emissions (kg/FU 150 000 km)	5.07E-04	4.16E-04
Fuel consumption (l/FU 150 000 km)	34	28
Metals recovery ratio	0.023[2]	0.32[3]

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[2] Data from Gabi process data set "*Steel mill scales - scrap credit*" based on average price ratio between Steel Benchmarker GLO plate and EU scrap price 2007 – 2010.

[3] Data from Gabi process data set *"Aluminium auto rads - scrap credit"* based on average price ratio between LME Al99.7 and EU scrap price 2007 – 2010.

Table 2. Overview of standard and innovative component general feature over their life cycle

LCA results demonstrate that the new design solution entails a significant impact decrease up to a 70% for all the impact categories with the most outstanding linked to the ADP $_{\text{elements}}$ with a sharp reduction of more than 90%. It can be observed that the highest discrepancy between the two solutions is given by raw material and manufacturing life cycle phases. However, further benefit are achieved also in the use phase, in fact the lower density of the new material allowed an overall mass reduction of about 22%. It can be observed that the three impact categories are affected by different component life cycle phases. The ADP$_{\text{elements}}$ is mainly related to the raw material phase, whereas the GWP and PED are affected by use phase and manufacturing.

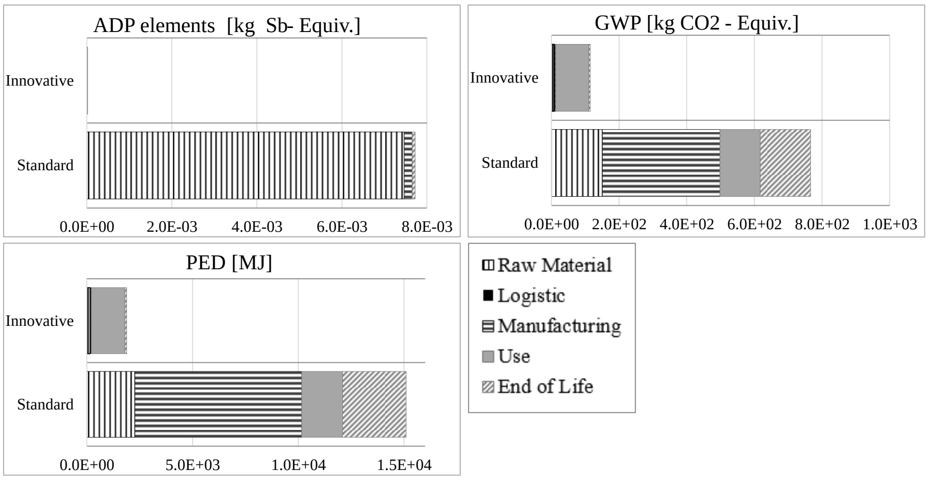

Fig. 4. LCIA results for the comparison of the standard and the innovative solutions for PED, GWP$_{100}$ and ADP$_{\text{elements}}$ indicators

Concerning the raw material phase, the standard solution involves the usage of heterogeneous-heavyweight raw materials (austenitic and ferritic stainless steel). The production process of stainless steel involves a numerous step and a consumption of hazardous materials as nitric and hydrofluoric acid during pickling process, ester and paraffinic mineral oil for surface quality control and so forth. The innovative solution leads to a significant reduction of resource consumption due to the use of recycled material, which also involves a lower energy consumption and less auxiliary materials consumption decreases (i.e. O_2, CH_4, Ca_2O_4Si $_{\text{powder}}$).

The reduction of the number of the parts in the innovative design concept lead to a simplification of the supply chain. In the standard case, the total distance covered by all the transportation is more than 3000 km with five suppliers involved. Instead, the innovative solution requires only one supplier with a total distance travelled of 780 km. As far as manufacturing phase is concerned, the CM standard solution involves processes that are more critical. In particular, welding and painting process are responsible for a great quantity of auxiliary materials (i.e. water and chemicals), take more time and consume more energy if compared to the die-casting production process. During the standard production process, the semi-finished product is transferred across difference lines dislocated along the production plant via huge-tape transport conveyors thus increasing electricity consumption. In contrast, the production process of the aluminum component consists of only two stages: die casting and machining. The energy expenditure for the production of the innovative CM is noticeably less and this influence the GWP and PED figures considerably. Overall, the advantages in terms of manufacturing phase are multiple: i) savings of energy expenditure due to the convey system simplification and production process substitution; ii) time cycle shortened; iii) more stable process and greater control through make- process strategy; iv) reduction of auxiliary materials; v) decrease of process waste generation. Vehicle use phase accounts for the greatest part of the generation of CO_2 emissions and fuel consumption whose decrease is 18.5% (Table 2). Concerning the EoL phase the innovative solution is still preferable since a higher recovery ratio can be obtained.

4.1 Combining LCA impact results and DfE approaches

$ADP_{elements}$ indicator quantifies the impact on resource depletion and so it is particularly influenced by raw material phase. The effect of Design to minimize material usage strategy could be measured through $ADP_{elements}$ indicator. The lightweight strategy has revealed to be effective for the following reason:

- The production process of stainless steel requires more energy and auxiliary materials compared to the secondary aluminum [25];
- The production process of standard CM requires a great amount of auxiliary materials;
- The recycling credit of aluminum is higher than the steel.

GWP quantifies the GHG emissions, whose great generation is related to vehicle operation and manufacturing process, could be representative of the Design for Energy Efficiency effect, but also answers for Design for Manufacturing objectives in the measurement of process energy-expenditure and Design for End-of-Life in terms of GHG saving for the material recovered. The PED indicator measures the total energy demand in terms of renewable and non-renewable energy resources. According to the LCA results, PED is particularly related to Design for Energy Efficiency approach but also to Design for Manufacturing and Design of End of Life.

Finally, the relationship between the selected DfE approaches and the CM life cycle phase is presented in Figure 5. The results revealed that the selection of Design to Minimize Material Consumption and Design for Energy Efficiency, through the substitution of aluminum as a lightweighting-strategy driver, revolutionized the whole life cycle of the crossmember. This is a clear example demonstrating that life cycle phases could be interlinked by specific driver selection in design decision: for the case in question the raw material substitution. The following life-cycle framework (Figure 5), offers a visible explanation of such concept; the lightweight strategy through the material substitution lead to consequences along the whole component life cycle and visible responses to all the DfE approach. The choice of aluminum has affected the manufacturing, therefore, a reformulation of a new production technology was necessary; this was occurred through the derivative of Design for Manufacturing: the Design to Minimize Energy Consumption and Design for Assembly, resulting in the diminution of production process energy expenditure and time cycle. From EoL point of view, the aluminum offers a good potential of recovery from the Automotive-Shredded Residue (ASR). In addition, the existing technology allows for a higher recovery-ration and less energy expenditure compared to the steel. Aluminum solution perfectly matches Design for End-of-Life objectives.

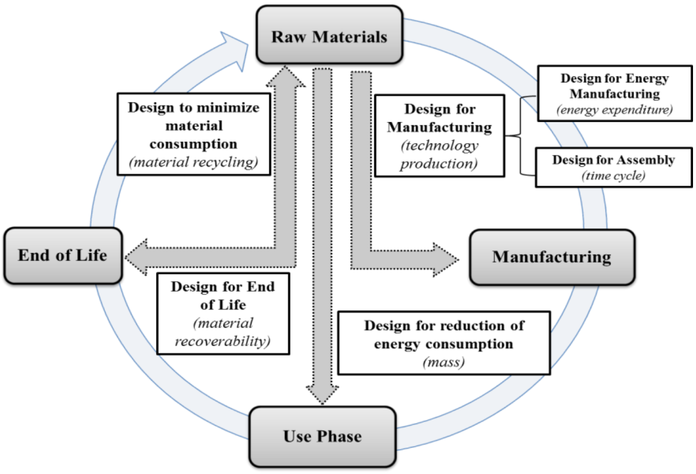

Fig. 5. Life cycle framework of design decision for environment application strategy for crossmember case study

5 Conclusions

Although the LCA is considered a powerful method for the environmental impacts evaluation of new product, there is a general skepticism bore out from some practical difficulties that could emerge during its implementation in the R&D process. This study tries to get through this by means of a concreate example of integration of DfE and LCA methodology application in the R&D process of a vehicle component produced by Magneti Marelli. In order to enhance the LCA results interpretation, an effort was dedicated to the selection of those impact categories able to evaluate the selected environmental issues - GHG emissions and resource depletion - and their analysis in relation to the product life cycle phases and DfE approaches. In this sense the GWP, $\text{ADP}_{\text{elements}}$ and PED were found relevant for evaluating the environmental issues GHG emissions and resource depletion, which the new design strategy intends to address. The lightweight strategy was found to produce several benefits in addition to the mass reduction: the production process of stainless steel requires more energy and auxiliary and hazardous materials compared to the secondary aluminum, moreover the recycling credits of aluminum is higher than the steel ones, further benefits regard the supply chain simplification and manufacturing time cycle shortening. LCA results demonstrate that replacing steel with secondary aluminum entails an overall impact decrease up to a 70%. Moreover, besides the significant mass reduction (-22%) and thus the use phase impact decrease, it was observed that the most benefits regard raw material and manufacturing life cycle phases. Such results confirmed the importance of primary data gathering as a way to obtain analysis that is more precise and reliable. Thought the collection of data directly at the manufacturing plant could be time intensive, nevertheless this could provide useful information that could be further systematically structured to build a company database more detailed that the current database. Future research directions should necessary regard further discussion about the implementation of a set of relevant and suitable environmental indicators, trade-off handling and multidisciplinary analysis as key elements from improving the R&D process in a sustainability perspective.

Acknowledgment

The authors would like to thank Magneti Marelli S.p.A. for the cooperation. In particular, the authors are very grateful to Mrs. Rubina Riccomagno for her fruitful contribution.

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