Materials selection in the Life-Cycle Design process: a method to integrate mechanical and environmental performances in optimal choice

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Abstract

The choice of materials takes on strategic importance in design aimed at harmonising the performance characteristics and eco-compatibility of products in line with the Life-Cycle Design approach. The objective of the present study is the development of a systematic method which introduces environmental considerations in the selection of the materials used in components, meeting functional and performance requirements while minimising the environmental impact associated with the product’s entire life-cycle. The proposed selection procedure elaborates data on the conventional and environmental properties of materials and processes, relates this data to the required performance of product components, and calculates the values assumed by functions which quantify the environmental impact over the whole life-cycle and the cost resulting from the choice of materials. As shown in the case study presented, the results can then be evaluated using multi-objective analysis techniques.

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1. Introduction

In the last decade, awareness of environmental problems has led to the development of strategies to promote an industrial production as ecological as possible, integrating environmental demands with product standards. In the context of the process of product development, interpreting these new requirements calls for a broader view of the problem, moving from a conventional approach, where the sale of the product is considered the final analytical step, to an innovative approach which extends to the end of the product’s useful life and to retirement. Thus environmental requirements must become factors of innovation for a successful, and therefore “sustainable”, product design. This is possible through a systematic approach to integral and simultaneous design, in accordance with the new principles of Life-Cycle Design (LCD) [1–3]. This is a design approach which takes into consideration all the phases of the product’s life-cycle, from concept development to retirement, analysing and harmonising determining factors such as quality, cost, production feasibility, requirements of use, servicing and, indeed, environmental aspects.

Products environmental impact is directly influenced by the environmental properties of the materials used, such as energy costs, emissions involved in production and manufacturing phases, and recyclability. The choice of materials therefore assumes strategic importance, and requires an extension of the characterisation of materials, integrating conventional characterisation aimed at defining physical–mechanical properties, with a complete characterisation of environmental performance. For the designer to make an optimal choice of materials, harmonising performance characteristics and properties of eco-compatibility, the selection process must take
account of a wide range of factors: constraints of shape and dimension, required performance, technological and economic constraints associated with the manufacturability of materials, environmental impact of all the phases of the life-cycle.

The enormous variety of materials available for engineering applications and the complexity of the set of requirements conditioning the choice of the most appropriate materials, leads to a taxing problem of multiple-criterion optimisation. In recent years, several systematic methods have been proposed to help the designer in the selection of materials and processes [4,5]. Of the more commonly used qualitative selection methods, that of Ashby is based on the definition of material indices, consisting of sets of physical–mechanical properties which, when maximised, maximise some performance aspects of the component under examination [6]. Defining these indices, it is possible to compile selection charts summarising the relations between properties of materials and engineering requirements [7]. Usually taking into consideration the physical–mechanical properties of materials, these selection charts can be extended to introduce some environmental properties [8]. From this standpoint, several important studies have been based on the definition of indices able to express the environmental performance of materials by introducing the energy consumption and emissions (into the atmosphere or water) associated with the materials [9], or eco-indicators developed on the basis of life-cycle assessment methods [10]. An alternative approach is that of translating environmental impact in terms of economic cost of production, introducing functions of environmental cost, such as energy consumption and toxicity, which again depend on the properties of the materials [11].

All the methods proposed are limited to quantifying the environmental impact of the choice of materials on the basis of their environmental properties associated with the production phase. Only particular studies have considered the influence of the choice of materials on the impact associated with the working life of the component [12]. To date, the problem of choice of materials from the viewpoint of LCD (taking into account the environmental impacts involved in all phases of the life-cycle, from production to retirement) has been considered only in general terms, with the aim of defining guidelines for a choice which integrates properties of materials, manufacturing demands and end-of-life impacts, suggesting a distinction of selection criteria between component design and assembled product design [13].

In accordance with the life-cycle design approach, the objective of the present study is to develop a systematic method which includes environmental considerations in the selection of materials used for components, satisfying functional and performance requirements while minimising environmental impact over the product’s entire life-cycle.

The proposed selection procedure elaborates data on the conventional and environmental properties of materials and processes, relates this data to the performance required of the product components, and calculates the values assumed by functions which quantify the environmental impact over the life-cycle, and the cost resulting from the choice of materials. The results can then be evaluated using multi-objective analysis techniques.

2. Life-cycle analysis and environmental characterisation of materials and processes

The optimal choice of materials, also in relation to environmental demands, requires a complete environmental characterisation, with particular regard to the following aspects:

- environmental impact associated with production processes (energy costs and overall impact);
- environmental impact associated with phases of end-of-life (recycling or disposal);
- suitability for recycling (expressed by the recyclable fraction).

Information on the energy costs and recyclable fractions of more common materials can be obtained from commercially available databases, such as that of the CES materials selection software [14]. Overall environmental impact can be evaluated using the techniques of life-cycle assessment, an analysis method used to quantify the environmental effects associated with a process or product through the identification and quantification of the resources used and the waste generated, evaluating the impact of using these resources and of the emissions produced [15,16]. Quantification of the impacts is based on inventory data [17], subsequently translated into eco-indicators such as those used here. These are evaluated according to the Eco-Indicator 99 methodology [18], calculated using SimaPro 5.0 software [19].

Environmental characterisation is also extended to common manufacturing processes, primary (forming) and secondary (machining), evaluating the indicators which quantify the impacts of standard processes per unit of process parameter or of volume/weight of material processed.

2.1. Data on materials and processes

For each material, it is necessary to integrate the information used in conventional design with that regarding environmental properties to obtain:

- general properties (density, cost);
- mechanical properties (modulus of elasticity, hardness, fatigue limit, etc.);
thermal and electrical properties (conductivity and thermal expansion, operating temperature, electrical resistance, etc.);

environmental properties (energy cost, environmental impact, recyclability).

As an example, the datasheet of Fig. 1, relating to a widely-used plastic material (polypropylene), shows the data on the environmental properties. Eco-indicators were evaluated with SimaPro 5 software, using the Eco-Indicator 99 method and expressing impacts in mPt (milliPoint). With this software it is possible to select the inventory data to be used for impact evaluation, in this specific case Buwal 250 data [20].

Regarding the primary and secondary manufacturing phases, the following information must be obtained:

- physical attributes of the final product;
- economic cost of standard process (fixed and variable costs);
- environmental properties (energy consumption, environmental impact of standard process).

3. Method of selection

The reference method (Fig. 2) is based on calculation models which quantify and interrelate the various performances required of the material in order to identify potential solutions, and a successive multi-objective analysis aimed at harmonising the conventional performance, costs and environmental performance of the product.

The first phase consists of defining the set of design requirements and parameters:

- primary performance (Pf1), in relation to the specific functionality of the component;
- secondary performance (Pf2), which can impose further restrictions to guide the selection;
- geometric parameters, distinguishing between fixed (Gf) and variable geometric parameters (Gv);
- typology of shape and relative level of complexity (Sh), which greatly effects the choice of forming processes;
- use of component (Us), which can influence an initial selection of materials.

The set of design requirements constitute the input for the procedure of selecting potential solutions. This procedure is based on two different types of analysis (Fig. 3). In the first stage, the production feasibility of
each hypothetical solution is evaluated, analysing some of the information given in the set of design requirements (in particular the typology of shape required and the intended use). The solutions identified in the analysis of production feasibility must then be evaluated in terms of the required performances \( P_{f1}, P_{f2} \). The potential solutions obtained are then analysed in subsequent phases of the selection method. Each potential solution \( S \) is defined by pairs of material-primary forming process \( (M, F_{Pr}) \), and by the performance volume \( (P_{fV}) \), representing the minimum volume needed to respect the requirements of primary performance. If appropriate, the definition of the generic solution \( S \) can also include any processes of secondary machining required after the initial forming.

In the second phase, the calculation models are applied to each potential solution in order to evaluate the indicators of environmental impact and cost over the entire life-cycle.

The final phase of the method regards analysing the results and identifying the optimal choice.

4. Analysis of production feasibility

The first stage of the selection procedure must correlate material, process, shape and function. The problem of the interaction between these factors is considered central to the selection of materials and has already been amply treated [7].

In the method proposed, this problem is addressed by considering shape (Sh) and use (Us) to be design requirements, expressed using binary vectors \( V^{Sh} \) and \( V^{Us} \), and is based on binary matrices correlating shape-process, material-use and material-process

\[
\phi^{S-P} = \left[ \begin{array}{c}
q_{p}^{S-P} \\
\vdots
\end{array} \right]_{p=1,...,p_{f}}
\]

\[
\phi^{P-M} = \left[ \begin{array}{c}
r_{m}^{P-M} \\
\vdots
\end{array} \right]_{m=1,...,m_{p}}
\]

where \( n_{m}, n_{f}, n_{p} \) and \( n_{u} \) are the numbers of, respectively, possible materials, processes, shape typologies and uses. Considering processes of primary manufacture only, on the basis of the correlation matrices (1) and vectors \( V^{Sh} \) and \( V^{Us} \), and following the calculation scheme summarised in Fig. 4, it is possible to obtain first the vectors \( V^{Pr} \) and \( V^{Mt} \), indicating, respectively, the primary processes able to produce the required typology of shape, and the materials suitable for the intended use. The subsequent application of the material-process correlation matrix gives a matrix of producible solutions

\[
\Omega = \left[ \omega_{pm} \right]_{m=1,...,m_{p}} \quad \text{where}
\]

\[
\omega_{pm} = \omega_{pm}(V^{Sh}, V^{Us}, \phi^{S-P}, \phi^{P-M})
\]

where \( \phi \) is the material-use correlation matrix.

This matrix indicates all the pairs of material-primary process \( S_{j} = (M_{m}, F_{Pr_{p}}) \) which constitute the set of producible solutions.

The material-use correlation matrix constitutes a filter in the pre-selection of possible solutions in that it limits the choice to those materials conventionally employed for the intended use. For a more open pre-selection, it is possible to by-pass this filter. In this case, the terms of matrix (2) would depend solely on \( V^{Sh}, \phi^{S-P} \) and \( \phi^{P-M} \).
Using the above approach in the analysis of production feasibility, it is possible to:

- operate an analytical and exhaustive selection of all the possible solutions which can satisfy the intended form and use;
- separate the selection conditioned by production feasibility from that conditioned by performance requirements, thereby evidencing the relationships between choice of material and effect on life-cycle impacts, relationships which, as shown below, depend on the different performance capacities of the materials.

This approach requires the prior compilation of the correlation matrices (1). Given the ever greater variety of engineering materials and related manufacturing processes, it is reasonable to consider compiling these matrices by typology of material.

Alternatively, for a first selection of material-process pairs, it is possible to use pre-existing software tools, such as CES, which implements Ashby’s methodology [7,14]. It must be remembered, however, that tools of this type allow a selection that already takes account of the performances required.

5. Analysis of performance

The second stage of the selection procedure allows the identification of producible solutions that respect the required performance characteristics. In this way a set of potential solutions is obtained which are then analysed, applying the calculation models to evaluate the environmental and economic impacts over the entire life-cycle.

In general, the analysis of performance can be simplified considering three different typologies of mathematical relations.

5.1. Function of performance volume (PfV)

Expresses the minimum volume necessary to respect the primary performance requirements. Generally it is a function of Pf1, the geometric parameters (Gf, Gv) and the properties of the material (MtPp)

\[ PfV = PfV(Pf1, Gf, Gv, MtPp) \tag{3} \]

5.2. Geometric conditions of performance

If the variable geometric parameters Gv are directly correlated with primary performance Pf1, the geometric conditions of performance can be expressed by functions constrained by a range of values (defined by the design requirements)

\[ Gv = Gv(Pf1, Gf, MtPp), \quad Gv \in [Gv1, Gv2] \tag{4} \]

5.3. Secondary conditions of performance

Conditions of this type can be generally expressed using functions dependent on the properties of the materials and the performance volume, to be compared with assumable limit-values

\[ Pf2 = Pf2(PfV, MtPp), \quad Pf2 \leq Pf2^{\text{lim}} \tag{5} \]

5.4. Final considerations

In conclusion, if a producible solution \( S_j = (M \ FPr) \) respects all the constraints and requirements of performance, it then becomes a performing solution and can be selected for final evaluation. The set of potential solutions consists of all the performing material-primary process pairs, integrated by the corresponding performance volume \( S_j = (M \ FPr \ PfV) \). The latter parameter acquires particular relevance in the proposed method because it directly conditions the values assumed by the life-cycle indicators which, defined below, guide the optimal choice. Using this approach, it is possible to correlate the search for environmentally and economically convenient solutions with the performance characteristics of the materials.

Only in the case of particularly simple design problems can the functions of type (3) be defined in analytical form. More generally, the performance volume cannot be explicitly ascribed to the factors effecting it, but rather is the result of design procedures employing modern methods of engineering design, implemented in commonly used tools based on parametric CAD and FEM softwares for structural-performance analyses.

6. Life-cycle indicators

The final phases of the selection method consist of applying the calculation models to the set of potential solutions, evaluating the indicators of environmental impact and cost (EILC, CELC) relative to the entire life-cycle, and then of analysing the results and identifying the optimal choice. The indicators are functions of the quantities of material necessary to produce the component, expressed by the performance volume.

The environmental impact of the life-cycle is expressed by

\[ EILC = EIMat + EIMet + EIUse + EIEnd \tag{6} \]

where \( EIMat \) is the environmental impact of the material needed to produce the component; \( EIMet \) the impact associated with its manufacture; \( EIUse \) the impact related to the entire phase of use (which can depend on the choice of material); and \( EIEnd \) is the impact of the end-of-life (recycling, disposal).

The first two terms of (6) constitute the Environmental Impact of Production \( EIProd \), which can be expressed by
The cost of production $C_{\text{Prod}}$ can be expressed in form analogous to (7), in function of the quantity of material to be employed and of the more significant process parameters. Alternatively, it is possible to use a conventional evaluation of the production costs of a component, distinguishing between variable and fixed costs, and dividing the latter by the size of the production batch [21].

The cost of end-of-life can be expressed as

$$C_{\text{Eol}} = c_{\text{Dsp}} \cdot (1 - \xi) \cdot W + c_{\text{Rcl}} \cdot (c_{\text{Rcl}} - r_{\text{Rcl}}) \cdot \xi \cdot W$$

where $c_{\text{Dsp}}$, $c_{\text{Rcl}}$, and $r_{\text{Rcl}}$ are, respectively, the cost of disposal, the cost of recycling processes and the proceeds from the sale of recycled material per unit weight of the material; $\xi$ is the recyclable fraction.
8.1. Definition of design requirements

The first phase of the method is the definition of the set of design requirements:

- primary performance required (Pf1) is that of guaranteeing, in relation to a reference condition of vehicle movement, efficient braking within a given distance, which in physical–mechanical terms translates into the dissipation of energy through friction and structural performance correlated with the mechanical and thermal loading conditions (stress–strain analysis);
- secondary performance (Pf2) is that of limiting the weight $W$;
- fixed geometric constraint (Gf) is the external radius of the disk $R_e$;
- variable geometric parameters (Gv) are the thickness $s$ and internal radius of the disk $R_i$;
- shape required (Sh) is a three-dimensional rotation solid.

8.2. Analysis of production feasibility

On the basis of the form required (Sh) and of the expected use (Us), the analysis of production feasibility suggests some hypothetical solutions of which two were considered (one conventional and one of recent introduction):

- $S_1$ consists of grey cast iron BS 350 as material, and green sand casting as primary forming process;
- $S_2$ consists of F3K20S Duralcan (aluminium matrix compound) as material, and squeeze casting (liquid metal forging) as primary forming process.

8.3. Analysis of performance

Defining the weight of the automobile, and imposing the required braking capacity, it was possible to determine the braking moment required on each wheel, and the pressures at the disk-pad contact necessary to produce this moment. The primary performance was therefore translated into the following conditions of correct functioning which must be guaranteed by the thermal-mechanical characteristics of the material:

- thermal peaks below the maximum operating temperature of the materials;
- global stress state, due to superimposition of mechanical and thermal loading, below the mechanical resistance limits of the materials;
- global strain state, due to the superimposition of mechanical and thermal loading, within the elastic limit of the materials.

Given the complexity of the problem, the performance analysis was conducted with the aid of the finite element software MSC Patran/Nastran [25], which allowed the correlation of performance properties of the materials, variable geometric parameters and the corresponding structural and thermal loading. As an example, Fig. 5 shows some results of the stress and thermal analyses on the disk. These FEM analyses were...
calibrated on the basis of experimental data available in the literature [26,27]. Both of the producible solutions under examination were found to function. Table 1 shows the values which the performance volume PfV and the variable geometric parameters (thickness s and internal radius Ri) must assume in order to guarantee the performance, together with the corresponding weights.

Comparing the two solutions under examination, that in Duralcan requires the greater performance volume PfV (and therefore the greater overall dimensions) to guarantee primary performance. The conventional solution in cast iron reduces the overall dimensions, but results in a greater weight (+56% compared to Duralcan).

8.4. Evaluation of life-cycle indicators and analysis of results

Functions (6) and (9) were used to calculate the indicators of environmental impact and cost for each performing solution. The results of the calculation models are reported in Table 2. The general models were simplified as follows:

- in the calculation of production impacts and costs, only the primary manufacturing processes were considered, ignoring secondary processes;
- in the evaluation of (9), the end-of-life costs expressed by (10) were ignored because of the difficulty of obtaining the relevant data. Thus only the cost of production CPROD was considered as cost indicator;
- in this first phase, (6) was evaluated ignoring the environmental impact related to the use.

From the values in Table 2, it is clear that the solution in Duralcan leads to an impact (2272.2 mPt) two orders of magnitude greater than that of the solution in cast iron (43.5 mPt). The graph shown in Fig. 6 describes the composition of the environmental indicator EI LC and is particularly interesting in that it evidences the different distribution of the environmental impact over the life-cycle for each potential solution. Comparing the two solutions, it is evident that:

- the overall impact of the solution in Duralcan is essentially due to the impact of producing the material itself, which also offers a negligible recycling fraction (low recovery of impact);
- the solution in cast iron has a much lower production impact and, further, its high recyclability allows a substantial recovery of impact at end-of-life.

The values reported in Table 2 clearly highlight which of the two solutions is more favourable, the conventional solution in cast iron, since it results in the lowest values of both CPROD and EI LC.

In conclusion, it is evident that when the properties considered most important for the final product are those of reduced cost and environmental impact of the life-cycle, the best solution is that in cast iron. The alternative solution in Duralcan is favourable only when lightness is chosen as the primary property. This is confirmed by the application of the multi-objective analysis method introduced in Section 7.

Considering EI LC, CPROD, weight W and performance volume PfV as objective functions, different values of the function to minimise γ are obtained for the two alternative solutions according to how the set of weight coefficients αi is defined. Fig. 7 shows the results for four different orientations of investigation, corresponding to the different importance given to the objective functions in the evaluation of γ: (1) maximum importance to environmental impact, medium to cost, low to W and PfV reductions; (2) maximum importance to W reduction, medium to cost, low to environmental impact and PfV reductions; (3) primary reduction of cost; (4) primary reduction of environmental impact. It can be seen that, compared to the solution in cast iron, the solution in Duralcan is interesting only in the second case.

9. Introduction of environmental impact of use: evaluation of life-cycle indicators and analysis of results

As noted, the solution in Duralcan has the primary advantage of reducing the weight of the disk. The consequent lightening of the vehicle can result in a sufficient reduction in the environmental impact of use to recover
the increased impact in production. To evaluate whether, and under what conditions, this is true, it is necessary to evaluate the term \( EI_{\text{Use}} \) of Eq. (6), ignored previously. Apart from this, all the other simplifications introduced in Section 8.4 remain the same. Having fixed an overall reference distance travelled (mission), the environmental impact of use \( EI_{\text{Use}} \) can be expressed as

\[
EI_{\text{Use}} = EI_{\text{Fuel}} + EI_{\text{Mission}}
\]

\[
= \frac{e_i}{C_1} \cdot q_{\text{Fuel}} + \frac{e_i}{C_1} \cdot q_{\text{Mission}},
\]

where \( e_i \) is the eco-indicator per unit weight of fuel; \( e_i \) is the eco-indicator associated with the use of the vehicle powered with this kind of fuel per unit of distance travelled; \( q_{\text{Fuel}} \) the quantity of fuel needed for the entire distance covered; and \( q_{\text{Mission}} \) is the total expected distance.

To evaluate all the quantities in play, the following assumptions were made:

- weight of vehicle = 1000 kg;
- mean fuel consumption = 0.0850 l/km;
- reduction in consumption due to a 10% reduction in total weight of vehicle = 4.5% (source: IKP, University of Stuttgart, Germany).

On the basis of these assumptions, and after having evaluated the overall reduction in weight due to the choice of 4 disks in Duralcan instead of cast iron (8.7 kg), it was possible to evaluate the reduced weight of the vehicle (991.3 kg) and the mean consumption of the lightened vehicle (0.0847 l/kg).

Table 3 shows the environmental indicators of the life-cycle, considering the environmental impact of use for an expected travelling distance of 150,000 km.

From the values in Table 3, it is clear that the solution in Duralcan results in a lower environmental impact than that in cast iron, in terms of both the phase of use alone (0.4%) and the entire life-cycle (0.3%). The
percentage reduction in $E_{ILC}$ also depends on the expected distance travelled. The graph in Fig. 8 shows, for the two solutions, the Break-Even Point of $E_{ILC}$. This represents the minimum distance which must be travelled for the $E_{ILC}$ corresponding to the solution in Duralcan to be less than the $E_{ILC}$ of the solution in cast iron (about 31,300 km).

The graph in Fig. 9 describes the new composition of the environmental indicator $E_{ILC}$, in relation to the different phases of the life-cycle for each potential solution (distance travelled = 150,000 km). Because of the different orders of magnitude, the components regarding the phase of use are shown in Pt rather than in mPt.

### Table 3
Results of the evaluation of life-cycle indicators (including phase of use)

<table>
<thead>
<tr>
<th></th>
<th>$E_{IPROD}$ (mPt)</th>
<th>$E_{IUSE}$ (mPt)</th>
<th>$E_{IEOL}$ (mPt)</th>
<th>$E_{ILC}$ (mPt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 350</td>
<td>208.9</td>
<td>2729884</td>
<td>-165.4</td>
<td>2729927</td>
</tr>
<tr>
<td>F3K20S</td>
<td>2293.3</td>
<td>2719201</td>
<td>-21.1</td>
<td>2721479</td>
</tr>
</tbody>
</table>

Fig. 8. Break-even point of $E_{ILC}$ for the two solutions.

Fig. 9. Composition of indicator $E_{ILC}$ in relation to phases of life-cycle (including use).
In conclusion, when the environmental impact relating to the phase of use, influenced by the vehicle weight, is also taken into account, the alternative solution in Duralcan is advantageous not only when lightness is chosen as the primary property, but also when the environmental impact of the entire life-cycle is considered. And this occurs from a minimum distance travelled of around 31,000 km.

Again, this consideration is confirmed applying the multi-objective analysis method. Considering $EI_{\text{LC}}$ (which now also includes $EI_{\text{USE}}$, calculated for the reference distance of 150,000 km), $C_{\text{PROD}}$, the weight $W$, and the performance volume $PfV$ as objective functions, the results shown in Fig. 10 are obtained for the four different investigation orientations described in Section 8.4. It can be seen that, again, the solution in cast iron is better for the first (maximum importance to environmental impact, medium to cost) and third (primary reduction of cost) investigation typologies, while that in Duralcan is better for the second one (maximum importance to weight reduction). For the last investigation typology, directed at reducing primarily the environmental impact, however, the two solutions are essentially equivalent, while for distances over 150,000 km the solution in Duralcan tends to be more advantageous than that in cast iron (since the lower value of $EI_{\text{LC}}$ due to the reduced weight tends to increase with the distance travelled).

10. Conclusions

The environmental impact of a product is directly effected by the environmental properties of the materials used, as impacts corresponding to production and manufacturing phases, and recyclability. In accordance with the life-cycle design approach, the present study proposed a systematic method which introduces environmental considerations in the selection of materials used in components, and harmonises functional and performance requirements with the minimisation of the environmental impact over the product’s entire life-cycle, from production to retirement.

The proposed selection procedure elaborates data, both conventional and environmental, regarding the properties of materials and processes. It relates this data to the performance requirements demanded of the product and calculates the values assumed by functions which quantify the environmental impact over the entire life-cycle, including the phases of use and retirement, and the costs resulting from the choice of materials. A complete application of the method in the design of an automobile component, the brake disk, allowed a direct comparison between the multi-objective optimal choice and that obtained in a conventional design approach. This evidenced the need to use new tools in order to guarantee, in the design phase, environmental safeguard in the development of industrial products, and the possibility of their full integration with conventional design tools.

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