Toward a customized multicriterion tool for product evaluation in the early design phases: the CMDET methodology

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Abstract

Owing to an increase in requirements and a reduction in time to market, evaluation phases have become particularly crucial steps in the design process, specifically during the early design stages. New domains of expertise are constantly being added to design processes, and the performance evaluation tools that are currently available are too heterogeneous to be used together. The differences mainly concern performance domains, which rely on different types of data. It is therefore necessary to create a methodology for merging compatible tools (i.e. usable during the same phase of the design process) and establishing the most appropriate form of evaluation. In this paper, we begin by describing the Creation of MultiDisciplinary Evaluation Tool methodology. This takes place in four stages: the analysis of existing tools, followed by their evaluation, selection and merger. This methodology will help designers create multicriterion evaluation tools that are tailored to their needs. We then report a case study involving the design of a sustainable and innovative product for additive manufacturing, where the characteristics of each domain were taken into account.

1 Introduction

Early design phases are where innovation takes place, and where design choices have the most impact [1]. It is commonly accepted that 80% of the overall costs (environmental and/or economic) of a product are defined during these early design phases.

Designers therefore have to use assessment tools to evaluate their products' performances, in terms of cost, quality, functionality, manufacturability, environmental performance, and so on. As assessment tools are becoming more numerous, it is becoming difficult for designers to choose between them. At the same time, the number of considerations to take into account is also increasing, making the assessment phases increasingly difficult. We therefore propose a methodology for defining specific evaluation tools dedicated to individual designers' needs. The Creation of MultiDisciplinary Evaluation Tool (CMDET) analyses the tools described in the literature, evaluates them in relation to a particular designer's specific needs, and finally merges the best ones to create a specific evaluation tool. The CMDET methodology has already been used to create a specific evaluation tool adapted to the early design phases, where the focus was on innovation, sustainable development, and additive manufacturing (AM).

Companies are increasingly taking sustainable development issues into account in the product development and production phases. Many methods have been developed to assess the lifecycles of design propositions, in order to select the product with the lowest environmental impact [2], but owing to the need for product data, this evaluation can only be made at the end of the design process, when each modification comes at a major cost [1]. Other studies focused on bringing about improvements in the production phase have sought to assess manufacturing processes [3, 4], and develop methods for managing these processes in order to reduce the overall impact of production [5]. The next target in the drive to reduce environmental impact in the course of product development needs to be the design process. For example, life-cycle analysis (LCA), the standardized and most widespread assessment method for environmental concerns,

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consumes a great deal of design resources. A product's environmental performance should therefore be assessed earlier, during the early design phases, and more quickly, in order to ensure greater efficiency. Designers must thus use a range of environmental impact assessment tools.

To design the best product, it is not enough just to analyse the environmental impact, as the product must meet innovation criteria if it is to match customers' needs and the firm's strategy. Designers therefore need to use innovation assessment tools.

In the case of nonconventional manufacturing processes, considering these processes during the early stages of design increases the designer's creativity [6]. The design rules for additive manufacturing (AM) are totally different from those for classic manufacturing. Early evaluation of the manufacturing potential allows designers to take this new technological paradigm into account. Designers must therefore use manufacturability assessment tools dedicated to AM. The research question is: how to evaluate intermediate representation regarding multi-disciplinary in the same stage of the design process?

The three levels of product performance assessment need to be brought together, so that designers can create products that are innovative, easy to produce by AM, and sustainable.

The interactive design appeared to join different engineering cultures [7]. The number of different disciplines involved in the design process makes it necessary to adapt an interactive approach i.e. an approach that facilitates the integration of new disciplines using expert tools.

Here, we present the CMDET methodology for creating a multicriterion evaluation tool. After describing the state of the art (Sect. 2), looking at how different aspects of performance are defined and how evaluations are carried out during design process, we present the CMDET methodology (Sect. 3), analysing (Sect. 3.1) and evaluating (Sect. 3.2) existing assessment tools, then selecting the best of these tools (Sect. 3.3) and creating a specific tool, dedicated to the designer's needs (Sect. 3.4). We then describe how this method was applied to create an evaluation tool for the early design phases, focusing on sustainability, innovation and AM (Sect. 4). In the Conclusion, we discuss future perspectives (Sect. 5).

2 State of the art

According to the literature [8–10], the design process involves innovation, especially in the early design phases [11]. The design process is defined as all the steps or actions between the problem and the product. According to Howard et al. [12], it can be modelled as four to six stages. In this paper, the design process is broken down into four stages: *problem analysis*, *ideas research*, *development* and *industrialisation*, as illustrated in Fig. 1.

This description of the state of the art focuses on the definition of performance, which lies at the heart of evaluation, particularly in the case of innovation, sustainability and AM.

2.1 Definition of performance

The definition of performance depends on two factors: the domain being studied and the design process phase being considered. A generic definition that is universally accepted is the quantitative measure of effectiveness and efficiency [13]. However, each area has its own definition of performance. For innovation, Shah [8] defined performance as the measure of the quality, quantity, novelty and variety of the ideas put forward during the design stages. For sustainability, performance is a combination of economic, environmental and societal performances [14]. As for manufacturing, Chenhall [15] defined performance as the quality of the product in relation to production costs.

To design a product that meets all requirements, performance has to be evaluated throughout the design process. The main problem of evaluation is the lack of data. As indicated earlier, the product is not sufficiently well defined during the early design stages, meaning that evaluations need specific methods and tools to be accurate. In the next three subsections, we focus on evaluation tools in three different domains: innovation, sustainability, and AM. The case study described in Sect. 4 looked at assessment across the four different design stages, in order to identify the different types of performance involved.

2.2 Innovation performance

The innovative aspect of a product is created during the early design phases [8]. We can differentiate between two kinds

Fig. 1 Design process and position of innovation. Adapted from [8, 12]
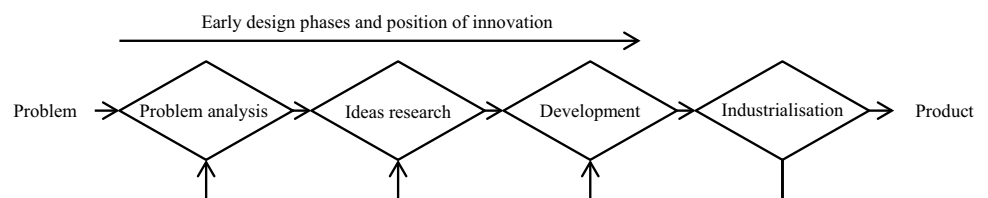
of innovation: incremental innovation, which improves an existing product [16], and breakthrough innovation, which results in new products to meet new needs [9, 17].

Innovation can be assessed during the design process in two different ways:

- Assessment of organisational potential, evaluating the firm's capacity to carry out the design project. The assessment tools are economic, and look at the potential success of the project without studying the data on the design process;
- Assessment of the design process potential, which can be defined as the evaluation of different intermediate representations of the product during the early design phases. This is the one targeted in this paper, as it is based on tangible data.

Given its position in the design process (Fig. 1), innovation needs to be evaluated during the first three stages: *problem analysis*, *ideas research* and *development*. The main problem is the lack of data during these early stages.

In the *problem analysis* stage, the design is reduced to the definition of the specifications, making it difficult for designers to identify the opportunities and drive the design process in the right direction. However, this stage allows the indicators of performance to be defined for the following stages, as Binz and Reichle noted for the assessment of the product concept [18].

In the *ideas research* stage, creative tools are used to conduct the search process. It is crucial to evaluate ideas, in order to select the best one. This can be performed via two types of evaluation:

- *Expert evaluation* designers rely on experts to set the design objectives. According to Zimmer et al. [19], the early selection of design ideas by experts is crucial for reducing design time and obtaining the best product at the end of the design process. Experts identify the potential of the design project according to four characteristics (utility, innovation, profitability and concept);
- *Tool evaluation* designers can evaluate the intermediate representations of their product by themselves, using specific tools. It is essential to use objective criteria. For Saunders et al. [16], innovative products have similarities, so an in-depth study of successful products allows characteristics to be extracted to evaluate fresh ideas.

The *development* stage is the last one where innovation evaluation is available and useful. The data are more meaningful and, most of all, the evaluation can be based on a classic method such as the function matrix, to compare the concepts with function goals or target characteristics. According to Binz and Reichle [18], the assessment of functions by

future users allows the future product's acceptability to be tested, and therefore helps to improve its innovative aspect.

In this section, we indicate the position of the different innovation evaluation methods and tools in the design process. Each method has different needs and goals, depending on its position in the process. This state-of-the-art review is not exhaustive, but makes it possible to explore how and when innovation is evaluated in the design process.

2.3 Sustainable performance

Sustainability means considering three aspects: social, environmental and economic. Performances in these three areas can be evaluated throughout the whole design process, using the Design For X (DfX) method of assessing sustainability (Design for Sustainability, DfS) [20, 21], where X is a lifecycle phase (e.g. Design for Environment) or an aspect of sustainability (e.g. Design for Recyclability). Evaluation methods depend on the quantity and quality of the data, and are therefore linked to the stage of the design process. As with innovation performance (see previous section), sustainable performance evaluation can be broken down according to the different design process stages.

In the *problem analysis* stage, sustainability is linked to the design goals. Here, the methods are used either to provide basic knowledge, as summed up in the 10 Golden Rules [22], or to establish the goals for redesigning products in an attempt to make them more environmentally friendly, as Cluzel et al. mentioned [23].

In the *ideas research* stage, the evaluation methods are similar to those to assess innovation, and based on the product's creative aspect. Some methods adapt creativity tools so that they include an environmental aspect [24], or to ask designers about sustainability indicators [25].

In the *development* stage, evaluation methods are used to assess the product's architecture. This evaluation can be used to compare concepts on sustainability indicators [26] or compare components in order to select the best one in terms of sustainable performance [27].

In the *industrialisation* stage, LCA is the common and standardized method. It is, however, complex, owing to the amounts of time and data needed. Some methods have been developed to simplify product evaluation during this phase, by recommending different indicators or breaking LCA down into different lifecycle phases (e.g. manufacturing), and suggesting that the processes should each be evaluated, in order to compare them [28].

The sustainability evaluation method allows the design process to be monitored. The problem is that the evaluation is not continuous, and requires just as many methods as design stages. This state-of-the-art review is not exhaustive, but makes it possible to see how the issue of sustainability evaluation fits into the design process.

2.4 Additive manufacturing performance

The evaluation of manufacturing performance is defined as the evaluation of the product or its representation according to its capacity to be manufactured using the proposed process [15]. It consists in determining whether the product is properly designed for a specific manufacturing process and whether the design rules are respected. It is carried out during the later design stages, in order to validate the process and the CAD product.

Implemented during the *ideas research* stage, the Design With Additive Manufacturing (DWAM) tool developed by Laverne [29] is intended to integrate AM knowledge during the early stages, in order to increase the product's creativity and the innovation level of intermediate representations, and then to evaluate its potential. As Rias' proposal underlines, during the search for ideas stage, there are insufficient product data to analyse the product's manufacturability, so experts may have to be called into analyse its potential [30]. Ideas can be evaluated with adapted tools, like those developed by Booth [31], taking the form of a matrix where design rules are graphically formulated to evaluate the AM potential.

In the *development* stage, the amount of data defining the product increases, and many AM evaluation methods can be found in the literature. The product's architecture can be evaluated with a view to being manufactured using AM processes. The Design By Additive Manufacturing (DBAM) methodology [32] uses the potential of the AM paradigm as assessment criteria and suggests an optimization tool in order to fulfil the AM process requirements. Methodologies are available for evaluating CAD parts, to analyse whether the geometry suits the process characteristics (e.g. building layers, part orientation or shell thickness [33].

During the *industrialisation* stage, AM performance is included in an overall Design For Additive Manufacturing (DFAM) methodology [34]. DFAM methods are aimed at optimizing the product, so that it can easily be manufactured using the AM process. These kinds of methods are applied during the later design stages to validate the industrialization proposal. Laverne et al. [35] distinguish between two types of DFAM methods: part-oriented and assembly-oriented optimization. Both types analyse the CAD model in order to identify its geometry and set it against design rules and design goals. DFAM is generally used to reduce the mass or volume of the material used [36].

The literature does not contain any AM evaluation methods for *problem analysis*. Manufacturing processes are regarded as a way of meeting requirements, rather than as an opportunity.

Performance in manufacturing is mostly evaluated in the final stages of the design process. However, assessing performance in the early design stages would make it possible to select intermediate representations that take full advantage of the possibilities offered by AM. Designers must therefore radically change their evaluation methods if their products are to be adapted to this new process. This state-of-the-art review, while not exhaustive, raises the issue of exactly when manufacturing, especially AM, should be assessed in the course of the design process.

2.5 Synthesis

This state of the art shows that the number of assessment tools is steadily increasing, and it is becoming difficult for designers to choose between them. These tools do not all have the same purpose, as it depends on how they are used in the design process and the area of expertise. As shown in the previous sections, evaluation during the design process is contingent not only on the domain of expertise, but also on the point at which it is applied during the design process. The present state of the art indicates that, in order to properly assess the performance of a product, designers need to:

- Evaluate the product as early as possible in the design process. However, this is not possible with all the traditional tools, as they often require data that arrive later on;
- Rely on tools, as it is not always easy to use experts, especially when looking at different areas of performance.

Designers therefore need to be offered an interactive method that allows them to create their own evaluation tools, according to their domains of expertise. The method we set forth in the following sections is based on an analysis of the literature.

The following methodology is based on an interactive approach. Each step of the proposal is generalized to fit to each disciplinary and each design process stage.

3 Creation of MultiDisciplinary Evaluation Tools (CMDET) methodology

The Creation of MultiDisciplinary Evaluation Tools (CMDET) methodology will allow designers to create a multicriterion assessment tool that is tailored to their particular needs. These needs vary according to the domain of expertise and the stage in the design process. The objective of the CMDET methodology is to create an MultiDisciplinary Evaluation Tool (MDET) from a list of performance domains that need to be evaluated in a design project, as shown in Fig. 2.
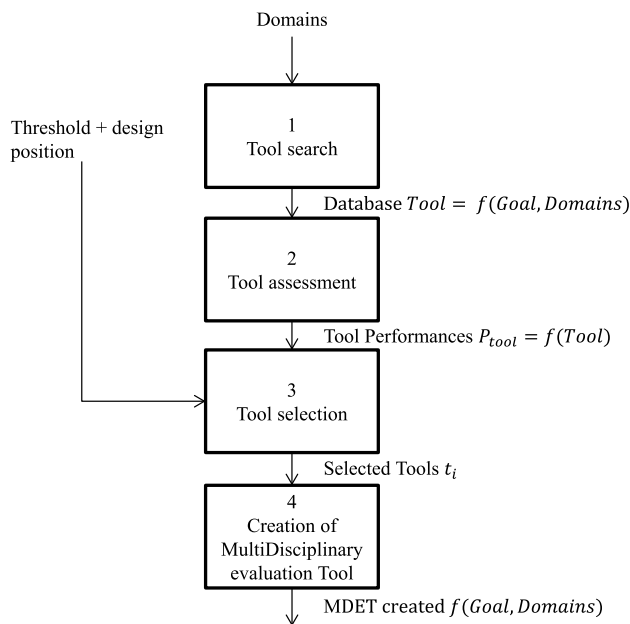
Fig. 2 Creation of MultiDisciplinary Evaluation Tools (CMDET) methodology

3.1 Tool search

To validate the objectives, the focus must first be on the analysis of existing tools, in order to select those most suited to extracting the information and outputs needed to create a multicriterion evaluation method. This is why the first stage of the methodology concerns the search for existing assessment tools in the literature, depending on which domains the designer wants to assess (e.g. innovation, sustainability, manufacturability, maintenance, recycling, lifecycle costing, etc.).

A database is then created, where the tools are classified according to the domains of the design project and the relevant stage in the design process.
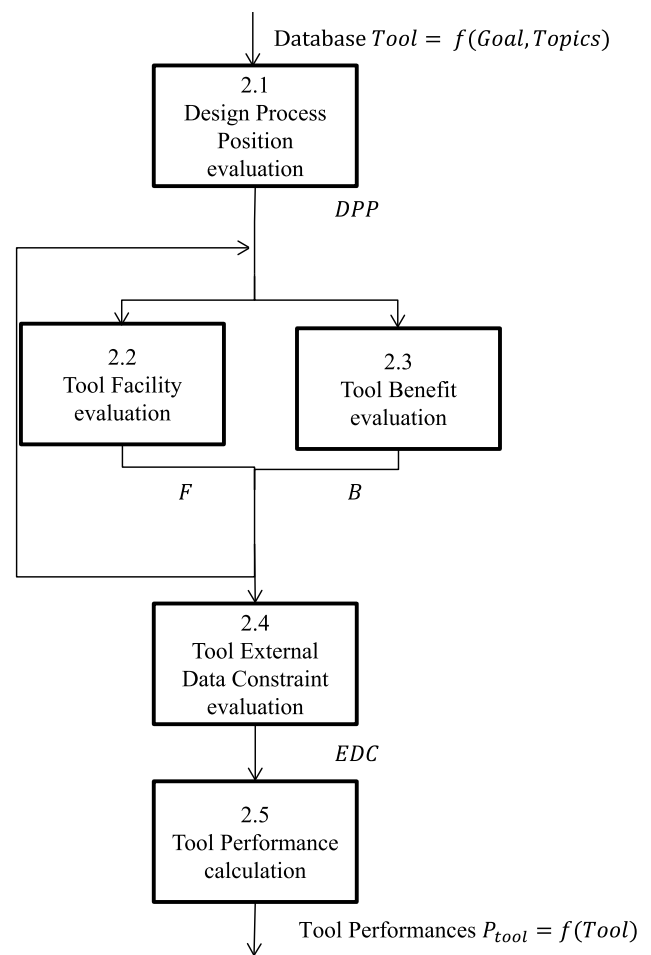
3.2 Tool assessment

3.2.1 Tool assessment criteria

Once existing tools have been found in the literature, the task is to select the ones that best meet the designer's needs. This assessment method is based on four criteria:

- Design process position (DPP).
- Facility of using the tool (F).
- Benefit of the tool (B).
- External data constraint (EDC).

These criteria were chosen because they are nonspecific and can therefore be used for the different domains of the

Fig. 3 Tool assessment method

design project. DPP helps to find out which design stage is concerned by the tool. F makes it possible to evaluate the need for expertise to use the tool. B is used to classify the different kinds of tool, as proposed by Bovea and Pérez-Belis [37]. EDC shows the amount of data needed to create the performance indicators.

The tools are assessed in five steps, using the method illustrated in Fig. 3.

3.2.2 Design process position evaluation

In this step, the tools are classified according to the stage in the design process (*problem analysis*, *ideas research*, *development* and *industrialisation*; see Fig. 1). DPP criteria are then assigned to the tool. If the tool is useful for more than one design stage, Steps 2.1–2.5 are completed for each stage.

3.2.3 Tool facility and benefit evaluation

In this step, the F and B criteria are applied to the tool for the relevant design stage, as set out in Table 1.

Table 1 Evaluation grid for F and B criteria

Value	Evaluation of facility	Evaluation of benefit
0	The tool is not used at this stage	The tool is not used at this stage
1	Expertise and long skilling time are needed	Pros and cons are identified by the tool
2	Expertise or long skilling time is needed	Indicators of performance are provided by the too
3	Knowledge of the field is required and/or skilling time is needed	Guidelines for improvement are provided by the tool
4	No expertise/knowledge is needed, or only a short skilling time	Potential improvements are proposed by the tool
5	No expertise/knowledge is needed, and only a short skilling time	A better performance solution is provided by the tool

Table 2 EDC evaluation grid

Value	Evaluation of external data constraint
0.5	Redesign: needs data on previous product
1	Needs data on previous stage option
2	Independent of external data

3.2.4 Tool external data constraint evaluation

In this step, the tool's EDC is evaluated, in accordance with Table 2. Calculating the EDC helps to identify tools that require a large amount of external data (e.g. complete definition of a previous product when the tool is based on comparisons with different products to assess performance).

3.2.5 Tool performance calculation

The tool performance (P_{tool}) calculation is done according to Eq. (1)

$$P_{tool} = (F + B) \times EDC \tag{1}$$

This equation is used to distinguish between the tools, by setting their intrinsic qualities of facility and benefit against their need for external data, which is a defect. The best adapted tool is the one with the highest P_{tool} value.

3.3 Tool selection

Once all the tools have been evaluated, the best ones can be selected. The goal of this step is to establish the threshold for selection and identify the DPP of the future MDET. An example is given in the case study section (Sect. 4.3).

3.4 MultiDisciplinary Evaluation Tool (MDET) creation

The MDET is created in two separate steps, as shown in Fig. 4.
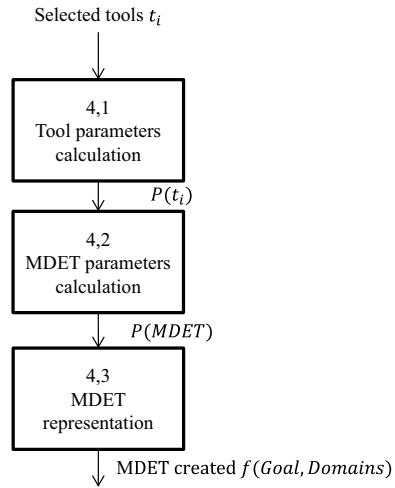
Fig. 4 Creation of the MDET

3.4.1 Tool parameters calculation

After the N best tools have been selected (noted t_i with $i \in [1 \dots N]$) in Step 3, Step 4 of the CMDET methodology is the creation of the MDET. In order to limit subjectivity in determining the overall tool, a more accurate characterization of the tools to be merged is needed.

Each selected tool is therefore divided into six parameters that serve to describe the data used and their operation. These parameters describe the tool when considering input data (internal and external P_1 and P_4), output data (P_6) and three internal steps (identification of criteria P_2, establishment of design rules P_3, and proposed evaluation P_5). Each parameter is associated with its own calculation model.

In Fig. 5, each tool t_i is defined by six parameters $P_1(t_i)$ to $P_6(t_i)$. Accordingly, the MDET is also characterized by these six parameters $P_1(MDET)$ to $P_6(MDET)$.

The parameter $P_1(t_i)$ defines the nature of the data available during the relevant stage of the design process. This parameter therefore depends directly on the DPP, and the different values are:

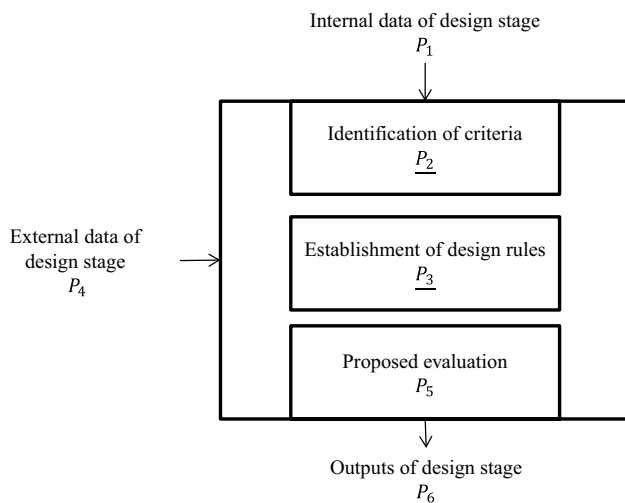- If the design stage concerned by the tool t_i is *problem analysis*, then $P_1(t_i) = 1$.

Internal data of design stage
P_1

Fig. 5 Parametrization of the tools

- If the design stage concerned by the tool t_i is *ideas research*, then $P_1(t_i) = 2$.
- If the design stage concerned by the tool t_i is *development*, then $P_1(t_i) = 3$.
- If the design stage concerned by the tool t_i is *industrialisation*, then $P_1(t_i) = 4$.

The parameter $P_2(t_i)$ is used to describe how the tool analyses and selects the criteria for the evaluation. It is composed of a vector with D coordinates, where D is the number of domains concerned by the evaluation. In the case study discussed in this paper, D was 3, as the design project specifically focused on three domains: Innovation/Sustainability/AM. For example:

- If the tool t_i only evaluates innovation and uses a single criterion for this, then $P_2(t_i) = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$ and note $p_{2,1}(t_i) = 1, p_{2,2}(t_i) = 0, p_{2,3}(t_i) = 0$.
- If the tool t_i only evaluates sustainability and uses two criteria for that, then $P_2(t_i) = \begin{pmatrix} 0 \\ 2 \\ 0 \end{pmatrix}$ and note $p_{2,1}(t_i) = 0, p_{2,2}(t_i) = 2, p_{2,3}(t_i) = 0$.
- If the tool t_i evaluates both innovation and AM, and uses one criterion for each domain, then $P_2(t_i) = \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix}$ and note $p_{2,1}(t_i) = 1, p_{2,2}(t_i) = 0, p_{2,3}(t_i) = 1$.

The parameter $P_3(t_i)$ is used to describe how the tool translates the selected criteria into design rules for the design phase. For example, if the tool t_i only evaluates sustainability

using the design rule "Use only reusable materials", then $P_3(t_i) = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$ and note $p_{3,1}(t_i) = 0, p_{3,2}(t_i) = 1, p_{3,3}(t_i) = 0$.

The parameter $P_4(t_i)$ quantifies the external data needed for the evaluation and is based on the EDC criterion. For example, if tool t_i requires four items of external data for the evaluation, then $P_4(t_i) = 4$.

The parameter $P_5(t_i)$ describes how the design rules are turned into an evaluation tool, be it a questionnaire, a matrix, or a comparison. For example:

- If the tool is a questionnaire, then $P_5(t_i) = 1$.
- If the tool is a matrix, then $P_5(t_i) = 2$.
- If the tool is a comparison tool, then $P_5(t_i) = 3$.

The parameter $P_6(t_i)$ defines the nature of the data at the end of the design stage being studied. The different values are:

- If the design stage concerned by the tool t_i is *problem analysis*, then $P_6(t_i) = 1$.
- If the design stage concerned by the tool t_i is *ideas research*, then $P_6(t_i) = 2$.
- If the design stage concerned by the tool t_i is *development*, then $P_6(t_i) = 3$.
- If the design stage concerned by the tool t_i is *industrialisation*, then $P_6(t_i) = 4$.

3.4.2 MDET parameters calculation

Once these six parameters have been defined for each of the selected tools, the relevant parts of each tool are selected to create the MDET. This tool is therefore characterized by six parameters calculated according to Eqs. 2–7 below.

As the MDET is created for a single design stage, the selected tools all have the same DPP. So all $P_1(t_i)$ and all $P_6(t_i)$ are equal for the selected tools. In future research, the MDET could be based on tools from different design stages.

$$P_1(MDET) = P_1(t_i) \tag{2}$$

$$P_2(MDET) = \begin{pmatrix} \sum_{k_1=1}^{n_{F_1}} p_{2,1}(t_{k_1}) \\ \dots \\ \sum_{k_D=1}^{n_{F_D}} p_{2,D}(t_{k_D}) \end{pmatrix} \tag{3}$$

where t_{k_j} are the tools that best meet criterion F for domain j, and n_{F_i} is the number of tools involved. For this calculation, therefore, only those tools t_i that have been judged in terms of ease of use are used.

$$P_3(MDET) = \begin{pmatrix} \sum_{k_1=1}^{n_{F_1}} p_{3,1}(t_{k_1}) \\ \dots \\ \sum_{k_D=1}^{n_{F_D}} p_{3,D}(t_i) \end{pmatrix} \quad (4)$$

where t_{k_j} are the tools for which the parameter F is best for the domain j, and n_{F_i} is the number of tools involved.

$$P_4(MDET) = \sum_{j=1}^{D} \sum_{k=1}^{N} P_4(t_{k_j}) \quad (5)$$

where t_{k_j} are the tools for which parameter F is best for domain j, and n_{F_i} is the number of tools involved.

$$P_5(MDET) = P_5(t_i) \, if F(t_i) = Max\{F_{t_i}\} \quad (6)$$

$$P_6(MDET) = P_6(t_i) \quad (7)$$

3.4.3 MDET representation

The MDET is represented in the same way as the tools (Fig. 5). It is now ready to be used by the designer to assess the product being designed—a unique evaluation tool dedicated to the designer's needs.

4 Case study

The robustness and viability of the CMDET methodology has been tested on several occasions, where different types of performance had to be assessed for a particular product design project. In the following sections, we describe one particular case study where the MDET was used to evaluate the innovation, sustainability and AM potential of an innovative phone case in an early design stage.

These three areas were chosen because:

- Innovation makes a product stand out from competing ones.
- Sustainability reduces the product's environmental impact.
- AM takes advantage of the emergence of 3D printers and allows a service to be offered, not just a product.

4.1 Tool search

The different tools we assessed in this case study were taken from the scientific literature and were designed to assess innovation, sustainability, and AM during the design process.

These tools, classified by domain (main domain/secondary domain), are described in Table 3. We refer to them using Greek letters when they deal mainly with innovation, capital letters when they evaluate sustainability, and roman numerals when they concern AM.

4.2 Tool assessment

The assessment involved 29 different evaluation tools (8 for innovation, 16 for sustainability, and 9 for AM). Some tools dealt with two domains, but for clarity's sake, we only retained the main domain.

Each tool was evaluated, and the best ones were selected according to the methodology set out in Fig. 3. Tool performance was evaluated according to Eq. 1. In Fig. 6, the performance of each tool is modelled as the length of a coloured bar and situated in one of the four design stages. The colour is blue when the tool dealt mainly with innovation (green for sustainability and yellow for AM).

The minimum value obtained was 2 (Tool II) and the maximum value obtained was 14 (Tools α, F, IV, J, V, H and D), although the theoretical maximum value was 20. This gap can be explained by the inability of the existing tools to find an optimum solution without requiring time or expertise.

Results were in line with the state of the art: innovation was evaluated in the early design stages; sustainability was monitored throughout the process; and AM was studied in the later phases.

4.3 Tool selection

In order to evaluate the product, the tools were selected by taking into account the top third of all the evaluation tools and the evaluation tools dealing with *ideas research*. Four tools t_{1-4} were retained:

- $t_1 = $ β, characteristics of innovative products [16].
- $t_2 = $ F, total lifecycle considerations [20].
- $t_3 = $ IV, DFAM worksheet [31].
- $t_4 = $ α, eco-ideation [23]

4.4 MDET creation for the assessment of innovation, sustainability and AM performance during early design stages

4.4.1 Tool parameter calculation

Tool t_1 was used for *ideas research* stage, so $P_1(t_1) = P_6(t_1) = 2$. The evaluation of innovation was based on five types of criteria ($P_2(t_1) = [5, 0, 0]$) divided into 12 design rules ($P_3(t_1) = [12, 0, 0]$). To create the criteria, the

Table 3 Evaluated tools

Name	References	Domain		ID
		1st	2nd	
10 golden rules in EcoDesign	[22]	S		A
Eco-innovation	[24]	I	S	η
Eco-ideation	[25]	I	S	α
Sustainable product design model	[38]	S		B
Eco innovative	[39]	S		C
Sustainable manufacturing	[40]	S	AM	D
Total life-cycle considerations	[20]	S		F
Roadmap for predicting product end-of-life costs	[41]	S		G
MA-AHP approach for selecting the highest sustainability index	[26]	S		H
Economics of AM for end-usable metal parts	[42]	S	AM	I
Streamlined LCA framework	[28]	S		J
Quality function deployment for optimum environmental performance improvement	[27]	S		K
Environmental performance strategy map	[43]	S		L
Environmental performance evaluation and indicators	[44]	S		M
LCA	[2]	S		N
CO2PE!	[3]	S	AM	P
Characteristics of innovative, mechanical products	[16]	I		β
Radical innovation project selection model	[9]	I		γ
Innovation evaluation	[18]	I		δ
Supporting product design by anticipating the success chances of new value profiles	[45]	I		ε
A method to set up a complexity index to improve decision making performance	[46]	I		ζ
Topology optimization	[36]	AM		VIII
Adding product value	[47]	AM		II
DFAM	[34]	AM		III
DWAM	[29]	AM		VII
Design for laser AM	[33]	AM		V
Creative early DFAM	[30]	AM	I	VI
DFAM worksheet	[31]	AM		IV
Eco-innovation dashboard	[10]	I	S	θ

This table sets out the results of our review of the state of the art, which did not seek to be exhaustive, but instead to summarize the most common tools in the literature

tool relied on the study of successful innovative products ($P_4(t_1) = 1$)). The evaluation yielded a binary result for each rule ($P_5(t_1) = 1$). Tool t_1 is represented in Fig. 7.

Tool t_2 was used to quantify the impact of intermediate representations on the search for *ideas research* ($P_1(t_2) = P_6(t_2) = 2$). The evaluation of sustainability was based on three types of criteria ($P_2(t_2) = [0, 3, 0]$) divided into 12 design rules ($P_3(t_2) = \overline{[0, 12, 0]}$). To establish the criteria, the tool needed to explore the product requirements and product environment ($P_4(t_2) = 2$). The result of the evaluation was a matrix ($P_5(t_2) = 2$). Tool t_1 is represented in Fig. 8.

Tool t_3 was used for *ideas research* stage ($P_1(t_3) = P_6(t_3) = 2$). The evaluation of AM was based on four types of criteria ($P_2(t_3) = [0, 0, 4]$) divided into eight design rules ($P_3(t_3) = \overline{[0, 0, 8]}$). To establish the criteria, the tool needed to study the possibilities of the AM process ($P_5(t_3) = 1$). The result of the evaluation was a graphic representation of a Likert scale evaluation. Tool t_3 is represented in Fig. 9.

Tool t_4 was used for *ideas research* stage ($P_1(t_4) = P_6(t_4) = 2$). The evaluations of innovation and sustainability were each based on five types of criteria ($P_2(t_4) = [5, 5, 0]$), divided into ten design rules ($\overline{P_3(t_4)} = [10, 10, 0]$). To establish the criteria, the tool needed to study the product requirements ($P_5(t_4) = 1$). The result of the evaluation was a three-level survey for each rule. Tool t_4 is represented in Fig. 10.
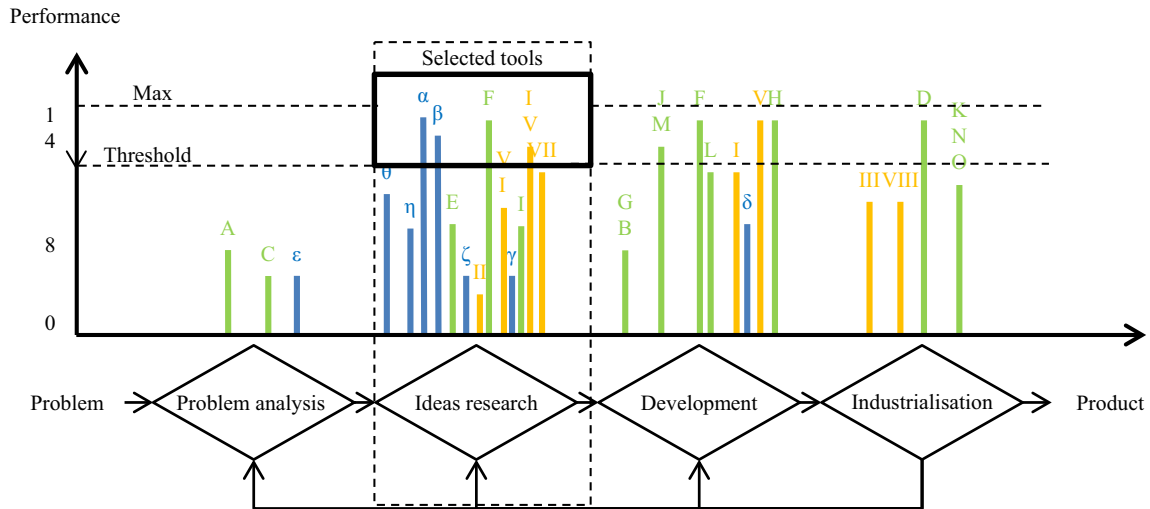
Table 4 sums up the tools' parameters.

Fig. 6 Results of tool evaluation in the case study on how to evaluate the innovation, sustainability and additive manufacturing potential of an innovative phone case in the early design stages
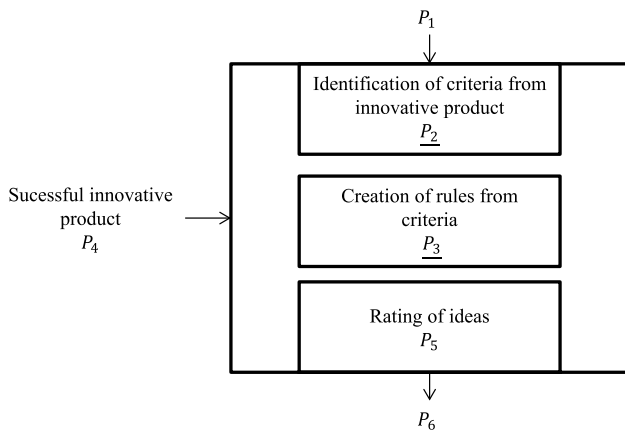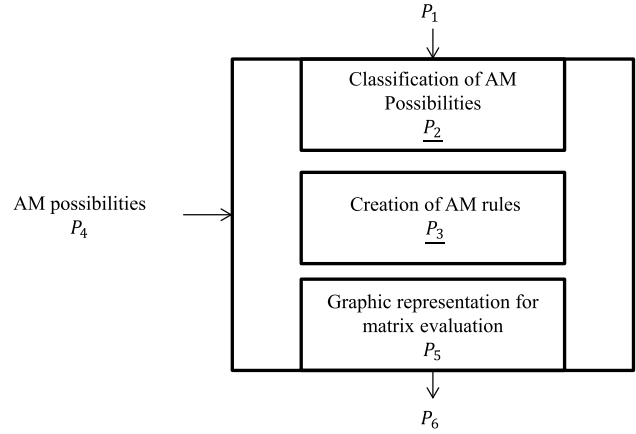

Fig. 7 Parametrization of t_1
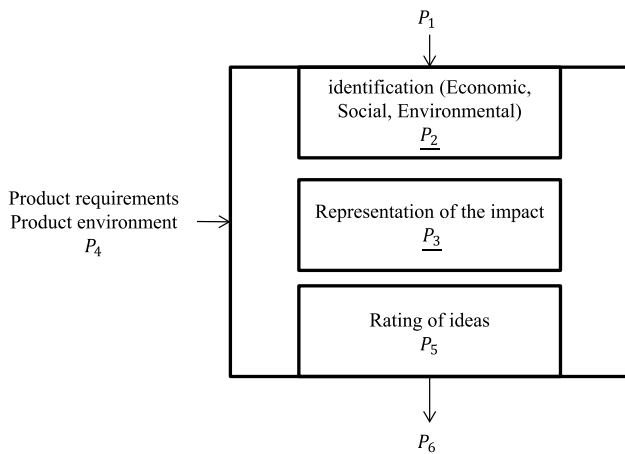

Fig. 9 Parametrization of t_3

Fig. 8 Parametrization of t_2
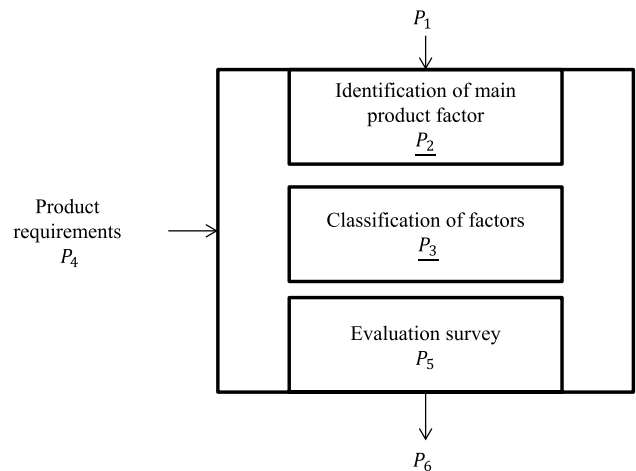
Fig. 10 Parametrization of t_4

Table 4 Parametrization of tools and MDET

Tool	t_1	t_2	t_3	t_4	MDET
P_1	2	2	2	2	2
P_2	$(5, 0, 0)$	$(0, 3, 0)$	$(0, 0, 4)$	$(5, 5, 0)$	$(5, 3, 4)$
P_3	$(12, 0, 0)$	$(0, 12, 0)$	$(0, 0, 8)$	$(10, 10, 0)$	$(12, 7, 8)$
P_4	1	2	1	2	1
P_5	3	3	3	1	1
P_6	2	2	2	2	2

4.4.2 Calculation of MDET

We used three of the four selected tools t_1, t_2 and t_3 ($n_F = 3$) to establish the criteria and transcribe them as design rules (one for each evaluated domain). Tool t_4 was used to transpose the design rules into an evaluation.

The parameters for the MDET were calculated according to Eqs. 2–7, and the results are set out in Table 4.

4.4.3 MDET representation

The MDET parametrization and model are represented in Fig. 11.

The MDET was then implemented as a numerical tool for use by the designer carrying out the design project concerned by the case study. It contained all the classic options (project management, customisation of tools). It is illustrated in Fig. 12, where the DPP indicates the type of intermediate representation the designer evaluated. Each criterion of t_1, t_2 and t_3 was divided according to the associated design rules. In order to satisfy the t_4 tool, each level of evaluation

was completed by a definition. The evaluation is monitored during all the stage.

5 Conclusion and perspectives

This paper sets out the limitations and possibilities of performance evaluation during the design process. Our review of the state of the art showed that performance has many definitions, depending on which domain is being studied. Given the multiple representations of the product during the design process, it is difficult to evaluate it during the early design stages. We therefore developed the CMDET methodology, which involves analysing the literature in order to identify the best evaluation tools for each design process stage and for multiple domains. The selection method can be used on its own. The goal of the CMDET methodology is to create a multicriterion evaluation tool. It is implemented in a numerical tool and used during design projects. CMDET methodology provide for the case study of a *phone case* an evaluation tool adapted to a specific design stage and regarding three different domains (innovation, sustainability and additive manufacturing).

This methodology is a part of a more global one for carrying out multicriterion improvements in the early design stages. The objective of future research will be to validate the evaluation tool elaborated with this methodology and provide to designers DfX adapted to the needs of the intermediate representation as shown on the Fig. 12. We are planning to conduct a full design project to validate the different steps of the overall methodology. Ultimately, this methodology will provide assessment tools tailored to each

Fig. 11 MDET representation
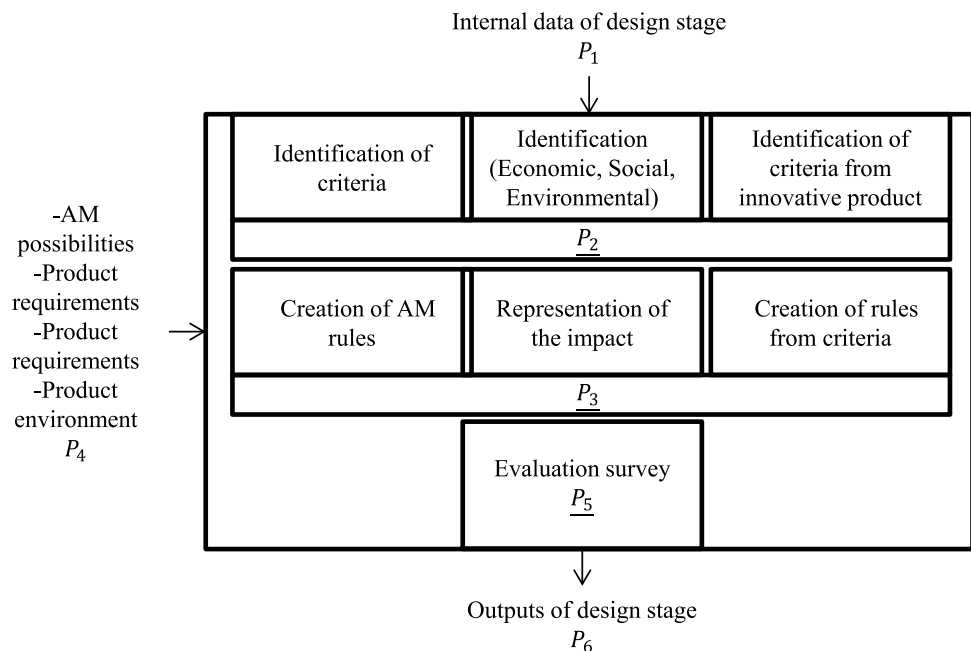
Fig. 12 Screenshot of the numerical MDET
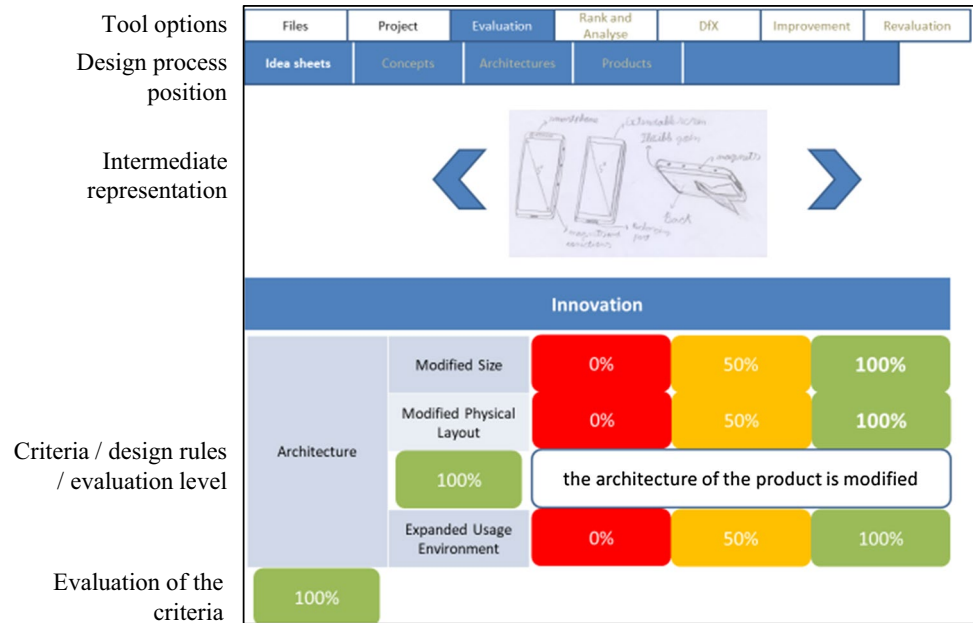
design project based on positioning in the design process and disciplines.

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