Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 70 (2018) 204–210

www.elsevier.com/locate/procedia

28th CIRP Design Conference, May 2018, Nantes, France

Selection method for multiple performances evaluation during early design stages

Kévin Audoux[a*], Frédéric Segonds[a], Olivier Kerbrat[b], Améziane Aoussat[a]

[a] *Laboratoire de Conception de Produits et Innovation, Arts et Métiers ParisTech, 151 boulevard de l'Hôpital 75013 Paris, France*
[b] *Univ Rennes, ENS Rennes, CNRS, Gem - UMR 6183, F-35000 Rennes, France*

* Corresponding author. Tel.: +33 (0)1 71 93 65 64; *E-mail address:* kevin.audoux@ensam.eu

Abstract

Because of their high impacts on the product's requirements, evaluation phases are crucial steps during its early design. Many indicators and tools are developed to help designers to assess performance during those stages. However, the design stakeholders' choice is really difficult when multiple performances (innovative, manufacturability, sustainability) are to be assessed. In fact, each tool uses its own form of data during a specific stage of the design process and its own set of questions. The global supervision is not possible without multiple methods. To facilitate the evaluation phases, we here lay out a method to realize a continuous supervision of the design process. The proposal aims to develop a method to select and assess existing tools to provide a global evaluation during the early stages. This method is divided into three steps: locating the adapted tools during the early design stages to evaluate the performance of the product, identifying the data needed by the tools and finally merging the different tools for the design phase. In the context of making a sustainable and innovative product conceived for additive manufacturing the differences between each expertise and tool have to be managed to provide a global evaluation method.

Keywords: Design method; Additive Manufacturing; Sustainable development; Innovation

1. Introduction

The time allowed to product development is more and more reduced. In fact, requirements evolve and the design process is different: produce better and faster with constant resources. The design process needs tools to evaluate the development to make the right choices and to identify the potential improvements as soon as possible. Therefore, evaluation is needed for ideas, concepts, architectures and product manufacturing to select the higher performance intermediate representation.

It remains difficult to define product's performance. In design, the highest performance product is the product which meets all requirements and gets the best return on investment. This definition amounts to define performance as the product's innovative aspect in regards to the standard [1]. However, the integration of sustainability aspects [2] during the design process is primordial to respond to a social as well as a political demands to develop products with a lower impact on environment. To produce innovative such products, Additive Manufacturing (AM) AM is considered as an emerging manufacturing process and according to Gibson et al. [3] and the need of methods is important. This process offers to designers the possibility of new geometry and allows to optimised products in terms of mass [4] and impact and encourage innovation [5] and sustainability[6]

Designers need tools to evaluate the product during the design process and especially during the early design stages where the product's value is set. First of all, the state of the art will focus on the performance's indicators study during the design process regarding the innovation, sustainability and AM. This study shows that no tool can be used during the whole design process for all the topics. A method is proposed to identify and select the adapted tools for the idea research stage. This paper aims to underline a framework to select the most effective tools for the evaluation of the product's performance during early design stages.

2. State of the art

The innovation phases are included in the design process [7]. It is defined as all the different tasks between the problem and the product. It can be described by four to six stages according to Howard et al. [8]. The creative process is

2212-8271 © 2018 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the 28th CIRP Design Conference 2018.
10.1016/j.procir.2018.03.295

described by four phases for them. The design process will be composed of four steps described by the product's evolution: problem analysis, idea research, concept development and industrialisation, as described on figure 1.
This state of the art focuses on the field of performance and to evaluate it in case of innovation, sustainability and AM.

2.1. Definition of performance

The definition of performance depends on the studied subject. The generic definition is defined as the quantitative measure of effectiveness and efficiency [9]. However, each subject developed during the state of the art has its own definition of performance. For innovation, it deals with the measure of the quality, quantity, novelty and variety of ideas purposed during the stages [7]. For sustainability, the performance is the merge of economical, environmental and societal performances [2]. For manufacturing, the performance is defined as the quality of the product compared to the production costs [10]. The performance of the product has to be evaluated throughout the whole design process, but the early design stages concentrate eighty percent of the product's engaged costs and therefore the design choices made during those stages are crucial [11]. In the following part of the state of the art, the focus is put on the evaluation tools during the four different design stages to identify the different performances.

2.2. Innovation Performance

The innovative aspect of a product is created during early design stages[7]. Two kinds of innovations are differentiated: incremental one which improve a product, and breakthrough one which corresponds to new products for new needs [12].
Two kinds of evaluations are presented in the design process:

- Evaluation of the organisation's potential allows to evaluate the firms' capacity to carry out the project's design. Those tools' indicators are economic and look at the potential success of the project without studying the data of the design process.
- Evaluation of the design process potential, which can be defined as the evaluation of the different aspect of the product during the early design stages. This kind of evaluation is the one targeted in this paper and is detailed afterwards.

As already mentioned, innovation is created during the early design stages, so evaluation tools must be present during the problem analysis, ideas research and concept development stages. The main problem is due to a lack of data during the first stages.
In the problem analysis phase, data is rare making it difficult for designers to identify the opportunities and to drive the design process in the right way. However, this phase allows to set the design indicator of performance for following phases [13].

- In the ideas research phase, creative tools are used to develop the research process. The evaluation of ideas is crucial to select the best one. It can be performed by two types of tools: rely on experts' evaluation or used evaluation tools. Designers rely on experts to select the design objectives. In one hand, according to Zimmer et al. [14], the early selection of the design ideas by experts is crucial to reduce the design time and obtain the best product at the end of the design process. Experts identify the potentials of the design project according to four product's characteristics.
- Innovation evaluation can be performed by designers themselves by using tools. The use of objective and criteria is necessary. It must use objective criteria. For Saunders et al. [15] innovative products have similarities and an in-depth study of successful products allows the extraction of characteristics to evaluate ideas.

The concept development phase is the last stage where innovation evaluation is available and useful. The data are more significant and, most of all, the evaluation is based on the function matrix to compare the concepts to function goals or to target characteristics. According to Binz et al. [13], the assessment of the functions by the future users allows to test the acceptation of the future product and improve the innovative aspect.
This state of the art section provides the position of different innovation evaluation methods. The needs and goals of each method are different due to their design process position.

2.3. Sustainable Performance

The sustainability is composed of three aspects: social environment and economy. These performances could be evaluated during the whole design process and follow the global methodology of Design for Sustainability (DfS) [16]. DfS follows the standard of Design for X [17] where X is a life cycle phase or an aspect of sustainability as Design for Environment or Design for Recyclability. The evaluation methods depend on the quantity and quality of data. The type of evaluation is linked to the stage of the design process.
In the problem analysis phases, the sustainability is connected to the design goals. In fact, methods are used to give basic knowledge as sum up in the 10 golden rules [18] or to

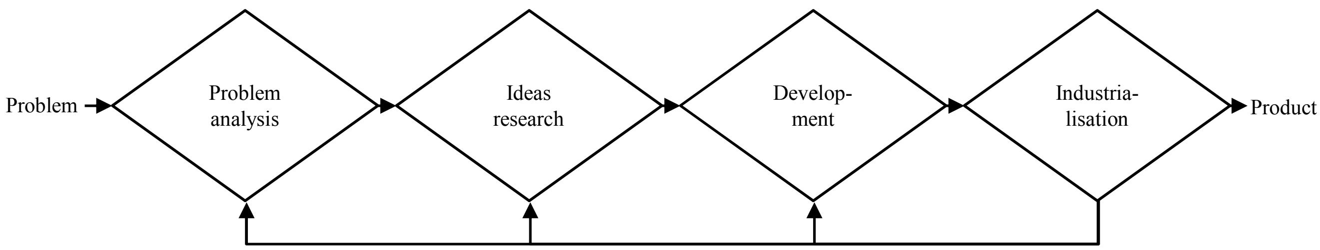

Fig. 1. Model of design process

position the goals of redesign products to attempt environmental improvement as Cluzel et al. mentioned [19].

In the ideas research phase, the evaluation methods are similar to the innovation evaluation and based on the product's creative aspect. Some methods divert creativity tools to integrate environmental aspect [20] or to question designers about sustainable indicators [21].

In the concept's development, evaluation methods are used to assess the product's architecture. This evaluation can be used to compare concepts regarding sustainable indicators [22] or compare components to select the best one in terms of sustainable performance [23].

In the industrialisation phase, the common and certificate tool is the life cycle assessment (LCA). LCA is complex due to the quantity of data and the time needed. Methods aims to simplify the product's evaluation during this phase by proposing different indicators or by dividing the LCA into different life cycle phase, as the manufacturing phase, and by proposing an evaluation of each process to compare them [24].

Sustainability evaluation method will allow the monitoring of the design process. The problem is that the evaluation is not continuous, and requires as many methods as design stages.

2.4. Additive Manufacturing Performance

The evaluation of the manufacturing performance is defined as evaluating the product or its representation according to its capacity to be manufactured by the proposed process [10]. This performance consists in evaluating if the product is properly designed for AM and if the design rules are respected. Manufacturing evaluation is basically studied during the downstream design stages to validate the process and the CAD product.

During the ideas research phase, Design With Additive Manufacturing (DWAM) [25] proposes to integrate AM knowledge during the early stages to increase the creativity and the innovation level of intermediate representation and to evaluate its potential.

As Rias proposal underlines, during the ideas research phase, the product data are not enough to analyse the classic performance, expert can be called to analyse the potential [5]. Ideas can be evaluated with adapted tools, like the ones proposed by Booth [26], taking the form of a matrix where design rules are graphically formulated to evaluated the AM potential.

The classic manufacturing evaluation aims to analyse the product's compatibility with manufacturing process characteristics.

In the concept development phase, the quantity of data which define the product grows and AM evaluation methods are multiple. The product's architecture can be evaluated by AM. Methodologies are available to evaluate CAD parts to analyse if the geometry suits to the process' characteristics, for example: its building layer part's orientation, shell's thickness [27].

During the concept development phase, the AM performance is included in the global methodology of design for Additive Manufacturing (DFAM) [28]. DFAM methods propose to optimise the product in order to manufacture by AM process. These kinds of methods are basically available during downstream design stages to validate the industrialisation proposal. Laverne et al. [29] distinguish two kinds of DFAM methods. DFAM oriented to optimise the part and DFAM oriented to optimise the assembly. Both DFAM analyse the CAD to identify its geometry and to compare it to design rules and design goals. DFAM is generally used to reduce the mass or volume of the material used [4].

This section only explores the evaluation of manufacturing reserved to downstream design stages. Therefore, methods try to evaluate the potential of ideas during early design stages by giving guidelines to designers

3. Proposed objectives

The state of the art shows:

- Present methods are various and disparate.
- The lack of multicriteria evaluation in the design process. Innovation, sustainability and AM can be evaluated.
- No evaluation method regroups all three aspects individually during the whole design process.

To remedy this, proposal aims to provide a method to select the adapted tools for the early design stages regardless of the studied subjects.

4. Proposition of a method to select evaluation tool

To validate the objectives, the research chose to focus on analysing the existing tools and to select the adapted ones to extract the information and outputs needed to create a multicriteria evaluation method.

The proposed method to select the best evaluation tools is independent of the studied subject. The evaluation is based on four criteria:

- The Facility of use of the tool (F)
- The Benefit of the tool (B)
- The Design Process Position (DPP)
- The External Data Constraint request (EDC)

These criteria have been chosen because they are unlabelled and as so can be used for the three topics. F permits to evaluate the need for experts. B is used to classify different kind of tools as done by Bovea et al [30] for environmental tools. DPP helps to know which design step is concerned by the tool evaluated and EDC criterion shows the quantity of data needed for create the performance's indicators. The ranking is based on a 5-level scale as shown in Table 1.

The evaluation of tools follows the method proposed in the figure 2 and is divided into 5 steps:

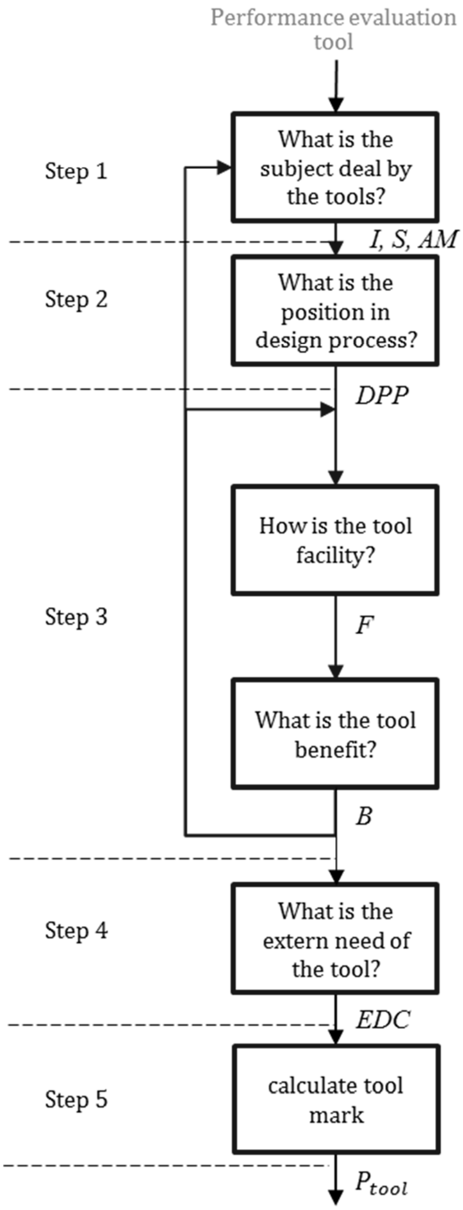

Fig. 2. Evaluation method

- Step 1: Identification of the subject
- Step 2: Situate the tools in the design process. If the tool is used for different design stage, the step 3 is made for each stage.
- Step 3: Evaluate F and the B criteria of the tool at this design stage according to Table 1.

Table 1: Evaluation grid for Facility and Benefit

Mark	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 time are needed to control it.	Pros and cons are identified by the tool.
2	Expertise or long time is needed to control it.	indicators of performance are proposed by the tool
3	Knowledge on the field is required or/and time is needed to control it.	tools proposed guidelines for improvement
4	No expertise/knowledge or only a short time is needed to control it.	Potential improvements are proposed by the tool.
5	No expertise/knowledge and only a short time are needed to control it.	Higher performance solution is proposed by the tool.

- Step 4: Evaluate the external data need constraint (EDC) of the tool, according to table 2.

Table 2: Evaluation grid of External Data Constraint request

Mark	Evaluation of external data constraint request
0,5	Redesign: need previous product
1	Need previous stage option
2	Independence criteria

- Step 5: calculate the performance P_{tool} of the tool.

It is defined as shown in the equation (1) where P_{tool} is the performance, F is the Facility, B is the Benefit and EDC the External Data Constraint request.

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

This kind of notation is used to distinguish two types of evaluation:

- The quality of the tool
- The penalty of the tool

Facility and benefit of the tool are intrinsic qualities to be opposed to the external need which is a default.
With the evaluation method the adapted tool will be the one with the highest value of P_{tool}.

5. Results

5.1. Performance evaluation tools

The investigation is conducted on 29 different evaluation tools with the characteristics sums up on Table 3.

Table 3. Description of the tools

Topics	Number of related tools
Innovation	6
Sustainability	16
AM	7

Some evaluations are dealing with two topics but to simplify the indication on the result, only the main subject is retained. These tools are detailed on the table 4.

5.2. Results of evaluation methods

This method permits to evaluate each tool and to position it in the design process to select the best ones according to the design goals. In figure 3, the performance of each tool is modelled as the length of bar and situate on one of the four phases. Three types of tool are being evaluated: Innovation tools are in blue and are represented by the letters (A), Sustainable one are in green and are represented by numbers (1) and AM tools are in yellow and are represented by roman numbers (I). The tool's performances are evaluated between 2 to 8. But in theory, the maximum is 18. This gap can be explained by the incapacity of the tool to find an optimal solution without requiring time or expertise.

These results are in line with the state of the art: Innovation is made on the early design stages; sustainability is monitored during all the process and AM is studied on downstream phases.

Furthermore, the evaluation of the intermediate product's representation is not valuable until the ideas research stages due to the tools' performance. According to Tichkiewitch et al. [11], eighty percent of the product value is decided during the twenty first percent of the design process. Therefore, making it the most attractive step for designers aiming to evaluate the product.

A cartography of academics tools is provided, the selection of tools will depends of requirements. The definition of the tool performance is defined by the authors' objectives.

A three criteria evaluation can be achieved during ideas research and development phases.

In order to evaluate the product, the selection of tools is made by screening the thirty percent higher performant ones.

For the author's requirements the tools selected for the next step are highlighted in the table 4.

6. Perspectives and conclusion

The proposed method is based on the analyse of evaluation methods during the design process and dealing with three aspects: sustainability, innovation and AM. To facilitate the analysis and make a unique and impartial analysis of the state of the art, a method is proposed to evaluate existing evaluation tool regarding fours characteristics: position in the design process, the facility, the benefit and the external data need of the tool.

This method allows to identify the adapted tools to use. These tools were analysed and permit the identification of the best indicators, design rules and evaluation form to create a multicriteria tool.

Future work's objective is to validate the benefit of this kind of evaluation on industrial projects and to allow designers to adapt the tool to their design goals. As an example, if the project doesn't need innovation criteria, the tools can adapt the external input and output requirements to these goals.

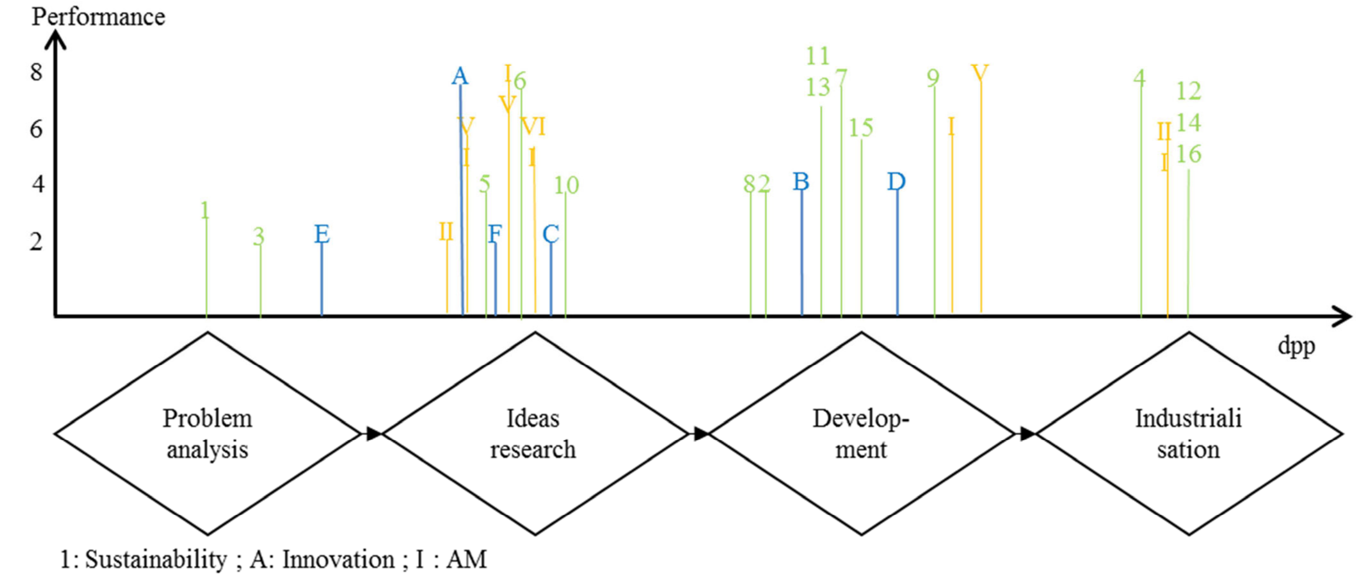

Fig. 3. Performances of the tools evaluated

Table 4. Lists of the tools evaluated by the method

A	[21]	F	[31]	5	[32]	10	[24]	15	[33]	IV	[25]
B	[15]	1	[18]	6	[16]	11	[23]	16	[34]	V	[27]
C	[14]	2	[35]	7	[36]	12	[37]	I	[4]	VI	[5]
D	[13]	3	[19]	8	[22]	13	[38]	II	[39]	VII	[26]
E	[40]	4	[6]	9	[41]	14	[42]	III	[28]		

References

[1] AENOR, "European Innovation Management Standard XP CEN/TS 16555." 2013.

[2] H. Brezet, "Ecodesign, a Promising Approach to Sustainable Production and Consumption," *U. N. Environ. Program UNEP*, 1997.

[3] I. Gibson, D. W. Rosen, and B. Stucker, *Additive Manufacturing Technologies*. Boston, MA: Springer US, 2010.

[4] D. Brackett, I. Ashcroft, and R. Hague, "Topology optimization for additive manufacturing," in *Proceedings of the solid freeform fabrication symposium, Austin, TX*, 2011, pp. 348–362.

[5] A.-L. Rias, F. Segonds, C. Bouchard, and S. Abed, "Towards additive manufacturing of intermediate objects (AMIO) for concepts generation," *Int. J. Interact. Des. Manuf. IJIDeM*, vol. 11, no. 2, pp. 301–315, 2017.

[6] F. L. Le Bourhis, O. Kerbrat, J.-Y. Hascoet, and P. Mognol, "Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing," *Int. J. Adv. Manuf. Technol.*, vol. 69, no. 9–12, pp. 1927–1939, 2013.

[7] S. Shah, "Sources and patterns of innovation in a consumer products field: Innovations in sporting equipment," *Sloan Sch. Manag. Mass. Inst. Technol. Camb. MA WP-4105*, 2000.

[8] T. J. Howard, S. J. Culley, and E. Dekoninck, "Describing the creative design process by the integration of engineering design and cognitive psychology literature," *Des. Stud.*, vol. 29, no. 2, pp. 160–180, 2008.

[9] A. Neely, M. Gregory, and K. Platts, "Performance measurement system design: A literature review and research agenda," *Int. J. Oper. Prod. Manag.*, vol. 15, no. 4, pp. 80–116, 1995.

[10] R. H. Chenhall, "Reliance on manufacturing performance measures, total quality management and organizational performance," *Manag. Account. Res.*, vol. 8, no. 2, pp. 187–206, 1997.

[11] S. Tichkiewitch and A. Riel, *The reasons for Integration in Design*. EMIRAcle, 2010.

[12] R. Garcia and R. Calantone, "A critical look at technological innovation typology and innovativeness terminology: a literature review," *J. Prod. Innov. Manag.*, vol. 19, no. 2, pp. 110–132, 2002.

[13] M. Binz and H. Reichle, "Evaluation method to determine the success potential and the degree of innovation of technical product ideas and products," *35 Proc. ICED 05 15th Int. Conf. Eng. Des. Melb. Aust. 15-18082005*, 2005.

[14] B. Zimmer and B. Yannou, "Proposal of a radical innovation project selection model based on proofs of value, innovation and concept," *70 Proc. Des. 2012 12th Int. Des. Conf. Dubrov. Croat.*, 2012.

[15] M. N. Saunders, C. C. Seepersad, and K. Hölttä-Otto, "The characteristics of innovative, mechanical products," *J. Mech. Des.*, vol. 133, no. 2, pp. 1–9, 2011.

[16] Jawahir, I. S., O.W. Dillon, Jr., K.E. Rouch, Kunal J. Josh, Anand Venkatachalam, and Israd H. Jaafar, "Total life-cycle considerations in product design for sustainability: A framework for comprehensive evaluation.," pp. 1–10, 2006.

[17] M. Tichem and T. Storm, "Designer support for product structuring—development of a DFX tool within the design coordination framework," *Comput. Ind.*, vol. 33, no. 2, pp. 155–163, 1997.

[18] C. Luttropp and J. Lagerstedt, "EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development," *J. Clean. Prod.*, vol. 14, no. 15–16, pp. 1396–1408, 2006.

[19] F. Cluzel, B. Yannou, D. Millet, and Y. Leroy, "Eco-ideation and eco-selection of R&D projects portfolio in complex systems industries," *J. Clean. Prod.*, vol. 112, pp. 4329–4343, 2016.

[20] J. A. O'Hare, "Eco-innovation tools for the early stages: an industry-based investigation of tool customisation and introduction," University of Bath, 2010.

[21] N. M. P. Bocken, J. M. Allwood, A. R. Willey, and J. M. H. King, "Development of an eco-ideation tool to identify stepwise greenhouse gas emissions reduction options for consumer goods," *J. Clean. Prod.*, vol. 19, no. 12, pp. 1279–1287, 2011.

[22] M. F. Hassan, M. Z. M. Saman, S. Sharif, and B. Omar, "An Integrated MA-AHP Approach for Selecting the Highest Sustainability Index of a New Product," *Procedia - Soc. Behav. Sci.*, vol. 57, pp. 236–242, 2012.

[23] A. Halog, F. Schultmann, and O. Rentz, "Using quality function deployment for technique selection for optimum environmental performance improvement," *J. Clean. Prod.*, vol. 9, no. 5, pp. 387–394, 2001.

[24] M. Arena, G. Azzone, and A. Conte, "A streamlined LCA framework to support early decision making in vehicle development," *J. Clean. Prod.*, vol. 41, pp. 105–113, 2013.

[25] F. Laverne, F. Segonds, G. D'Antonio, and M. Le Coq, "Enriching design with X through tailored additive manufacturing knowledge: a methodological proposal," *Int. J. Interact. Des. Manuf. IJIDeM*, vol. 11, no. 2, pp. 279–288, 2017.

[26] J. W. Booth, J. Alperovich, T. N. Reid, and K. Ramani, "The Design for Additive Manufacturing Worksheet," in *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2016, pp. 1–8.

[27] C. Emmelmann, D. Herzog, and J. Kranz, "10 - Design for laser additive manufacturing," in *Laser Additive Manufacturing*, M. Brandt, Ed. Woodhead Publishing, 2017, pp. 259–279.

[28] R. Ponche, O. Kerbrat, P. Mognol, and J.-Y. Hascoet, "A novel methodology of design for Additive Manufacturing applied to Additive Laser Manufacturing process," *Robot. Comput.-Integr. Manuf.*, vol. 30, no. 4, pp. 389–398, 2014.

[29] F. Laverne, F. Segonds, N. Anwer, and M. Le Coq, "Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study," *J. Mech. Des.*, vol. 137, pp. 1–8, 2015.

[30] M. D. Bovea and V. Pérez-Belis, "A taxonomy of ecodesign tools for integrating environmental requirements into the product design process," *J. Clean.*

Prod., vol. 20, no. 1, pp. 61–71, Jan. 2012.
[31] L. Budde, O. Nagler, and T. Friedli, "A Method to Set up a Complexity Index to Improve Decision-making Performance," *Procedia CIRP*, vol. 36, pp. 53–58, 2015.
[32] D. J. H. Spangenberg, "Design for Sustainability (DfS): Interface of Sustainable Production and Consumption," in *Handbook of Sustainable Engineering*, J. Kauffman and K.-M. Lee, Eds. Springer Netherlands, 2013, pp. 575–595.
[33] C. Labuschagne, A. C. Brent, and S. J. Claasen, "Environmental and social impact considerations for sustainable project life cycle management in the process industry," *Corp. Soc. Responsib. Environ. Manag.*, vol. 12, no. 1, pp. 38–54, 2005.
[34] K. Kellens, W. Dewulf, M. Overcash, M. Z. Hauschild, and J. R. Duflou, "Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 2: case studies," *Int. J. Life Cycle Assess.*, vol. 17, no. 2, pp. 242–251, 2012.
[35] G. Howarth and M. Hadfield, "A sustainable product design model," *Mater. Des.*, vol. 27, no. 10, pp. 1128–1133, 2006.
[36] W. M. Cheung, R. Marsh, P. W. Griffin, L. B. Newnes, A. R. Mileham, and J. D. Lanham, "Towards cleaner production: a roadmap for predicting product end-of-life costs at early design concept," *J. Clean. Prod.*, vol. 87, pp. 431–441, 2015.
[37] L. De Benedetto and J. Klemeš, "The Environmental Performance Strategy Map: an integrated LCA approach to support the strategic decision-making process," *J. Clean. Prod.*, vol. 17, no. 10, pp. 900–906, 2009.
[38] C. Jasch, "Environmental performance evaluation and indicators," *J. Clean. Prod.*, vol. 8, no. 1, pp. 79–88, 2000.
[39] R. I. Campbell, H. Jee, and Y. S. Kim, "Adding product value through additive manufacturing," 2013.
[40] Y. Borgianni, G. Cascini, F. Pucillo, and F. Rotini, "Supporting product design by anticipating the success chances of new value profiles," *Comput. Ind.*, vol. 64, no. 4, pp. 421–435, 2013.
[41] E. Atzeni and A. Salmi, "Economics of additive manufacturing for end-usable metal parts," *Int. J. Adv. Manuf. Technol.*, vol. 62, no. 9–12, pp. 1147–1155, 2012.
[42] A. M. Contreras, E. Rosa, M. Pérez, H. Van Langenhove, and J. Dewulf, "Comparative Life Cycle Assessment of four alternatives for using by-products of cane sugar production," *J. Clean. Prod.*, vol. 17, no. 8, pp. 772–779, 2009.