Holistic eco-design tool within automotive field

A Antonacci¹, F Del Pero¹, N Baldanzini¹ and M Delogu¹

¹ Department of Industrial Engineering, University of Florence, Italy

andrea.antonacci@unifi.it

Abstract. In the last decades, sustainability has become a critical issue for the vehicle industry. Today automotive manufacturers are subjected to several government regulations aimed at making the industry more environmentally sustainable. In this context, many research and industrial activities are focused on the eco-design field by developing innovative materials, novel manufacturing technologies, and new methodology; the main objective is to combine the best design performance with increased environmental responsibility. In this paper, a holistic design and sustainability analysis method based on a multi-criteria approach is presented to support the designer in the early conceptual phase finding the best trade-off in terms of performance and sustainability. The new methodology generates a single-score index (SSI) based on product design/sustainability metrics; data normalization, weighting, and aggregation processes are also included in the evaluation method. This method is integrated into an eco-design framework developed through HyperWorks and MATLAB software tools. A case study, based on a reference geometry, a load case, and a list of materials and processes chosen by the designer, is described to show the potential of the proposed methodology. Finally, a critical review and concluding remarks are described following the SSI results; suggestions for further improvements are made.

1. Introduction

Over the past few decades, there has been a growing interest in sustainable development [1], with environmental and cost sustainability aspects being the main pillars for business and societal decision-making. In the industrial field, the eco-design of new products represents a key element to help policymakers, stakeholders, and customers to make decisions towards a more sustainable society [2]. In this context, the Life Cycle (LC) sustainability assessment becomes essential for decision support and sustainable development indicators are widely used to assess the environmental profile of new products.

Road transport contributes heavily to the overall environmental impact of anthropogenic activities (about 20% of GHG emissions are caused by road transportation [3][4][5]). For this reason, vehicle manufacturers are facing strong regulatory pressure pushing for sustainability in several aspects, such as reducing resource consumption in production, improving the recyclability of materials, and reducing tailpipe emissions during operation. Sustainable design, investment in clean technologies, and value creation for local and global communities [5][6] are some of the efforts made by the automotive companies to achieve these challenging goals.

Regarding the design aspect, lightweighting, manufacturing processes/technologies optimization, vehicle assemblies/components redesign, and more efficient materials usage are the most common strategies used by Original Equipment Manufacturers (OEMs). Innovative design solutions certainly
offer improvements in driving and technical features (e.g., in terms of performance, road safety, and drivability) and energy consumption [7]; however, the production and manufacturing of new materials and advanced components are usually associated with higher GHG emissions compared to conventional design solutions. For instance, Carbon Fiber Reinforced Plastics (CFRP) cause significantly greater impacts than conventional steels both in raw material acquisition and in semi-finished product processing [8]. Moreover, the innovative materials usage is often associated with greater problems in the End-of-Life (EoL) management: lower recovery rates and greater amounts of waste sent to landfill (due to the unavailability of separation processes and recycling technologies) are the main causes of an increased environmental burden. Thus, the innovative design solutions, even if remarkable technical advantages are obtained, may involve increased environmental impacts in the production and EoL phases, with an overall negative effect in the LC perspective [9-10].

For these reasons, the development of advanced solutions requires the conception of eco-design methodologies capable of simultaneously addressing design performance and sustainability aspects in the whole vehicle LC perspective. Life Cycle Sustainability Assessment (LCSA) is considered a suitable approach to assess sustainability in the early design phase of products. Considering the whole Life Cycle (LC), this methodology compares different product concepts, providing information on possible improvements (e.g., alternative materials or processes) and clearly describing the possibility of trade-off. Multi-Criteria Decision Analysis (MCDA) methods are used in the implementation of LCSA, to help designers and product developers solve decision problems to determine the best option when evaluating a set of alternatives based on multiple and conflicting criteria.

The automotive eco-design literature presents a huge number of articles, where type, objective, the complexity of the application process, and available inventory data vary significantly [11-12]. In this context, the sustainability analysis is considered a supporting, functional tool for validating lightweight designs. Delogu et al. [13], Sun et al. [14], Sun et al. [15], and Cecchel [16] are some of the many papers underlining this statement. These studies develop LCA of innovative automotive solutions compared to a baseline design, performing a detailed assessment of the car assets considered, including all the LC phases (production, use, and EoL), and assuming different impact categories to express the results. However, the performance/design requirements are not considered, because the competing concepts are evaluated assuming that they are strictly equivalent from a functional point of view. Fassi et al. [17] and Deng et al. [18], instead, go beyond the above studies, performing sustainability assessment on design equivalence basis. Other works focus on the development of eco-design tools rather than the pure assessment of specific case studies. Examples for this are represented by Ghadimi et al. [19] and Delogu et al. [20], which define holistic assessment methods integrating environmental, economic, and social aspects. The studies presented above incorporate the sustainability issue into the concept development phase, providing valuable support for designers and decision makers by measuring and making transparent sustainable information. However, these researches consider the environmental analysis downstream of the design process and they use it purely for validation purposes.

The only studies that integrate sustainability aspect into the design process using a systematic computer-aided design procedure are Reimer et al. [21], Russo and Matina [22] and Russo and Rizzi [23]. Reimer et al. proposes a methodology to support the conceptual design of lightweight body panels for Electric Vehicles (EVs) with a combined perspective on structural integrity and Green-House-Gas (GHG) emissions. The refined tool analytically combines numerical design and LC GHG estimation, thus providing a systematic impact assessment of design decisions on mechanical performance, lightweighting and sustainability potential. Russo and Matina and Russo and Rizzi present an eco-design approach implemented in a software framework that supports the designer in optimizing design solutions for automobiles from an environmental perspective. The integration of CAE, Life Cycle Modeling (LCM) and LCA tools represents the core of the method, as a supporting tool for the designer in the conceptualization design stage. The above studies represent very interesting attempts to integrate design and sustainability issues. That said, the conceived methods are suitable to
automatically generate the optimized solutions, but the data processing requires a direct involvement of the user.

The review of automotive eco-design literature highlights the need for holistic eco-design methods able to assess both performance, design, and sustainability aspects, to evaluate at the same time implications of different nature over the entire product LC.

This paper describes a holistic eco-design approach to support designers in the early design stage, simultaneously considering design requirements and sustainability aspects. An accessible and easy-to-use tool, functional to generate and compare different design options in the automotive field, is provided. The combination of design requirements, concept physical-technical characteristics and LC inventory data allows the framework to automatically generate different design alternatives, providing a set of indicators that quantify both design performance and sustainability profile. Finally, a tailored single-score index developed through MCDA methods is used to rank and select the most promising design options.

2. Materials and Method

The presented work defines a method functional to compare alternative design solutions for monomaterial automotive components considering both design and sustainability aspects. An integrated single score indicator (Product Sustainability Level, PSL) is developed on the multi-criteria decision methods; the overall methodology is implemented within the Design and Sustainability Analysis (DeSA) tool, targeted at providing a ready-to-use tool for engineers and designers. The DeSA allows broadening the range of considered design options and at the same time easing the comparative assessment process.

The following paragraphs present the design method according to two main sections:

- selection and sustainability analysis phase, where design and sustainability pillars are described, and related mid-point indicators are defined.
- classification phase, where PSL is assessed using the mid-point indicators calculated for each solution and the ranking of design alternatives is performed.

A schematic overview of the DeSA framework is presented in Figure 1.

**Figure 1.** DeSA framework.

2.1. Selection and sustainability analysis

The DeSA tool performs the design and sustainability analysis based on a series of input data belonging to three main areas (in Figure 1):
• Design inputs, in terms of the main physical and technological features of the component in the automotive asset.
• Sustainability inputs, including Life Cycle Inventory (LCI) data functional to assess the environmental profile of the entire component LC.
• Vehicle features inputs, in terms of parameters and operating conditions that characterize the automotive component LC.

The list of parameters required by the methodology, for each of the three main areas indicated above, is reported in Table 1.

**Table 1. Methodology input data.**

| Input Data          | Design Inputs          | Sustainability Inputs | Vehicle Features Inputs |
|---------------------|------------------------|-----------------------|-------------------------|
| Primary Shape       | Design limitations     | Materials Data        | Vehicle Lifetime        |
| Load case           | Boundary conditions    | Processes Data        | Reference Vehicle       |
|                     |                        |                       | Powertrain Characteristics|

The PSL indicator represents the final output, and it represents the sustainability level of different design solutions. The calculation of PSL includes four major steps (Figure 2): selection, sustainability analysis, and classification. The following sections describe in detail each stage of the PSL assessment.

**Figure 2. DeSA methodology main phases.**

2.1.1 *Selection.* This phase determines the list of all design solutions that are feasible from a technical point of view and that satisfy the design requirements at the same time. The screening applies design constraints and design choices in terms of shape, material, and process. The methodology uses two
main types of design constraints: the requirements on physical and technological features which characterize the different design options (see Table 2) are the first type and they are imposed by the tool’s user. Instead, the technical compatibility between the material, manufacturing process, and component shape (for instance, the materials that can be processed through a specific manufacturing process) represents the second type of design constraints. Thus, the simultaneous application of physical, technological, and compatibility constraints allows discarding all the “shape-material-process” combinations that do not meet the design constraints, obtaining the list of feasible options.

Table 2. Design requirements imposed by the designer.

| Design Requirements   |
|-----------------------|
| Mass                  |
| Section thickness     |
| Batch size            |
| Tolerance             |
| Surface roughness     |

The first step of the selection phase is the choice by the designer of the component’s primary shape, which is selected based on the following available options:

- Prismatic (1D): circular, noncircular.
- Sheet (2D): flat, dished.
- Three-dimensional (3D): solid, hollow.

The definition of a production database (see Figure 2) is the selection’s second step, where the entirety of materials and manufacturing processes available to the designer is stored. The database’s materials section characterizes materials in terms of all properties used to establish if a material can be used for a specific application. The database classifies materials according to the following scheme:

- Metallic materials and alloys.
- Polymeric materials.
- Ceramic materials and glasses.
- Hybrid materials (foams, composites, and natural materials).

Table 3. Material properties in production database.

| Material Properties         |
|-----------------------------|
| Density (ρ)                 |
| Young modulus (E)           |
| Poisson ratio (η)           |
| Yield strength (σ)          |
| Global Warming Potential (GWP_mat) |

Table 3 reports the technical and environmental properties that characterize the materials in the database. The database’s manufacturing section collects all the applicable manufacturing processes organized into a hierarchical order (see Figure 3) and defined in terms of the following features, reported in Table 4:
Figure 3. Scheme of the manufacturing processes hierarchy.

- Material features: the subset of materials that the process is able to use and transform.
- Shape features: list of shapes that can be made through the process (in this work, only shaping process family, reported in Figure 3, is considered).
- Physical features: physical properties related to the size (mass, section thickness), tolerance, roughness, and batch size.
- Environmental features: Global Warming Potential (GWP), caused by the process applied to the different database’s materials.

Table 4. Process features in production database.

| Process Features | Material Features | Shape Features | Physical Features | Environmental Features |
|------------------|-------------------|----------------|-------------------|------------------------|
|                  | Materials List    | Shapes List    | Size Range        | Global Warming Potential (GWP) |
|                  |                   |                | Batch size         | man)                  |
|                  |                   |                | Tolerance          |                       |
|                  |                   |                | Surface roughness  |                       |

The third and final step of the selection is the application of constraints to all the available design options. The methodology applies the constraints using

- Numerical limitations referring to intrinsic physical and technological features of both materials and manufacturing processes (see Table 2)
- Shape-process compatibility (see Table 4)
- Material-process compatibility (see Table 4)

and they are analytically modelled through bar charts and binary matrices. Technical requirements and shape-material-process compatibility are combined to perform the selection, thus obtaining all the feasible solutions (Figure 2) which are characterized through the following features:

- shape (fixed by the designer);
- design constraints (provided by the case study);
- material and primary shaping process (obtained from the selection phase).

The final list of all the feasible design options represents the input for the sustainability analysis.

2.1.2 Sustainability analysis. This phase evaluates the different design alternatives obtained in the selection step through the Product Sustainability Level (PSL), an aggregated single-score indicator
that considers both the design performance and the environmental profile. The sustainability analysis is structured in two main sections, dealing with design and environmental aspects, respectively.

**Design analysis.** In this section, the Finite Element Method (FEM) simulation modeling of all the feasible solutions provided by the selection step is performed. The design performance is assessed through a Performance Index (PI), calculated basing on performance level in terms of structural integrity provided by the design solution. In this work, PI will be defined as a safety factor provided by the ratio between the material’s yield stress and the stress level on the component obtained through FEM simulations. For the FEM simulations setting, the analysis needs the following design input data:

- **Fixed design input data (DI):** geometric features (G) and boundary conditions (BC), which remain unaltered when passing from one feasible design solution to another (see “design inputs” of Table 1).
- **Variable design input data (VI):** material (MAT) and manufacturing process (MAN) obtained from the selection phase, variables when passing from one design solution to another (see “sustainability inputs” of Table 1).

The variable design input data are provided as ranges instead of single values. For this reason, the generic design solution $S$ provided by the selection phase presents several sub-solutions. The number of sub-solutions ($n$) changes in terms of material and process features and depends on the variation range of the variable data. Considering the generic data range, $I = [I_{\text{min}}, I_{\text{max}}]$, the range size $\phi$ is calculated as follows in equation (1):

$$\phi = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{avg}}}$$

Where:
- $I_{\text{min}} = $ the minimum value of generic data range
- $I_{\text{max}} = $ the maximum value of generic data range
- $I_{\text{avg}} = $ the average value of generic data range (i.e., $(I_{\text{max}} + I_{\text{min}})/2$)

The number of ranges is directly related to the materials properties and the processes features inserted in the production database (see Table 3 and Table 4). Therefore, the solution domain space $\Omega_{\text{sol}}$ is defined in equation (2):

$$\Omega_{\text{sol}} = \prod_{k}^{M} \phi_{l_k}$$

Where:
- $M = $ the number of data ranges used for solution domain calculation
- $\phi_{l_k} = $ the size of $k$-generic data range

Each value of $\Omega_{\text{sol}}$ will be divided by the minimum value obtained from several alternatives $S_i$ (i.e., $\text{min}(\Omega_{\text{sol}})$) and finally converted, via linear regression into simulation runs between values determined by the designer. An example of the domain space is presented in Figure 4.
Figure 4. Example of domain space of design solutions.

In this example, the designer defines a minimum number of simulations for the generic solution \( n_{\text{min}} = 2 \), and a maximum value \( n_{\text{max}} = 5 \); for instance, the solution identified with ID = 9 will have a number of sub-solutions \( n_{i \rightarrow n_9} \) equal to 3.

Assuming \( S_{ij} \) as the generic sub-solution \( j \) of \( S \), the PI of \( S_{ij} \) is function of both fixed and variable design inputs, as provided by the following relation (equation (3)):

\[
S_{ij} = f(DI,V_{ij}) = f(G,BC,MAT_{ij},MAN_{ij})
\]  

(3)

The sample of variable data \( V_{ij} \) to be considered for the generic solution \( S_{ij} \) is obtained through the Latin Hypercube Sampling (LHS) [24][25].

The calculation of parameter elasticity (EL) for each sub-solution \( S_{ij} \) completes the design analysis; EL is defined as the potential improvement of a sub-solution without compromising the design performance. The elasticity will be defined according to equation (4):

\[
EL = PI - I = \frac{\sigma_y}{\sigma_{FEM}} - I
\]  

(4)

Where:

\( \sigma_y \) = yield stress of the material component.

\( \sigma_{FEM} \) = stress level on the component calculated through FEM simulations.

The methodology provides the calculation of PI (function of design inputs) and EL (function of PI) through the combined use of MATLAB and Altair HyperWorks simulation software for each design sub-solution \( S_{ij} \) (see equation (5)):

\[
S_{ij} \rightarrow \begin{cases} 
PI_{ij} = f(DI,VI_{ij}) \\
EL_{ij} = f(PI_{ij}) 
\end{cases}
\]

(5)
As a consequence, each sub-solutions $S_{ij}$ is characterized by a combination of PI-EL indexes. The methodology provides that:

- PI is used to calculate the PSL (see paragraph 2.2. – Classification);
- EL is used in the classification phase (see the following steps).

**Environmental analysis.** This step is aimed at assessing the environmental profile of the feasible sub-solutions $S_{ij}$ provided by the design analysis section. The environmental assessment is carried out by means of the Life Cycle Assessment (LCA) impact category Global Warming Potential (GWP) according to the ILCD 1.09 impact assessment method [26]. The GWP indicator is determined considering the environmental impacts related to the entire Life-Cycle (LC) of the component, subdivided into the following main stages:

- materials acquisition;
- manufacturing;
- use;
- End-of-Life (EoL).

The GWP assessment is carried out according to the following calculation framework (see equations (6-19) reported in Table 5).

### Table 5. List of Life Cycle Equations in DeSA methodology.

| Life Cycle Equations |
|----------------------|
| $GWP_{prod} = GWP_{mat} + GWP_{man}$ |
| $U = \frac{mil_{comp}}{mil_{veh}}$ |
| $GWP_{raw} = \frac{m_{ij} \cdot gwp_{ij}^{mat}}{U}$ |
| $GWP_{man} = \frac{m_{ij} \cdot gwp_{ij}^{man}}{U}$ |
| $GWP_{use} = GWP_{WTT} + GWP_{TTW}$ |
| ICE Vehicles (ICEV) | Electric Vehicles (EV) |
| $GWP_{WTT} = gwp_{fuel} \cdot EC_{comp}$ | $GWP_{WTT} = gwp_{mix} \cdot EC_{comp}$ |
| $GWP_{TTW} = CO_{2veh} \cdot mil_{veh} \cdot \frac{EC_{comp}}{EC_{veh}}$ | $GWP_{TTW} = 0$ |
End of Life

\[ GWP_{\text{EoL}} = GWP_{\text{shr}} + GWP_{\text{sep}} + GWP_{\text{rec}} + GWP_{\text{enr}} + GWP_{\text{disp}} \] (13)

\[ GWP_{\text{shr}} = \frac{m_{ij} \cdot \text{gwp}_{\text{shr}}}{U} \] (14)

\[ GWP_{\text{sep}} = \frac{m_{ij} \cdot \text{gwp}_{ij}^{\text{sep}}}{U} \] (15)

\[ GWP_{\text{rec}} = \frac{m_{ij} \cdot \text{gwp}_{ij}^{\text{mat}} \cdot \text{gwp}_{ij}^{\text{mat}}}{U} \] (16)

\[ GWP_{\text{enr}} = \frac{m_{ij} \cdot \text{gwp}_{ij}^{\text{enr}} \cdot (1 - \chi_{ij}^{\text{enr}})}{U} \] (17)

\[ GWP_{\text{disp}} = \frac{m_{ij} \cdot \text{gwp}_{ij}^{\text{disp}} \cdot \chi_{ij}^{\text{enr}}}{U} \] (18)

\[ \text{LC} \]

\[ GWP_{\text{LC}} = GWP_{\text{Mat}} + GWP_{\text{Man}} + GWP_{\text{Use}} + GWP_{\text{EoL}} \] (19)

Where:

- \( GWP_{\text{prod}} \) = environmental impact of the production phase \([\text{kg CO}_2\text{eq}]\).
- \( U \) = the number of potential utilizations of the component (based on its durability) [-]; it is the ratio between the predictable duration of component (mil\text{comp}) and the vehicle’s lifetime (mil\text{veh}).
- mil\text{comp} = component mileage [km].
- mil\text{veh} = vehicle mileage [km].
- \( GWP_{\text{raw}} \) = environmental impact of the material acquisition to produce the component \([\text{kg CO}_2\text{eq}]\).
- \( \text{gwp}_{\text{mat}}^{\text{ij}} \) = environmental impact per mass unit of the material of generic sub-solution \( S_{ij} \) \([\text{kg CO}_2\text{eq}/\text{kg}]\).
- \( m_{ij} \) = component mass of generic sub-solution \( S_{ij} \) [kg].
- \( GWP_{\text{man}} \) = environmental impact of the manufacturing process \([\text{kg CO}_2\text{eq}]\).
- \( \text{gwp}_{\text{man}}^{\text{ij}} \) = environmental impact per mass unit of the manufacturing process related to the generic sub-solution \( S_{ij} \) \([\text{kg CO}_2\text{eq}/\text{kg}]\).
- \( GWP_{\text{use}} \) = environmental impact of the use phase \([\text{kg CO}_2\text{eq}]\).
- \( GWP_{\text{WTT}} \) = environmental impact of well-to-tank use stage phase \([\text{kg CO}_2\text{eq}]\).
- \( \text{gwp}_{\text{fuel}} \) = environmental impact of fuel production (for internal combustion engine vehicles) \([\text{kg CO}_2\text{eq}/\text{kg}]\).
- \( \text{gwp}_{\text{mix}} \) = environmental impact of electrical mix grid production (for electric vehicle) \([\text{kg CO}_2\text{eq}/\text{kWh}]\).
- \( \text{EC}_{\text{comp}} \) = amount of Energy Consumption during operation of component; [\text{kg}] for ICEVs, [\text{kWh}] for EVs.
- \( \text{GWP}_{\text{TTW}} \) = environmental impact of tank-to-wheel use stage phase \([\text{kg CO}_2\text{eq}]\).
- \( \text{EC}_{\text{veh}} \) = amount of Energy Consumption during operation of vehicle; [\text{kg}] for ICEVs, [\text{kWh}] for EVs.
- \( \text{CO}_2_{\text{veh}} \) = vehicle \( \text{CO}_2 \) emissions \([\text{kg CO}_2\text{eq}/\text{km}]\).
- \( GWP_{\text{Eol}} \) = environmental impact of the end-of-life (e.g., recycling, recovery, disposal) \([\text{kg CO}_2\text{eq}]\).
- \( GWP_{\text{dis}} \) = environmental impact of component disassembly \([\text{kg CO}_2\text{eq}]\).
- \( GWP_{\text{shr}} \) = environmental impact of component shredding \([\text{kg CO}_2\text{eq}]\).
- \( \text{gwp}_{\text{shr}}^{\text{ij}} \) = environmental impact per mass unit of shredding of generic sub-solution \( S_{ij} \) (constant average value for all materials) \([\text{kg CO}_2\text{eq}/\text{kg}]\).
- \( GWP_{\text{sep}} \) = environmental impact of shredded material component separation \([\text{kg CO}_2\text{eq}]\).
gwp$^{sep}_{ij}$ = environmental impact per mass unit of separation of generic sub-solution $S_{ij}$ [kg CO$_{2eq}$/kg].
GWP$^{rec}_{rec}$ = environmental impact of separated material component recycling [kg CO$_{2eq}$].
$X^{mat}_{ij}$ = material substitution factor of generic sub-solution $S_{ij}$ (quota of avoided primary production impact due to recycling) [-].
GWP$^{enr}_{enr}$ = environmental impact of post-separation material component energy recovery [kg CO$_{2eq}$].
gwp$^{enr}_{ij}$ = mass-specific GWP of incineration with energy recovery for sub-solution $S_{ij}$ (referred to plastic fraction) [kg CO$_{2eq}$/kg].
$\vartheta^{enr}_{ij}$ = share of fibers for generic sub-solution $S_{ij}$ (composite materials) [-].
GWP$^{disp}_{disp}$ = environmental impact of residual component disposal [kg CO$_{2eq}$].
gwp$^{disp}_{ij}$ = environmental impact per mass unit of disposal of generic sub-solution $S_{ij}$ [kg CO$_{2eq}$/kg].
GWP$_{LC}$ = environmental impact of LC component [kg CO$_{2eq}$].

As a consequence, each sub-solution $S_{ij}$ is characterized by a $GWP_{LC}$, which is used to calculate the PSL together with $PI$ (see paragraph 2.2. – Classification).

To perform the sustainability analysis, the methodology provides the definition of a sustainability database which provides the GWP of all LC processes for the competing design sub-solutions. Additionally, the calculation framework requires the setting of user-define operating conditions that characterize the considered case study. Table 3 and Table 4 report the sustainability database GWP parameters for material-process combination, while the user-defined operating conditions of the case study are reported in Table 1 (see vehicle features inputs).

2.2. Classification

Once sustainability analysis is carried out for each of the sub-solutions $S_{ij}$, classification phase is performed in the following sections:

- PSL calculation of alternative solutions.
- Elasticity screening, where new constraints and design choices are applied in terms of component elasticity.
- Final ranking of acceptable solutions.

PSL Calculation. The Multi-Criteria Decision Analysis (MCDA) is the methodological principle of the PSL calculation, which integrates complex criteria to evaluate alternative decisions or solutions [27]. In this study, the values of indicators described above are used to obtain a tailored overall efficiency score, i.e., PSL. The PSL is evaluated from methodology proposed via three operations: normalization, weighting, and score aggregation; this score is performed using a weighted sum formula to combine the relative importance weights of criteria with performance scores for each product alternative.

Physical data collected for each aspect cannot be summed up together directly, due to the inconsistency and difference of units of measurements [28]. Thus, the values of these indicators need to be scaled into dimensionless values such that they can be analyzed and compared. This process is called normalization; in general, there are different statistical methods that can be used for this phase, but in this work, the “Max method” is used for the normalization of indicators [29]. According to this method, each indicator with an impact (positive or negative) on the product’s sustainability ($I^+_k$) is normalized using the equation:

\[
I^*_{Nk} = \frac{I^+_k}{I^+_{k_{max}}}
\]

Where:
$I_{N_k}$ = normalized indicator for the dimension of generic sustainability $k$ with an impact on overall sustainability.

$I_k$ = indicator for the dimension of sustainability $k$ with an impact on sustainability.

$I_{\text{max}}^k$ = the highest value of the indicator for the dimension of sustainability $k$ with an impact on sustainability (e.g., $I_{\text{max}}^k = \max(I_k^z)$).

Regarding the weighting, several methods are commonly used, which are: equal weighting, subjective weighting (such as Analytic Hierarchy Process (AHP)), and weighting from analytical approaches. To compare the sustainability performance of several product solutions by mean of the proposed framework, the equal weighting will be applied in this methodology. In this case, weights $w_i$ are defined by the equation (21) ($i = 1, \ldots, E$ is index of sustainability elements):

$$\sum_{k=1}^{E} w_k = 1$$

In the aggregation phase, the normalized data are systematically aggregated into the single score based on the weighting factors assigned before and a conclusive sustainability index is finally derived. The Product Sustainability Level (PSL) is expressed by the following relation (equation (22)):

$$PSL = \sum_{k=1}^{E} w_k I_{N_k}$$

Where:

$w_i$ = the weighting factor for the $i_{th}$ aspect (i.e., design, environmental, economic, and social aspect).

$I_{N_i}$ = the normalized score of $i_{th}$ aspect.

In this case, considering only the design and environmental aspects (see sustainability analysis), the following formula (equation (23)) will be defined for DeSA methodology:

$$PSL_i = K \left( \frac{I}{w_1 \cdot cor + PI_{N_i}} + \frac{I}{w_2 \cdot cor + EI_{N_i}} \right)$$

Where:

$K$ = PSL scale factor chosen by designer
$cor$ = Correction coefficient (equal to 0.1).
$w_j$ = the weighting factor for the $j_{th}$ aspect (design and environmental aspects)
$PI_{N_i}$ = the normalized score for the design aspect of $i_{th}$ alternative solution
$EI_{N_i}$ = the normalized score for the environmental aspect of $i_{th}$ alternative solution

With the presence of the correction coefficient ($cor$), the value of PSL varies between the following limit values (see equation (24)):

$$\begin{cases} 
\max(PSL) = 10K \\
\min(PSL) = 0.91K 
\end{cases}$$

**Elasticity screening.** Once each index has been calculated for each sub-solutions $S_{ij}$, PSL is calculated (according to the above paragraph). The sub-alternatives results are merged since variable
design input data (VI) were stored as ranges; a PSL range (PSL\textsuperscript{range}), as well as elasticity range (EL\textsuperscript{range}), is defined. If \(i\) represents the index of the generic solution, while \(n_i\) (in this case \(n_i = m\)) indicates the number of sub-solutions, the PSL\textsuperscript{range} of solution \(S_i\) is defined in the following way, through the minimum and maximum values of the sub-alternatives.

\[
S_i \rightarrow \{\{PSL_{i1}, PSL_{i2}, ..., PSL_{im}\} \rightarrow PSL^{\text{range}} = \left[\min(PSL_{ij}), \max(PSL_{ij})\right] \}
\]

\[
\{EL_{i1}, EL_{i2}, ..., EL_{im}\} \rightarrow EL^{\text{range}} = \left[\min(EL_{ij}), \max(EL_{ij})\right]
\]

(25)

All solutions analyzed in the sustainability phase can be represented through ellipses, in a PSL-EL "bubble chart" (see an example in Figure 5). Only solutions with positive elasticity (i.e., EL>0) are considered, since they can be improved from the sustainability point of view without affecting the performance of the product itself.

A new screening is assessed through an Elasticity Line (EL\textsubscript{L}) and Flexibility Filter (FF), whose values are defined through the designer experience. Two distinct zones in the bubble chart are defined by EL\textsubscript{L} (as shown in Figure 5):

- A (Acceptable Zone): solutions with high EL improvement margins.
- B (Non-acceptable Zone): solutions with low EL improvement margins.

The acceptable solutions (\(S_{\text{acc}}\)) are those that present an elasticity value (EL) greater than the limit imposed by the designer (i.e., EL\textsubscript{L}) and fall into the A zone; for these reasons, they will be considered in the final ranking. Instead, the design alternatives not acceptable (i.e., depending on the choice of the designer, it will not be able to fulfill the performance), fall into the B zone and they are discarded.

Figure 5. Bubble chart of design solutions with FF=100%.

If the generic solution \(S_i\) is present in both zones, the solution will be accepted or discarded depending on the filtering level (given by FF) set by the designer, according to equations (26-29):
\[ \%EL^{\text{right}}_i \leq FF \]  
\[ \%EL^{\text{right}}_i = \frac{\text{diff}^{\text{range}}_i}{EL^{\text{range}}_i} \]  
\[ \text{diff}^{\text{range}}_i = \max(EL_{ij}) - EL_L \]  
\[ EL^{\text{range}}_i = \max(EL_{ij}) - \min(EL_{ij}) \]

Where:
\( \%EL^{\text{right}}_i \) = elasticity range percentage to the right of elasticity line (\( EL_L \)).
\( EL^{\text{range}}_i \) = elasticity range of solution \( S_i \).
\( \text{diff}^{\text{range}}_i \) = elasticity range of solution \( S_i \) to the right of elasticity line (\( EL_L \)).
FF = flexibility filter (fixed by the designer).

- if \( EL^{\text{right}}_i < FF \), the generic solutions that touch \( EL_L \) will be discarded and not considered in the final ranking phase (see Figure 5).
- if \( EL^{\text{right}}_i \geq FF \), the generic solution that touch \( EL_L \) will be accepted and considered in the final ranking phase (see Figure 6).

For instance, \( EL_L \) is equal to 0.5 in Figure 5 and Figure 6 (i.e., safety factor is equal to 1.5). Considering the first figure, the FF value is equal to 1 (or 100%); in this case all solutions that intersect \( EL_L \) are not considered; instead, in the other figure, the FF value is equal to 0.5 (or 50%) and the solutions having 50% of the EL range to the right of \( EL_L \) are considered in the next step of classification.

![Product Bubble Chart](image)

**Figure 6.** Bubble chart of design solutions with FF=50%.

**Final ranking.** In this last phase, the final ranking of the acceptable solutions \( S^{\text{acc}}_i \) is compiled and the PSL values are compared. Since each solution has a PSL\(^{\text{range}}_i \), the final ranking is done through the average value of that range; it is defined as PSL\(_{\text{avg}} \) as follows (equation (30)):
\[ PSL_{ss} = \frac{PSL_{range max} + PSL_{range min}}{2} \]  

(30)

Where:
PSL_{ss} = single score of Product Sustainability Level.

The acceptable solutions S_{acc} are ranked through the value PSL_{ss} calculated for each bubble/solution.

3. Case study
Since the main goal of this paper is the application of DeSA methodology, a case study of an engine bracket in automotive context is chosen. In order to obtain the product sustainability level (PSL), the possibility to freely explore materials and manufacturing processes is given to the designer, while remaining consistent with system functional/performance requirements (i.e., boundary conditions). The main features/inputs of the case study are synthesized in the form below (see Table 6).

| Table 6. Case study input data. |
|--------------------------------|
| Input Design Data              |
| Design Inputs                  |
| Primary Shape                  |
| Design limitations             |
| Loadcase                       |
| Boundary conditions            |
| Sustainability Inputs          |
| Materials Data                 |
| Processes Data                 |
| Vehicle Features Inputs        |
| Vehicle Lifetime               |
| Vehicle Class                  |
| Powertrain Characteristics     |
| Driving Cycle                  |

3.1. Selection
The first step of the selection phase is the choice of the component primary shape; The Figure 7 presents the initial FEM model of engine bracket for DeSA methodology. As shown in figure, the chosen shape by the designer for the case study analysis is the three-dimensional shape (3D).

Figure 7. Engine bracket FEM model.

The second step is the definition of production database which consists of the entirety of materials and manufacturing processes available. For this case study, the list of allowable materials is only made of metals and alloys: each material is defined by an ID (i.e., Mxx) and its mechanical (such as density,
Young modulus) and environmental properties (i.e., GWP). Table 7 presents the materials chosen for this case study. Appendix A collects all of the materials data used in the case study analysis.

Table 7. List of allowable materials in production database.

| Mat ID | Material Class       | Material Subclass | Material Name                 |
|--------|----------------------|-------------------|-------------------------------|
| M1     | Metals and Alloys    | Ferrous           | High Carbon Steel            |
| M2     | Metals and Alloys    | Ferrous           | Low Alloy Steel              |
| M3     | Metals and Alloys    | Ferrous           | Stainless Steel              |
| M4     | Metals and Alloys    | Non-Ferrous       | Age-Hardening Wrought Al-Alloys |
| M5     | Metals and Alloys    | Non-Ferrous       | Titanium Alloys              |

Then, the list of allowable processes is only composed by processes capable of creating three-dimensional (3D) shapes: each process is defined by an ID (i.e., CAxx) and its mechanical and environmental features. Table 8 presents the processes chosen for this case study. Appendix B collects all the processes data used in the case study analysis.

Table 8. List of allowable processes in production database.

| Pr ID | Process Class     | Process Subclass               | Process Name             |
|-------|-------------------|--------------------------------|--------------------------|
| CA1   | Casting           | Investment Casting Processes   | Investment Casting       |
| DE1   | Deformation       | Bulk Deformation Processes     | Forging                  |
| PO1   | Powder Methods    | Powder Pressing Processes      | Pressing and Sintering   |

The final step is the screening phase, where the objective is determining the list of all design solutions that are feasible from a technical point of view and that satisfy the design requirements at the same time. The application of design constraints and design choices in terms of primary shape, materials and processes will automatically provide several solutions. All the combinations that do not meet the functional requirements are not included in the list.

3.2. Sustainability analysis.

This phase is aimed at evaluating the different design alternatives obtained in the selection step by means of the PSL. In design analysis phase, Finite Element Method (FEM) simulation modelling of all the feasible solutions is provided by the screening step. The loadcase is assessed through the Performance Index (PI), on the basis of the performance level in terms of structural integrity provided by the generic design solution.

The boundary conditions (BC) of engine bracket are presented in Figure 8: the connection with engine and the link between bracket and vehicle chassis are defined by zone A and B, respectively. The connection between engine and bracket is modelled through bolted joints (see Figure 9); the bolts head are modelled with 1D deformable element (RBE3) in order to restrict degree of freedom without adding further stiffness to the FEM model (see the red spider webs in Figure 9). Instead, bolts stem is modelled with 1D solid circular section beam element (see the blue lines in Figure 9). The screws characteristics are shown in
Each screw is pretensioned with a force (i.e., $F_{pre}$) defined by the following equation (31):

$$F_{pre} = 0.6 \cdot \sigma_y \cdot A = 0.6 \cdot \sigma_y \cdot \frac{\pi \cdot D^2}{4} \approx 30160 \text{ N}$$  \hspace{1cm} (31)$$

The load is applied to zone C as a pressure vector (according to the global system in Figure 8); one component in $x$-direction (longitudinal), the second component in $y$-direction (lateral), and the latter component in $z$-direction (vertical). The pressure load is calculated considering a static distribution of the engine mass on each bracket used for mounting the engine to the cradle (i.e., $F_{eng}$) and multiplying this result by load coefficients consistent with the case study. Finally, the resultant forces are divided by the load application surface (i.e., the crowns where the bolts heads are placed, $S_{cr}$, equal to 265 mm$^2$) (see equations (32-35)). The engine mass must be consistent with the vehicle used for the case study simulation (in this case, a vehicle with a V4 engine):

$$m_{eng} = 100 \sim 150 \text{ kg} \rightarrow m_{eng} = 150 \text{ kg}$$  \hspace{1cm} (32)$$

$$F_{eng} = \frac{m_{eng}}{4} \cdot g \approx 375 \text{ N}$$  \hspace{1cm} (33)$$

$$\begin{cases} F_x = 0.5 \cdot F_{eng} \approx 190 \text{ N} \\ F_y = 0.5 \cdot F_{eng} \approx 190 \text{ N} \\ F_z = 1.5 \cdot F_{eng} \approx 570 \text{ N} \end{cases}$$  \hspace{1cm} (34)$$
\[
\begin{align*}
p_x &= \frac{F_x}{4S_{cr}} \approx 0.18 \text{ MPa} \\
p_y &= \frac{F_y}{4S_{cr}} \approx 0.18 \text{ MPa} \\
p_z &= \frac{F_z}{4S_{cr}} \approx 0.55 \text{ MPa}
\end{align*}
\]

The y-directional motion of zone A (i.e., where the connection between engine bracket and engine is made) is prohibited. Finally, in zone B (i.e., link between cradle and bracket) a cylindrical constraint is applied, locking the displacements respect to the axial and radial axes.

Since each design solution presents data ranges, Latin Hypercube method (LH) is performed to use this information in the design simulations. In this case study, a variable number of simulations ($n_{sim}$) is defined (variable between 2-5), depending on the solution considered (as shown in Figure 4).

![Figure 9. Bolt joints representation.](image)

In the environmental analysis phase, the assessment of the environmental profile of the feasible sub-simulations provided by the design performance analysis section is carried out. The environmental assessment is carried out by means of the LCA impact category GWP according to the ILCD 1.09 impact assessment method. The first step of this phase is the choice of the vehicle where the case study is mounted for hypothesis. The chosen vehicle for the analysis is VOLKSWAGEN Golf 2.0 TSI GTI, whose characteristics are shown in Table 10. Finally, the lifetime of engine bracket is equal to vehicle lifetime (in this case, no substitution is required).

| Vehicle Features Inputs                  |       |
|------------------------------------------|-------|
| Vehicle Mass                             | 1355 [kg] |
| Vehicle Lifetime                         | 150000 [km] |
| Vehicle Class                            | C     |
| Powertrain                               | ICEV  |
| Driving Cycle                            | WLTP  |
| CO\(_2\) Consumption                     | 149 [g/km] |
3.3. Classification.
In this phase the Product Sustainability Level (PSL) is calculated by means of indexes calculated for each sub-solutions and the final ranking of design alternatives is performed. In the PSL calculation phase, the aggregated score is evaluated using a weighted sum formula to combine the relative importance weights of criteria with performance scores for each design alternative (see equation (23)). The PSL scale factor (K) chosen for the case study is equal to 10; with the presence of the correction coefficient (cor), the value of PSL varies between the values reported in equation (24).

In the Elasticity screening step, the determination of the list of all design solutions that are acceptable from an elasticity point of view is occurred. This screening is assessed through an Elasticity Line (EL$_L$) and Flexibility Filter (FF); in this case study, EL$_L$ is equal to 1.5 (i.e., safety factor equals to 2.5); FF is equal to 50%, i.e., all solutions that have less than 50% of the elasticity range (EL$\text{range}$) to the right of EL$_L$ will be discarded and not considered in the final ranking phase.

In the Ranking phase, the PSL values of the acceptable solutions will be compared; as mentioned, this ranking is done by mean of PSL$_{ss}$.

3.4. Results
The solutions created in the selection phase is reported in Table 11. Each design solution is identified with an ID defined as follows:

$$Design\ Solution\ ID \rightarrow n_{ID} \text{-} \text{Shape} \text{-} \text{MAT}_{ID} \text{-} \text{PR}_{ID}$$

Where:
- $n_{ID}$ = Solution number.
- Shape = Primary component shape defined by designer.
- MAT$_{ID}$ = Material ID (see Table 7).
- PR$_{ID}$ = Process ID (see Table 8).

The application of design constraints and design choices in terms of primary shape, materials and processes created 13 solutions. The LH method created 5 simulations, grouped according to the materials in the list, with a total of 16 sub-simulations. The elasticity screening passed all 13 solutions, divided in two groups:

- Solutions that present an elasticity range always greater than the EL$_L$ value (see green lines in Table 11).
- Solutions that present an elasticity range with values lesser than the EL$_L$ value (see yellow lines in Table 11).

All analyzed solutions in the sustainability analysis phase can be represented through ellipses, in a PSL-EL bubble chart. The engine bracket bubble chart is shown in Figure 10: the full-acceptable solutions S$^{accu}$ (in green) are those that present an elasticity value (EL) always greater than the limit imposed by the designer (i.e., EL$_L$); instead, the FF-acceptable solutions S$^{accf}$ (in yellow) are those that can present an elasticity value (EL) lesser than the limit imposed by the designer. The other design alternatives that are not acceptable are discarded; however, in this case study no solution has been discarded by the methodology.
Finally, Table 12 comparing the PSL values of the acceptable solutions is compiled. Looking at the first 3 solutions in the ranking (see Table 12), they present the same material type (i.e., Age-Hardening Wrought Al-Alloys, with ID = M4), but the manufacturing process differs from one solution to another. Considering the best solution (with ID = 4), the main life cycle phases (reported in logarithmic values) are presented in Figure 11:

The raw material phase, compared to the other phases, has high value, and depends on the component material.

Looking at the generated solutions, they present very large elasticity ranges and away from elasticity line EL₁ (with the exception of solutions that touch EL₁, but still show massive ranges). This highlights how the finite element model (with its boundary conditions) used for the case study presents possibilities for improvement.
Table 11. List of solutions created from selection phase.

| Design Solution ID   | PSL Range       | EL Range       | Screen   |
|----------------------|-----------------|----------------|----------|
| 1_Solid_M1_CA1       | [17.3701,19.9418]| [4.4379,7.5181]| OK       |
| 2_Solid_M2_CA1       | [16.559,18.0186]| [6.2095,8.9864]| OK       |
| 3_Solid_M3_CA1       | [16.7473,24.8011]| [1.4024,5.7481]| OK       |
| 4_Solid_M4_CA1       | [23.8281,35.0472]| [0.44898,3.8531]| OK, With FF |
| 5_Solid_M1_DE1       | [17.9333,20.5535]| [4.4379,7.5181]| OK       |
| 6_Solid_M2_DE1       | [17.195,18.6049]| [6.2095,8.9864]| OK       |
| 7_Solid_M3_DE1       | [16.9081,24.9975]| [1.4024,5.7481]| OK       |
| 8_Solid_M4_DE1       | [21.6142,32.7787]| [0.44898,3.8531]| OK, With FF |
| 9_Solid_M5_DE1       | [9.4244,11.3832]| [5.4898,8.2355]| OK       |
| 10_Solid_M1_PO1      | [15.542,18.2384]| [4.4379,7.5181]| OK       |
| 11_Solid_M2_PO1      | [14.7071,16.2157]| [6.2095,8.9864]| OK       |
| 12_Solid_M3_PO1      | [15.4796,23.4742]| [1.4024,5.7481]| OK       |
| 13_Solid_M4_PO1      | [17.3816,28.6046]| [0.44898,3.8531]| OK, With FF |

Table 12. Final ranking table of acceptable solutions.

| Design Solution ID | PSLss         | PSL_max | Rank |
|-------------------|---------------|---------|------|
| 1_Solid_M1_CA1    | 18.6559779    | 19.9418 | 8    |
| 2_Solid_M2_CA1    | 17.2888227    | 18.0186 | 10   |
| 3_Solid_M3_CA1    | 20.7742002    | 24.8011 | 5    |
| 4_Solid_M4_CA1    | 29.437672     | 35.0472 | 1    |
| 5_Solid_M1_DE1    | 19.2434075    | 20.5535 | 7    |
| 6_Solid_M2_DE1    | 17.8999635    | 18.6049 | 9    |
| 7_Solid_M3_DE1    | 20.9527804    | 24.9975 | 4    |
| 8_Solid_M4_DE1    | 27.1964416    | 32.7787 | 2    |
| 9_Solid_M5_DE1    | 10.4037791    | 11.3832 | 13   |
| 10_Solid_M1_PO1   | 16.8902052    | 18.2384 | 11   |
| 11_Solid_M2_PO1   | 15.4614015    | 16.2157 | 12   |
| 12_Solid_M3_PO1   | 19.4768603    | 23.4742 | 6    |
| 13_Solid_M4_PO1   | 22.9930991    | 28.6046 | 3    |

Finally, the best acceptable solution is solution with ID=4, whose characteristics are shown in Table 13.

Table 13. Best solution characteristics.

| Best Solution Characteristics |          |
|------------------------------|----------|
| Shape                        | Solid (3D) |
| Material                     | Age-Hardening Wrought Al-Alloys (ID: M4) |
| Process                      | Investment Casting (ID: CA1) |

4. Conclusions
In this work, a design and sustainability analysis method is defined and applied to design solutions in the automotive field. The single score indicator Product Sustainability Level (PSL), obtained through
the integration of finite element simulations and environmental modeling in the LCA perspective, is based on the multi-objective approach and is evaluated for design solutions generated by DeSA methodology.

An engine bracket is the case study used to explain the method. The combination of shape (chosen by the designer), materials and manufacturing processes (defined through the production database) allowed to observe several design alternatives and compare their level of sustainability, demonstrating the potential of the methodology. From the case study results, the use phase shows an extremely high weight in the PSL calculation. Thus, solutions having the same material, but different processes present almost the same level of sustainability.

The integration of performance and environmental issues into the product's concept design is the methodology contribution: several design solutions (combination of shape, materials, and technologies) are defined, analyzed, and compared using a single score index and engineering charts. However, the current approach presents several limits, summarized into the following key points, but which will be the subject of future developments in methodology:

- the method is limited to the structural analysis of the product to be studied and analysis of the environmental issues.
- only primary processes are considered in the creation of the several design alternatives (secondary and joining processes are not considered).
- a certain amount of data to perform the framework is needed.
- the sustainability index (i.e., PSL) of alternatives is generated, but it does not give any information to improve the same index and to consider the component lightweighting.

Further work development will be the application of the topology optimization to acceptable solutions $S_{acc}$, achieving both product lightweighting and a possible sustainability improvement and completing the overview on performance and sustainability potentialities within the automotive field.

### Appendix A

**Table A1.** Design material data in production database.

| ID | Material Class | Material Subclass | Material Name            | Density [kg/m$^3$] | Young Modulus [MPa] | Poisson Ratio [-] | Yield Stress [MPa] |
|----|----------------|-------------------|--------------------------|--------------------|---------------------|--------------------|-------------------|
| M1 | Metals and Alloys Metals and Alloys | Ferrous Metals and Alloys Metals and Alloys | Ferrous Metals and Alloys Metals and Alloys | High Carbon Steel High Carbon Steel | 7800-7900 7800-7900 | 200000-215000 205000-217000 | 0.285-0.295 0.285-0.295 | 400-1160 400-1500 |
| M2 | Metals and Alloys Metals and Alloys | Ferrous Metals and Alloys Metals and Alloys | Ferrous Metals and Alloys Metals and Alloys | Low Alloy Steel Low Alloy Steel | 7800-7900 7800-7900 | 205000-217000 205000-217000 | 0.285-0.295 0.285-0.295 | 400-1500 400-1500 |
| M3 | Metals and Alloys Metals and Alloys | Ferrous Metals and Alloys Metals and Alloys | Ferrous Metals and Alloys Metals and Alloys | Stainless Steel Stainless Steel | 7600-8100 7600-8100 | 189000-210000 189000-210000 | 0.265-0.275 0.265-0.275 | 170-1000 170-1000 |
| M4 | Metals and Alloys Metals and Alloys | Non-Ferrous Metals and Alloys Metals and Alloys | Non-Ferrous Metals and Alloys Metals and Alloys | Age-Hardening Wrought Alloys Age-Hardening Wrought Alloys | 2500-2900 2500-2900 | 68000-80000 68000-80000 | 0.32-0.36 0.32-0.36 | 95-610 95-610 |
| M5 | Metals and Alloys Metals and Alloys | Non-Ferrous Metals and Alloys Metals and Alloys | Non-Ferrous Metals and Alloys Metals and Alloys | Titanium Alloys Titanium Alloys | 4400-4800 4400-4800 | 110000-120000 110000-120000 | 0.35-0.37 0.35-0.37 | 750-1200 750-1200 |
Table A2. Environmental material data in production database.

| ID | Material Class | Material Subclass | Material Name           | GWP primary [kgCO$_{2eq}$/kg] | GWP EoL – Energy Recovery [kgCO$_{2eq}$/kg] | Substitution Factor [-] |
|----|----------------|-------------------|-------------------------|-------------------------------|------------------------------------------|-------------------------|
| M1 | Metals and Alloys | Ferrous | High Carbon Steel       | 1.71-1.89                     | 0                                      | 0.25                   |
| M2 | Metals and Alloys | Ferrous | Low Alloy Steel         | 1.93-2.13                     | 0                                      | 0.25                   |
| M3 | Metals and Alloys | Ferrous | Stainless Steel         | 4.73-5.23                     | 0                                      | 0.25                   |
| M4 | Metals and Alloys | Non-Ferrous | Age-Hardening Wrought Alloys | 12.2-13.4 | 0 | 0.15 |
| M5 | Metals and Alloys | Non-Ferrous | Titanium Alloys          | 44.1-48.7                     | 0                                      | 0.15                   |

Appendix B

Table B1. Design process data in production database.

| ID | Process Class | Process Subclass          | Process Name                               | Mass Range [kg] | Economic Batch Size [-] |
|----|---------------|---------------------------|--------------------------------------------|-----------------|------------------------|
| CA1| Casting       | Investment Casting Processes | Investment Casting                        | 0.001-100       | 1-100000               |
| DE1| Deformation   | Bulk Deformation Processes | Forging                                   | 0.01-5000       | 1000-100000            |
| PO1| Powder Methods| Powder Pressing Processes  | Pressing and Sintering                    | 0.01-5          | 5000-500000            |

| ID | Process Class | Process Subclass          | Process Name                               | Section Thickness [mm] | Tolerance [mm] | Roughness [µm] |
|----|---------------|---------------------------|--------------------------------------------|------------------------|---------------|----------------|
| CA1| Casting       | Investment Casting Processes | Investment Casting                        | 1-75                  | 0.05-0.25     | 0.5-3.2        |
| DE1| Deformation   | Bulk Deformation Processes | Forging                                   | 3-250                 | 0.2-1         | 3.2-12.5       |
| PO1| Powder Methods| Powder Pressing Processes  | Pressing and Sintering                    | 1.5-8                 | 0.025-1       | 1-10           |
Table B2. Design process/shape compatibility data in production database.

| Primary Shape Type | Process ID | 1D - Circular | 1D – Non-Circular | 2D - Flat | 2D - Dished | 3D - Solid | 3D - Hollow |
|--------------------|------------|---------------|-------------------|----------|------------|------------|------------|
| CA1                | 1          | 1             | 0                 | 0        | 1          | 1          |            |
| DE1                | 0          | 1             | 0                 | 0        | 1          | 0          |            |
| PO1                | 1          | 1             | 0                 | 0        | 1          | 1          |            |

Table B3. Design process/material compatibility data in production database.

| Material ID | Process ID | M1 | M2 | M3 | M4 | M5 |
|-------------|------------|----|----|----|----|----|
| CA1         | 1          | 1  | 1  | 1  | 1  | 0  |
| DE1         | 1          | 1  | 1  | 1  | 1  | 1  |
| PO1         | 1          | 1  | 1  | 1  | 1  | 0  |

Table B4. Environmental process/material compatibility data in production database.

| Material ID - GWP manufacturing [kgCO₂eq/kg] | Process ID | M1          | M2          | M3          | M4          | M5          |
|---------------------------------------------|------------|-------------|-------------|-------------|-------------|-------------|
| CA1                                         | 0.807-0.892| 0.819-0.906 | 0.809-0.894 | 0.819-0.906 | 0           |
| DE1                                         | 0.247-0.273| 0.238-0.263 | 0.562-0.621 | 5.24-5.79   | 1.05-1.16   |
| PO1                                         | 2.7-3.27   | 2.83-3.43   | 2.89-3.31   | 20.2-24.4   | 0           |

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