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Multi-criteria decision model of sustainable industrial production: A case study on 3D printed carbon PA

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Abstract. In the Concurrent Engineering (CE) approach, several aspects of the life cycle of a product are considered at the same time during the design phase. This allows to respond more quickly to the market needs and improves the final products quality. However, with this approach, the design phase could result more time consuming and expensive and needs simple and easily applicable optimization models. For this reason, a new multi-criteria decision model is proposed in this paper. Additive manufacturing technologies for high performances polymers are gaining increasing interest as they are a valid option for the manufacturing of structural components. For these reasons, high performance 3D printed isogrid structures in short carbon fibers reinforced polyamide were selected as a case study. Production processes of as-printed and dried isogrid structures were carried out; mechanical characterization and environmental and cost analysis were performed on the considered scenarios. Following the proposed model, the results of the analyses were used to calculate a single value indicator for each product. In this way, it was possible to compare the different alternative and select the optimal solution.

Introduction

Nowadays, the development of increasingly complex industrial products, the increased competitiveness of companies, the need to reduce production times, and countless regulations and design standards are forcing engineers to develop high quality products that are as environmentally sustainable as possible and at the lowest cost, in order to be competitive in the global market.

In this context, Concurrent Engineering (CE) has become the foundation of modern engineering as it allows an optimal balance between cost and quality to be achieved. CE was born in the 1980s and represents a set of methodologies and tools that enable an integrated approach to product design and related manufacturing processes. The areas of product development that can be considered simultaneously during the design phase can cover all phases of the product life cycle, from conception to end-of-life. CE moves away from the traditional sequential approach in the execution of the design, process planning, production, and demanufacturing phases, and the individual activities are performed in parallel, so that the product can be evaluated over its entire life span, starting as early as the design phase [1,2].

CE is crucial when products of high complexity, with long development phases and the difficulty in predicting the impact of design decisions on next phases of the product life cycle is high; this is often coupled with the need to respond to a rapidly changing demand that inevitably requires shorter product life cycles.

It is obvious that, in such a complex context, the role of the engineer within companies is strongly oriented towards decision-making and the process of making decions in the short, medium or long term can determine the success or failure of production activities. Therefore, it’s crucial to develop decision-making techniques that make decision-making more efficient and easier. The decision-making process starts with the identification of the problem and the objectives to be achieved, followed by the choice of decision criteria, their weights and the definition of a performance index to be maximised or minimised [3]. Consequently, to improve the performance index, alternative solutions must be developed, analysed and compared in order to choose the best alternative. It is also crucial that a mechanism of continuous implementation of the identified solutions is triggered through constant monitoring of the results achieved. The choice of criteria is not unique but depends on the specific case of application [4].

Traditionally, the decision criteria to be related to system performance are those represented in the production tetrahedron: time, cost, flexibility and quality. To these is added sustainability.

The concept of sustainability was first introduced in 1972, during the first United Nations Conference on the Environment, and, in 1987, within the so-called Brundtland Report, a sustainable model was defined as one that meets the needs of the present without compromising the ability of future generations to meet their own needs [5].

Environmental sustainability is becoming a cornerstone in industrial production and in general in any activity of modern society, thanks to the realisation that the planet's resources are not infinite but must be preserved, without waste, respecting ecosystems and biodiversity.

Thus, the need for environmental sustainability is linked to environmental protection, but in recent years, in addition to considering the ecological aspects, it has also been declined from an economic and social point of view.

There are qualitative evaluation criteria, such as checklists and guidelines, or methods capable of quantifying the environmental impacts of a system according to different impact categories; among these, Life Cycle Assessment (LCA) is the most widely used methodology. LCA quantifies environmental impacts, considering resource consumption and atmospheric emissions, and can be applied to the entire life cycle (from cradle to grave) [6-8].

In this context, a new mathematical model is proposed as a decision-making support for industrial applications that can be used as a product/process optimisation tool. The literature lacks a model capable of considering multiple decision criteria and simple to apply. Unlike the theoretical approaches present in the literature, this model has the possibility of being easily usable at an industrial level due to its mathematical simplicity and application. In fact, the novelty of this paper lies in the ease of application of in industrial context and the possibility of being adapted to specific cases (products/processes) in a short time.

In this regard, was examined the case of composite isogrid structures made by additive manufacturing processes [9]. The mechanical performances, the economic and environmental sustainability and production time of isogrids in different configurations (as-printed and dried) were evaluated. In addition, through the application of the theorised model, various scenarios were compared.

Materials and Methods

In a concurrent engineering perspective, it is crucial to develop quantitative models to consider multiple variables and criteria at the same time. Their ease in application is also required to be applied in an industrial context and help the design process.

The model here presented may include whichever factor the decision makers want to take into account as long as it can be evaluated in a quantitative way. Hence, it pairs well with procedures such as Life Cycle Assessment, flexibility and quality assessment tools that quantifies aspects of a process or a product that would be otherwise difficult to measure [6,10]. Moreover, the model can also consider traditional criteria such as cost (or Life Cycle Costing) and mechanical properties. It can be used to compare both products or industrial processes that have similar functions or yield to similar outputs. The mathematical model allows the comparison between different alternatives by calculating a performance index for each of them; the lower the index, the better the alternative. The index is calculated as sum of dimensionless parameters, each of which is the ratio between the criteria value for the considered system and that of the reference scenario.

An arbitrary number of parameters can be taken into account, depending on the design requirements; in this way, even complex decision problems can be easily solved. In addition, the model can be used to optimize a given process or a product by estimating the value of the performance index as key process parameters vary.

The general model is as follows:

$$I_i = p_i \frac{t_{0_i}}{t_{0_r}} + p_2 \frac{C_i}{C_r} + p_3 \frac{F_i}{F_r} + p_4 \frac{L_i}{L_r} + p_5 \frac{E_i}{E_r} + \cdots = \sum_j (p_j \frac{K_k}{K_r}) \quad (1)$$

where:

- I_i is the performance index for the i-th alternative
- p_j is the ponderation factor of the j-th decision criteria evaluated according to the company policies and the specific case study. Tools similar to a Weighted Decision Matrix can be employed to define $p_{i.}$ The sum of al the ponderation factors is equal to 1.
- K_i and K_r are the quantitative values of the decision criteria for the i-th alternative and the reference system. They can be referred, for example, to the production time (t_{0i}, $t_{0r)}$, product cost (C_i, C_r), mechanical performances, quality (L_i, L_r), system flexibility (F_i, F_r), environmental impacts (E_i, $E_{r)}$, etc.

The reference scenario is used as a benchmark to evaluate the performances of the other systems and it is characterized by an Index I_r equal to 1. In the case of production systems, it can represent a traditional process previously used by the company or by a competitor and the production of a defined number of parts. If multiple options have to be compared and no previous system is known, the reference system can be chosen between one of these; then, if no alternative gets an index value lower than one, the reference scenario is also the best choice according to the considered criteria.

Evaluation of the decision criteria.

The value related to the environmental sustainability decision criteria can be calculated by means of the standardised methodology of Life Cycle Assessment. LCA is an iterative approach constituted by 4 phases defined by the ISO standard 14040 and 14044 [6,11]. It allows to quantify the environmental impacts of a product or a process according to several impact indicators (e.g. Global Warming Potential, damage to Human Health, ect.) and considering all the aspects of their life cycle. The standard procedure phases are: goal and scope definition, in which the focus of the analysis, the functional unit, the goal and the system boundaries are defined; Life Cycle Inventory, where the inputs and outputs of the system are identified and directly or indirectly quantified; Life Cycle Impact Assessment, in which the inputs and outputs are translated into potential environmental impacts according to selected indicators. Dedicated software are used to automatically carry out this phase; finally, the LCIA results are critically reviewed and criticalities and improvement possibilities are identified. E_i and E_r can be retrieved from the LCIA results by considering an impact indicator that is representative of the studied system. LCA can be paired with the Life Cycle Costing analysis, an economic tool used to evaluate the cost incurred by a functional unit throughout its life cycle. LCC can also be used to calculate the economic criteria indicator (C_i, C_r) of the performance index.

The production time expressed in seconds can be used as a decision criteria value; it can be directly measured during the production of the components or calculated by estimating the process time, the inspection time, the movement time and the queue time.

The reciprocal of the load at break of a component could be used as a decision criteria value related to the quality of the scenario. In this way, if the mechanical properties of the component increase, the value of the index of performance decreases. More in general, if a feature of the product or the process should be maximized, it is possible to use its reciprocal as a decision criteria value. Further criteria and assessment methodologies could be introduced in the model to respond to the designers requirements.

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Ponderation decision matrix.

The design requirements that affect the production process can be translated into values depending on the evaluation that is associated with each aspect by the producer.

This type of evaluation has the function of assigning a value on a scale from 1 to 5 depending on the importance or weight that one wishes to assign to each factor that contributes to the generation of the performance index. The matrix thus generated, an example of which is shown in Table 1, is called Ponderation Decision Matrix (PDM) and allows values to be assigned for the calculation of the weighting factors p_i, shown in the previous section. The p_i calculation is done through the ratio of the value assigned to the specific parameter in the PDM, divided by the sum of the values assigned to all decision criteria.

Table 1. Ponderation Decision Matrix.

Decision Criteria	**Weight 1**	**Weight 2**	**Weight 3**	**Weight 4**	**Weight 5**	p_i
Mechanical Properties		**X**				2/14 = **0.14**
Environmental Sustainability				**X**		4/14 = **0.29**
Costs			**X**			3/14 = **0.21**
Production Time					**X**	5/14 = **0.36**
TOT	**0**	**2**	**3**	**4**	**5**	**14** / **1.00**

Case study: 3D printing of composite isogrid structure.

The case study analyzed in this work refers to an additive manufacturing production system for CFRP components. In particular, isogrid structures, generated by particular geometric configurations, have been realized through FFF technology and reported in Fig. 1.

The isogrid structures were designed by means of a CAD software by choosing rib width, rib thickness, cell height, global length and global width of 3, 8, 18, 106 and 80 mm, respectively, and then were exported as an .STL file for the creation of a .GCODE by the slicing software. The geometric construction parameters mentioned before are shown in Fig. 1.

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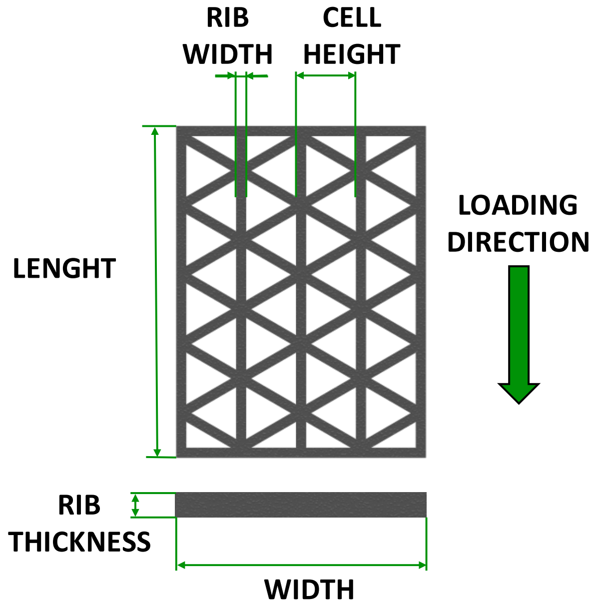

Fig. 1. Geometrical parameters of an isogrid structure.

The composite material used in this study, defined as Carbon PA, consists of a polyamide 6 reinforced with short (about 25 microns in length) carbon fibers at 20% in weight. According to the material datasheet, Carbon PA is characterized by an elastic modulus of 15.5 GPa and a ultimate tensile strength equal to 138 MPa, as also shown by authors in [9]. The material is supplied by Roboze S.P.A. in the form of a 1.75 mm diameter filament, suitable for processing through the Fused Filament Fabrication technique (FFF). The Roboze One+400 3D printer, equipped with FFF technology and supplied by Roboze Spa, was used for the additive manufacturing process, with the aim of realizing isogrid structures.

As the material is highly susceptible to moisture absorption, which causes a significant decrease in mechanical properties, Carbon PA was subjected to a drying process for about 4 h at the temperature of 120°C before the printing process. Moreover, during the printing phase, the material was maintained at 70°C in order to avoid moisture adsorption improving printing quality, reducing void formation. Main printing parameters for the realization of isogrid structures in CarbonPA through FFF technology are reported in Table 2.

Table 2. Main printing parameters.

Process Parameter	
Extruder Temperature	260°C
Bed Temperature	110°C
Infill Density	100%
Layer thickness	0.15 mm
Nozzle Diameter	0.4 mm
Nominal Printing Speed	50 mm/s
Infill Type	Linear
Raster angle	0°

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With these process parameters, the effective printing time for the realization of each isogrid structure detected at the end of printing equals to 2.15 hours [7]. 3 on 6 printed isogrids were subjected to another drying process in the oven for 4 hours at 120°C to remove the moisture absorbed during and after printing, before being tested under compression load.

The mechanical performance of the as-printed and dried isogrid structures was calculated by subjecting them to compression tests with an MTS 810 universal testing machine under displacement control at a speed of 0.5 mm/min. The acquisition system connected to the machine's load cell made it possible to record the compressive load values associated with the relative displacement. The maximum load values in kN were then derived from each test.

Case study: Life Cycle Analyses.

The LCA methodology was employed to quantify the environmental impacts of the 3D printed isogrid structures. As for the mechanical test, two different scenarios were considered: the as printed isogrid structure (Scenario 1) and the one subjected to the drying process (Scenario 2). The goal of the study is to quantify and compare the impacts of the two scenarios with particular focus on the drying heat treatment of the printed structure. In fact, the LCA results are then to be used to calculate the multi objective performance index to determine whether or not the heat treatment represents a process improvement. Global Warming Potential (GWP, expressed in kg CO_2 eq) was selected as the environmental impact value of the performance index decision criteria. This impact indicator is widely used in literature LCA for production processes of composite parts and it is well representative of their environmental behaviour [12,13].

The functional unit is therefore defined as the 3D printing of a carbon fiber reinforced polyamide isogrid structure with defined dimensions (see paragraph 0). Considering the focus of the case study on the manufacturing process, a “cradle to gate” approach was used, and the following production phases were included: materials production (PA and short carbon fibers), transport, filament drying and temperature control during the printing, 3D printing process and isogrid post drying (only for Scenario 2). The use and End of Life phases were excluded from the analysis.

The Life Cycle Inventory phase is based on a previous work of the authors [14]. Primary data were retrieved from direct measurements during the production processes; this includes the energy consumptions of the machines and the weight of the components. Considering the composition of the filament defined in the datasheet (80% polyamide, 20% carbon fibers), the quantity of each constituent was calculated. Polyamide and electric energy impacts were retrieved from the Ecoinvent database while CF impacts were modelled according to Khalil et al [15]. Impacts related to the production of the machines used for the production and postprocessing were not included as their useful life is much longer than the time horizon considered in this study and they would have led to negligible contribution.

LCIA results were calculated by using the SimaPro software, equipped by default with the Ecoinvent commercial database. The environmental impacts analysis was paired with an economic assessment (LCC) that considered the same functional unit and the same scenarios. The cost associated with each structure was calculated considering all direct and depreciation costs and by considering appropriate allocation procedures.

Material cost was calculated considering the purchase price (120 €/kg) of the filament and the weight of the components (41.25 g). Energy costs were calculated considering the measured consumptions (1.366 kWh) and the cost per kWh. Machines depreciation was calculated considering their purchase price, their use time for the considered scenarios, their service life (expressed in hours) and their maintenance costs. Labour and design time were measured (0.3 h and 0.5 h respectively) and multiplied by the hourly staff cost (30 €/h for laboratory operator and 35€/h for designer) to evaluate personnel contribution to the total cost. Direct measurements of time required for the production phases were also employed to calculate the total production time required for the two scenarios (4.45h for the first scenario and 6.55 h for the second one).

Results and Discussion

Fig. 2 shows the mean load vs. displacement curves of the dried and as-printed isogird structures tested under compressive load. It can be seen that there is a significant increase in performance when the material is subjected to a drying cycle prior to testing. The percentage increase in performance is equivalent to approximately 23%.

The average values of the maximum load measured for as-printed and dried isogrid structures are 13.08 kN and 16.08 kN, respectively.

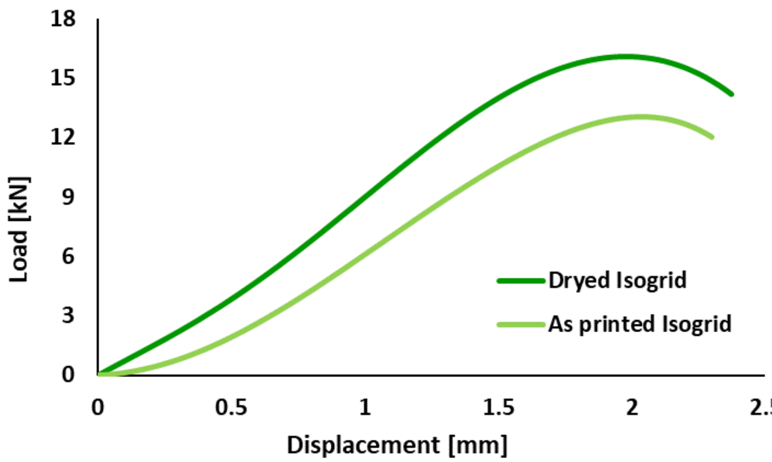


Fig. 2. Load vs. displacement curves of dried and as-printed isogrid structures.

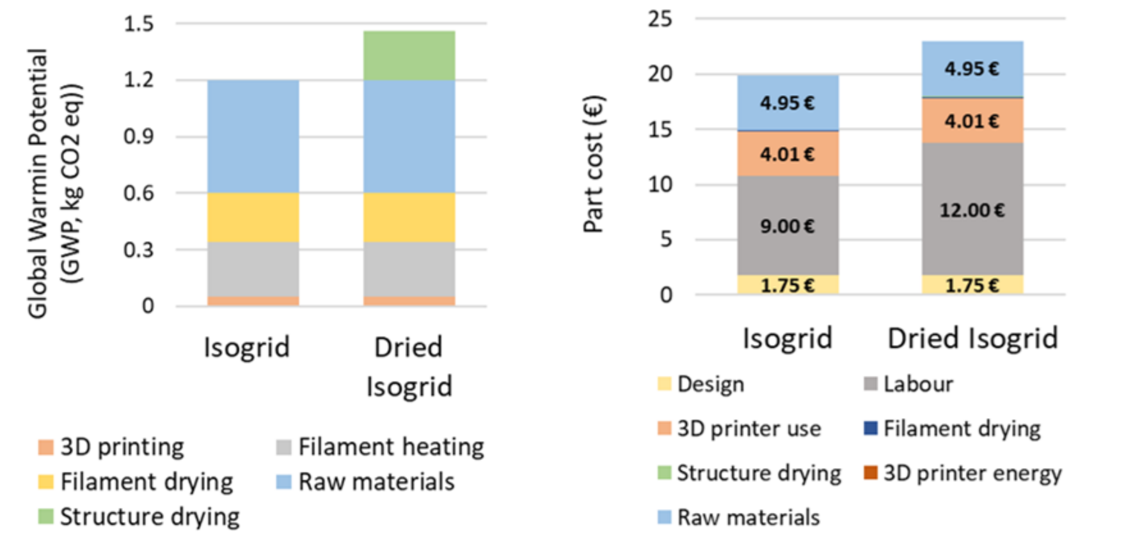
Fig. 3 (a) presents the results of the LCA analysis in terms of Global Warming Potential. The two scenarios are the same with the exception of the structure drying process that is only present in Scenario 2. The as-printed isogrid structure showed environmental impacts about 20% lower than those of the heat treated parts (1.20 kg CO2 eq vs 1.46 kg CO2 eq). This is due to the electric energy production and consumption of the isogrid drying process.

Indeed, most of the production phases that include an electric energy consumption resulted in relevant environmental impacts; this also includes the filament initial drying (0.26 kg CO2 eq) and the filament temperature control during the printing phase (0.26 kg CO2 eq). This is due to the fact that the Italian energy mix is mainly composed of non-renewable sources. Improving the sustainability of the energy use could strongly reduce the overall impacts of the scenarios (e.g. by using renewable distributed energy sources).

The 3D printer has very low energy requirements for the stepper motors control and the nozzle heating and therefore resulted in low impact (0.05 kg CO2 eq). The most impactful phase is represented by the raw material (0.6 kg CO2 eq, between 41% and 50% of the total impacts, depending on the scenario); this is a common finding in many LCA literature studies focused on CFRP and it is attributed to the high-energy requirements of the matrixes and carbon fibers production.

Fig. 3 (b) reports the results of the economic assessment analysis for the two scenarios. As for the LCA, Scenario 2 is the best alternative with a total cost of 23.00 € while Scenario 1 has a total cost of 19.90€.

The main difference between the two scenarios is represented by the labour cost required in Scenario 2 for the post processing of the isogrid structure. Labor is also the most expensive cost item in both the alternatives. In 3D printing, labor is almost independent from the components dimensions (and so the raw materials and machines use costs); hence, for small parts labor can be a major cost even if the process is highly automated.



(a) **(b)**

Fig. 3. LCA results in terms of GWP (a) and cost analysis results (b) for the two considered scenarios.

The depreciation costs of the oven for the heat treatment and the drying system are basically negligible due to their low purchase prices. Differently from the environmental assessment, the energy use has low relevance (about 1% of the total costs). Table 3 presents the production time of the different phases and the total manufacturing time of the two scenarios. The printing phase is the most time consuming, closely followed by the structure and filament drying. Overall, the post-printing heating treatment determines an increase in production time of about 50%.

Table 3. Production time for the two scenarios.

Production time		
Filament drying	2	h
Printing time	2.15	h
Printing setup	0.2	h
Part removal	0.1	h
Structure drying	2.1	h
Scenario 1	4.45	h
Scenario 2	6.55	h

Scenario 1 was selected as the reference scenario and the performance index of Scenario 2 was calculated accordingly. In line with the model, Scenario 1 index is equal to 1; Scenario 2 index is equal to 1.22 (Table 4), which means that it performed 22% worse than the baseline process according to the sum of decision criteria. The drying process allows to improve by 23% the decision criteria related to the mechanical properties. However, it lowers the performance of the system according to every other indicator, as it is time consuming, expensive and with high electrical energy requirement. The weight factors used for this case study are appropriate for low cost products with modest mechanical performances requirements (e.g. aesthetic components) and for which the sustainability is a major concern (e.g. for green labelled parts).

It is evident how the weight values are crucial for a correct use of the performance index and should be carefully identified in accordance with the company vision and the specific case study.

For example, considering the present case study, if the environmental sustainability criteria is not taken into account (weight factor equal to zero), the production time and cost relevance weight are lowered to 2 and 1 respectively, and the mechanical properties factor is set equal to 5, Scenario 2 becomes the best alternative with an index score equal to 0.98. That would be the case of structural components

This remarks the importance of a proper choice of the weighting factors and also the flexibility of the model. In fact, it can be a useful decision tool in almost every industrial sector for every set of decision criteria that the stakeholders wish to include in their evaluation process.

Table 4. Performance indexes for the two scenarios.

	Weight	**Weighting factor**	**Scenario 1**	**Scenario 2**
Mechanical properties	2	0.14	13.08 kN	16.08 kN
Environmental sustainability	4	0.29	1.2 kg CO2 eq	1.46 kg CO2 eq
Cost	3	0.21	19.9 €	23 €
Production time	5	0.36	4.55 h	6.55 h
Performance Index			1	1.22

Summary

In this paper, a new multi criteria decision model for industrial products and processes was proposed. The mathematical model provides a simple and effective tool to compare different alternatives and to select the best one according to several decision criteria. The tool can also be employed to optimize a base scenario by evaluating a multicriteria performance index as a function of defined variables.

The model was employed to compare “as printed” and “dried” 3D printed composite isogrid structure. Four different criteria were assessed: mechanical performances by means of compression tests, economic and environmental sustainability by means of LCA and LCC analyses and production times. The main results can be summarized as follows:

- On average, the drying process improves the compression resistance of the isogrid structures by 23% but it has negative effects for the other three decision criteria.
- The weighting factors can be calculated by means of the ponderation decision matrix considering the company vision and the analysed scenarios.
- The value of the performance index is strongly influenced by the weighting factors associated with each decision criteria. The best alternative can change depending on these factors and, therefore, on the company goals. For this reason, the model is suitable for a large variety of industrial components and decision criteria.

Future work could be focused on different applications of the proposed model to further validate it and to provide reference values for multicriteria decision processes.

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