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Design for Sustainability Tools: Definition and criteria towards practical use

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ABSTRACT

The evolution of design to meet the growing sustainability challenges has led to the development of knowledge expressed in different approaches, principles and strategies. To be able to operationalize this knowledge, several design for sustainability (DfS) tools have been created. However, these tools have not been the target of massive and systematic practical use by designers, nor have they been the subject of many studies that allow analyzing, classifying and understanding their capabilities in a real context to improve application rates.

With the end goal of supporting designers in using DfS tools more systematically, this research work aims to establish two essential foundations that can lay the ground for the practical selection and application of tools in the future: 1) a clear and comprehensive definition of what constitutes a DfS tool from the designer's perspective, including its scope and boundaries; 2) a list, hierarchization, and evaluation of criteria for classifying, organizing, and selecting tools based on project and designer needs.

The methodology used in this research incorporates three main methods: 1) literature review to establish the state-of-the-art, basis for constructing a definition of DfS tool and for identifying and selecting criteria; 2) survey for designers to validate the main components of the DfS tool definition; 3) value analysis methodology for classifying and valuing the classification criteria by designers.

Based on this process, it was possible to construct a comprehensive definition of what a DfS tool is and to establish and organize a set of criteria that can facilitate the classification and organization of tools. This allows for better identification of their characteristics, demands and functionalities to align the tools with the design process and its needs.

1. Introduction

Over the last few decades several design approaches has been developed, such as green design, eco-design, product-service systems design, emotionally durable design, cradle to cradle design, biomimetic design, design for the base of the pyramid, design for social innovation or design for sustainability (DfS), which aim to reduce the environmental and social impact of products and, in general, contribute to a paradigm shift towards sustainability (Ceschin and Gaziulusoy, 2019). These approaches have increasing levels of maturity, scope and complexity, and in the case of design for the circular economy, they also present greater pragmatism in their relationship with the economic context but still maintain the social dimension as the most underrepresented (Chrispim et al., 2022). To homogenize the language in the present article, and because DfS has the broadest scope, this will be the designation used in this paper to refer to all approaches and consider the several dimensions of sustainability such as environmental, social, economic, functional, and cultural issues.

The operationalization of these design approaches has been supported by many tools which aim to facilitate the integration of the growing number of sustainability criteria into the design process. However, this large number of DfS tools has not been widely used by designers and has not been applied systematically and effectively in product design projects (Camocho, 2022). The increasing creation of new tools has also not been followed by the development of many studies and evaluations of existing tools (Baumann et al., 2002) to determine their true capabilities and added value for the real work context. This means that more research with review, test, validation and categorization of existing tools is needed (Schäfer and Löwer, 2020).

The literature also indicates that many tools fail because they are not focused on design (Lofthouse, 2006) and are not aligned with the design practice needs. As already summarized by Rossi et al. (2016) tools

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developed according to academic principles often diverge from the real context of the industry and the needs of the design project, which reduces their relevance and application. There is also no adequate resource to help the industry select the most suitable tool (Faludi et al., 2020). Examples like Eco-Tool Seeker (Rousseaux et al., 2017) although being target to sustainability are too broad in scope for designers, and examples like the industrialdesignthinking.com (Gouveia, 2024), although being agile and rich in information on every tool, don't involve design tools specifically oriented towards sustainability.

On the other hand, only a small fraction of the literature identified (Beskow et al., 1998; Ritzen, 2000; Baumann et al., 2002; Gómez-Navarro et al., 2005; Vicente, 2012; Lindahl and Ekermann, 2013; Rousseaux et al., 2017) presents a definition of what a DfS tool is, and these definitions either do not present an approach from a design point of view, or they are incomplete or are so vague that they make it possible to classify too many types of instruments as a DfS tool that cannot be operationalized by the field of design. Likewise, although there are several studies classifying DfS tools, as compiled in Vicente and Camocho (2023), only 3 identify the criteria used in this classification (Byggeth and Hochschorner, 2006; Bovea and Pérez- Belis, 2012; Rossi et al., 2016). Other criteria may exist but have not been made explicit in the classifications and categorizations of DfS tools. The criteria known in the literature are not exhaustive, do not present a language and structure adaptable to all existing DfS tools and, furthermore, do not allow the classification of tools in a useful way both for academia and, especially, for designers and product development teams.

Thus, identifying the need to adopt a harmonized language that can be useful for the practical context of the industry and for the scientific context of academia and, also, understanding the potential that a robust list of classification criteria can have in a more adequate selection of tools, and, therefore, in the promotion of a more systematic use of DfS tools, this article discusses, presents and validates a definition, suitable for designers and academia, of what a DfS tool is, as well as brings together, analyzes and hierarchizes by importance for designers, the criteria that can allow the classification and organization of the large number of DfS tools that exist.

These are the two initial steps of Project TOOL. S - Tools for Sustainable and Circular Design (https://lida.pt/research/tool-s/), which the overall structure can be found in Appendix 1, and they will allow the subsequent work of survey, evaluation and organizations, so that, in the end of the project, it will be possible to create a system that makes it easier for designers to select the most appropriate tool for their context and project, and, therefore increase adoption and use of DfS tools, that will, ultimately, support the development of more sustainable solutions.

The structure of this article is as follows. Chapter 2 presents the research methodology, indicating the topics covered in each phase and the methods used to do so. In chapter 3, a new definition of DfS tool is developed, presented and validated. In chapter 4, the survey and systematization of criteria for classifying DfS tools are presented. The evaluation and ranking of the criteria from the designer's perspective is also reported. Chapter 5 presents the conclusion and discusses possible future paths.

2. Methodology

In order to create a structured and systematic process for this first part of the TOOL. S project, a research methodology (Fig. 1) of a mixed nature was designed, with qualitative and quantitative methods, focused on gathering information from scientific sound sources and from design professionals. The first phase of this methodology concerns a standard literature review with the goal of establishing the state-of-the-art, clearly identifying the problem and supporting the formulation of the definition and the set of the classification criteria list. This literature review was developed based on the analysis of papers and other scientific documents retrieved directly from reference journals (as Journal of Cleaner Production, Journal of Industrial Ecology, Sustainability and The Design Journal) and through SCOPUS, WoS, Google Scholar and RCAAP, with the key words "Design for Sustainability"; "Design for Circular Economy"; "Eco-design"; "Design Tools"; "Tools Definition"; "Criteria". The analysis of this first group of documents enabled a second iteration of search through cross references made in this first batch. Other relevant documents were analyzed, namely final reports of R&D projects that have produced DfS tools, and also dictionaries and encyclopedias to support the definition production.

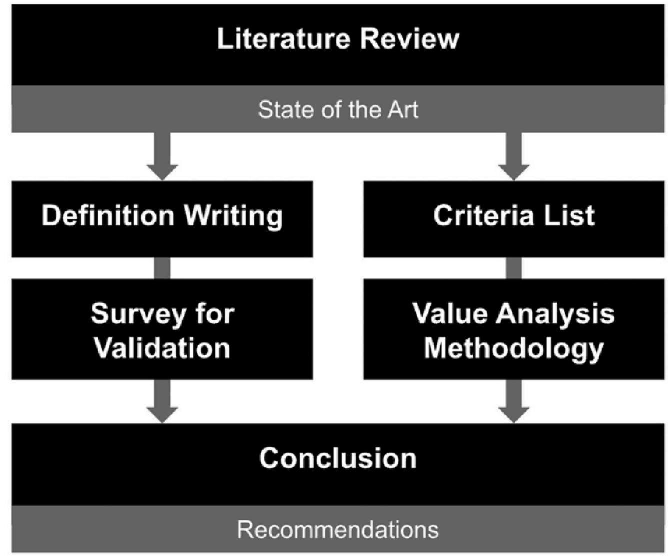

Fig. 1. Research methodology.

For the creation of the definition, a logical and literary consolidation based on the literature review was carried out with the development being based on 5 defining constraints of what a DfS tool is. After constructing this definition, a questionnaire survey targeting designers was carried out to validate its defining dimensions, gathering both qualitative and quantitative data to assess the opinion of designers regarding the definition, ensuring it is robust and can be widely accepted within the design community.

In parallel, a list of classification criteria was created using the consolidated theoretical base from the literature review, namely on the study of DfS tools and grounded on the identification and analysis of available tools. A list that was completed and homogenized by the authors based on the known characteristics of the tools. A value analysis methodology, a quantitative technique, was then applied to weigh the established criteria list. This analysis allowed to determine which criteria are most important to design professionals when classifying and identifying design tools. The result was a hierarchy that can guide the organization, selection and application of tools in the context of sustainable product design development.

3. Definition of DfS tool

Aiming to build a definition of DfS tool suitable for designers and the design scientific context, a framework was designed, corresponding to the first phase of the methodology, which analyzes 4 areas that contribute to the construction of the definition of DfS tool: 1) the first area analyzes the classic definitions of tools in a general context and in the context of design; 2) the second analyzes the needs of designers regarding the use of tools within the scope of the design project; 3) the third identifies the characteristics that a tool must have to allow it to meet the complexity inherent to sustainability and, consequently, to be able to be called a tool "for sustainability"; 4) the fourth area determines the boundaries of what should be considered as a design for sustainability tool, namely in terms of scope, area of intervention, potential for use and relationship with the design process and the design professionals, considering their role in a strategic problem-solving process that drives innovation, builds business success, and leads to a better quality of life through innovative products, systems, services, and experience (WDO, 2015), in the definition of the features and the profile of products and services integrating sustainability and circularity aspects in the process.

3.1. Definition of tool

The etymology of the word tool in English (OLD, 2023a) has origins in Old English or Proto-Germanic "*tol*", that designates what is used to prepare something. This allows us to understand that a tool is described as a means used to achieve a certain objective or as an instrument that helps to perform a task. Therefore, generally speaking, a tool is something that provides an advantage (mechanical or mental) to facilitate an activity and increase its performance.

From a designer's perspective, a design tool is any type of instrument - physical, digital or conceptual/abstract/methodological - that supports the generation, organization and manipulation of resources (whether material or immaterial) to perform tasks and to support the decision-making process throughout the phases of the design process (Erlhoff and Marshal, 2008). Therefore, these tools are considered important to improve the performance of the project and, consequently, the resulting solution (Ritzen, 2000) and need to be applied with knowledge of the facts (Mkrttchian et al., 2019), whether it is the design process or information about the specific area that those tools work on. To be considered a tool that can be used in a process such as design, it must go through the three essential stages of a process (Duberly, 2004):

1) input - the designer (or other professional involved in the design process) introduces a set of data, which can be of different types, degrees of complexity and origin;
2) processing - the information is processed by the tool according to a specific underlying and pre-established method. This information processing method can be autonomous, that is, without any intervention from the designer, or it can be participatory, meaning that the designer is co-responsible for processing the data;
3) output - a tangible result is generated in terms of information, which, depending on the characteristics of the tool, is translated into a specific format. Based on this result, the designer and the product development team will, in principle, be in a better position to make a more correct decision (outcome) and move the project to the next phase.

It is also important to note that the designation tool is sometimes used together and without distinction with others like "approach", "method" or "model" (Byggeth et al., 2007; D'Eusanio et al., 2019; De Fazio et al., 2021; Faludi et al., 2020; Flipsen et al., 2020; Ghazilla et al., 2008; Lindahl and Ekermann, 2013; Lindgreen et al., 2020; Kalita et al., 2021; Kurt, 2021; Marseglia, 2017). Jarzabkowski and Kaplan (2015) even state that a tool is a generic name that also covers "frameworks" and "concepts". But, since a method is a systematized and organized way of doing something (OLD, 2023b) and a model is a simple way of describing a system in order to explain how something works (OLD, 2023c), none of these concepts present the operative and practical dimension that a tool must have to effectively be an instrument to support the design process. As mentioned by Gómez-Navarro et al. (2005) the term tool implies an analogy with conventional tools, which are systems with a form and a function. As, in this context, tools are "*structured knowledge activity proposals*" (Gómez-Navarro et al., 2005, p.5), the designations "method" or "model" should only be used to describe the conceptual engine underlying the tool or its framework, but they are not a tool in themselves.

3.2. Needs and barriers of designers and the design process

The design process provides a methodological and procedural structure for carrying out a result-oriented project. Being the process led by the designer as a way of building the future and materializing what does not yet exist, this is, inherently, a process of probing the unknown that is carried out in stages and iteratively (Cross, 1989). It is also a process that integrates skills and information from different areas of knowledge and that involves great flexibility and agility to be compatible with the requirement to create innovative solutions that meet the identified needs. Dealing with a lot of information from diverse and very specialized areas and making informed but quick decisions in all stages of the design process requires culture and technical expertise, but it also requires designers to rely on design tools to provide structure and help to visualize the objective of the process (Royo et al., 2023). For product development to be carried out efficiently, designers need various types of data throughout the design process, which includes environmental information (Bakker, 1995), and this happens right from the problem identification/briefing phase that will serve as the basis for developing the solution (Luttropp and Lagerstedt, 2006). Designers' information needs, which support constant decision-making, must accompany the various stages of the process, namely in concept design, preliminary design and detailed design (Pahl and Beitz, 1992).

In recent years we have seen significant growth in the development and availability of tools to support the design process, with a greater predominance in digital tools, which have a relevant impact on the product development process (Witkowski, 2017), that has become more agile, flexible and fast.

However, in connection with sustainability, the use of tools is still very limited, and, in most cases, designers integrate strategies and criteria in a non-systematized way, and therefore without the support, guidance or validation of available tools (Camocho, 2022). Despite the wide array of design tools available, both free and paid (commercial or academic), their usage remains low due to various barriers hindering their implementation:

- lack of alignment of the tools to the product design culture (Sherwin, 2000);
- need for knowledge, on the part of designers, about sustainability and the correct application of tools in order to provide correct results (Ritzen, 2000);
- time demand for using the tools (Hemel and Cramer, 2002);
- lack of focus on design (Bhamra and Lofthouse, 2003);
- limited human and financial resources (Hillary, 2004);
- tools are not suitable in function, form or both (Gómez-Navarro et al., 2005);
- lack of alignment between project requirements and tools (Lofthouse, 2006);
- lack of perception of the benefits of its use (Camocho, 2022).

The large number of existing tools makes it difficult for designers to select them - the paradox of choice (Schwartz, 2016) - which, also, becomes an obstacle to the application of the tools. There are still barriers and weaknesses that hinder the use of the tools, and which can be directly attributed to each of the tools, as identified by Rossi et al. (2016) and Faludi et al. (2020), barriers that must be overcome through the design of the tools themselves.

In view of project needs, the tools with the greatest potential for practical implementation are those that best align with the design process and, therefore, do not block its creative fluidity. It is, therefore, essential to understand that the alignment of tools with 1) the design culture, the designer's knowledge and skills, and with 2) the objectives, resources and needs of the projects are key elements for their integration into the processes and in design practice. In this context, several factors must be considered:

- Time factor - several tools produce important and useful results in the design process, however, given the time required to obtain these results, associated with projects, in most cases, with very tight and conditioned timings, exploration and use of very time-demanding tools is not possible;
- Cost factor - several tools, with good potential for use, have very high costs, which makes them accessible only to large scale organizations and projects. These types of resource needs are not supported by projects with smaller budgets or, being bearable, are not perceived as a suitable investment;
- Data factor - The need for specific data that is difficult to access in many cases is another factor that puts into question the use of tools and also the relevance of the results obtained;
- Effort vs results factor - The balance between the effort required to use the tools and the relevance of the results obtained is a very important factor in this type of tool. It is also important that there is a realistic perception of the potential results that are obtained and the effort required to produce them;
- Technical knowledge factor - The need for specific knowledge outside the scope of design can act as an obstacle in the application of tools, as they must have seamless integration in the design process.

3.3. Sustainability requirements

The degradation of society and the planet's overall condition, stemming from the immense environmental pressure of the production and consumption of resources and generation of waste and emissions, the related social and cultural impacts, and the economic crisis in the recent decades have highlighted the challenges faced by humanity and have demanded for new solutions from policymakers, science, and society.

The European Union has advanced a series of policies and efforts to achieve the Sustainable Development Goals defined by the United Nations in the 2030 Agenda and to ensure well-being for all, while staying within planetary boundaries. Notable macro-level efforts include the Green Deal (European Commission, 2019) and the 8th Environment Action Programme (European Parliament, 2022), which address areas that include sustainable production and consumption, that is directly related to the potential for design intervention, as expressed in the renewed Circular Economy Action Plan (European Commission, 2020) and the proposal of establishing a framework for defining ecodesign requirements for sustainable products (European Parliament, 2023). The comprehensive network of European policies not only places the EU at the forefront of combating climate change, decarbonization and other environmental issues but also clearly demonstrates the importance of sustainability in contemporary society, and within its scope, assigns significant responsibility to design in pursuing this objective. Design also presents a relevant part in promoting social changes towards sustainability, since all types of projects can support individual and collective transition processes (Manzini, 2015).

Several international standards also help frame and give support to the operationalization of several dimensions of sustainability, as is the case of ISO 14000 family on environmental management (ISO, 2015), the ISO 29000 on social responsibility (ISO, 2010) or, the more recent, ISO 59000 on circular economy (ISO, 2024).

Although the concept sustainability is characterized by ambiguity, for these tools to be considered "for sustainability," they must interface with and holistically support the integration of various dimensions, pillars, categories, values and requirements of sustainability (Patara and Dhalla, 2022), following the strategies, objectives, and policies already internationally outlined. This means comprehensively addressing the various indicators of environmental, economic, circularity, social, and cultural dimensions. They should handle this information and make it accessible to sustainability non-expert target groups, such as designers.

Therefore, sustainability for designers is a complex field, involving a great deal of information from many different subjects and is, at the same time, only one of the many specialized areas they must deal with in the product development process. This intrinsic complexity of sustainability is, at first glance, antagonistic to the demand for flexibility and agility in the design process, which underscores the need for instruments that facilitate its integration during project development and allow for a life-cycle approach. This means translating the values and criteria of sustainability into a language that can be adopted by designers in different project contexts.

3.4. Boundaries

Beyond what has been previously mentioned, it is necessary to define the boundaries that separate what can or cannot be considered a DfS tool, promoting greater application of these by designers at various levels of the design process. Design practice, although based on a multidisciplinary approach that interfaces with numerous fields associated with solving complex problems, requires leveraging its process with tools of various natures and disciplines (Lofthouse, 2006).

One boundary is related to the permeability of design to other disciplines, which may bring the challenge of dealing with knowledge that the designer does not master. In the scope of sustainability-oriented design, designers should have access to and apply tools appropriate to the nature of the product, the quantities to be produced, and the capabilities of the team (Penty, 2019), but many tools are not design tools. Tools developed in and for neighboring areas such as engineering, management, economics, or environmental sciences are tools that, while useful for those areas and for sustainability, may fall outside the scope of design (they are not possible to integrate into the design process) and outside the designer's capabilities for use (knowledge not possessed by the designers).

Another boundary is the necessity for designers to manipulate the tools without needing to resort to non-designer specialists. In such cases, it would be a tool from another area being used by others to bring additional information into the design process. To clearly set this boundary it's important to understand the scope of designers activity, namely those that are involved in product development in any type of industry and geography, as defined in the International Standard Classification of Occupations Ref. #2163 for Product and garment designers, that states that these professionals *"design and develop products for manufacture and prepare designs and specifications of products for mass, batch and one-off production (...)"* (ILO, 2012, p. 123).

Another limit to be considered is that the tool must not be a blocker of the design process, but rather a facilitator/accelerator. Therefore, the characteristics of the tool (structure, necessary information, etc.) must align with the agility of the design process.

3.5. New definition of DfS tool

Taking into consideration the previous analysis and the logical construction built upon it, the following definition can be presented:

A design for sustainability tool is an operative instrument that systematically integrates sustainability principles, strategies, and criteria into one or more phases of the design process. It aims to enhance the circularity and sustainability performance of the solution being developed. Regardless of its specific objectives, complexity, or formal and functional characteristics, a design for sustainability tool always involves three steps: input, processing, and output. It must align with the designer's needs, available resources, and project objectives, and be useable by designers independently, without requiring specialized expertise from other fields.

Having as a starting point the research conducted with the goal of building an effective definition of DfS tools, beginning in the etymological definition of what is meant by tool, the needs and barriers designers and the design process face towards sustainability and its requirements and boundaries, a new definition was developed by the authors considering 5 fundamental criteria of eligibility (Table 1) that

Table 1
Eligibility criteria for selecting DfS Tools.

Criterion 1	Facilitate the integration of principles, strategies and criteria of sustainability in a systematic way into the design process
Criterion 2	Focus on one or more phase of the design process, to improve the circularity and sustainability performance of the solution under development
Criterion 3	Must go through 3 main steps: input, processing, output
Criterion 4	Must be aligned with the needs of designers, available resources and project objectives
Criterion 5	Must allow to be used autonomously by designers, without recourse to non-designers specialists

were set to enable the future selection of DfS tools through their separation from other types of tools. For a tool to be considered of design for sustainability and suitable for any specific designer and project it must comply with the 5 criteria cumulatively.

3.6. Validation of the DfS tool definition

To validate the DfS tool definition presented, an online survey was conducted and disseminated within the design community within reach of the authors. It was built a database of designers based on the Portuguese Designers Association to which was added a group of national and international design professionals that have participated in design for sustainability and circular economy initiatives, research projects, training and other events and other contacts from the authors, to which the survey was sent. The invitation to participate in the survey and the link to the questionnaire (Appendix 2) was sent individually by e-mail and the survey operationalized in Google Forms. From this universe it was possible to receive 103 responses, of which 101 were valid (2 answers were considered not valid - 1 was blank and another wasn't a designer). The questionnaire consisted of two parts: an initial part on identification, characterization and an open question on what a DfS tool is for the respondents. The second part, in which each question derived from the 5 main statements presented in the DfS definition and of the 5 eligibility criteria to be evaluated using a 4-point Likert scale (strongly disagree, disagree, agree, strongly agree, plus room for justification if relevant).

From the analysis of the first part, it is possible to characterize the respondents as 66% being industrial/product designers, 21% from graphic/communication designers, and 13% designers from other areas, including design professors. From the open question to define a DfS tool, respondents say these tools are versatile instruments that guide, support, and facilitate the development of more sustainable products and services. They support designers to make conscious and informed decisions, integrating principles of equity and considering all factors of sustainable development, including the environmental, social, and economic impacts of design decisions. For these designers the tools enable an understanding of the overall sustainability level of a product, from life cycle analysis to the choice of materials and processes. They also enhance creativity and innovation, allowing designers to optimize methods, plan, foresee, and execute more efficient and sustainable projects. Acting at all stages of the design process, they seek solutions that minimize impact and maximize benefits in all dimensions. DfS tools are guiding, assisting, and evaluating instruments (digital or other) that empower designers to create products and services that meet current socio-economic needs without compromising the future. They are essential for promoting more effective development with continuous improvement, steering the project towards more sustainable outputs and offering support for the design process of sustainable solutions at all stages. Moreover, tools that are accessible and useable, up-to-date and reliable, and that provide clear and concise results are seen as the most desirable.

Regarding the second part, a simple statistical analysis was conducted (Table 2) that states, in average, an elevated rate of agreement

Table 2
Simple statistical analysis of the 2nd part of the survey.

Question	Average ± standard deviation	Mode	Median
Q. 2.1	3,65 ± 0,52	4	3
Q. 2.2	3,47 ± 0,66	4	2,5
Q. 2.3	3,09 ± 0,61	3	3
Q. 2.4	3,41 ± 0,79	4	2,5
Q. 2.5	3,09 ± 0,76	3	2,5

with the 5 statements, with high consistency in the replies since it presented a small deviation from the standard.

As demonstrated in Fig. 2, almost all designers (98%) agreed with the statement that "a tool should facilitate the systematic integration of principles, strategies, and criteria of design for sustainability into the design process". Only one designer disagreed with this statement, expressing that this integration of principles is part of the design process and depends on the designer's capabilities rather than the application of a tool.

93% agreed that "design for sustainability tools should focus on one or more phases of the design process to improve the circularity and sustainability performance of the solution in development," with several respondents emphasizing that they should focus on all phases. The 7% who disagreed with the statement indicated that the tools should focus on all phases of the process, ruling out the possibility of tools focusing on a specific phase.

Regarding formal and functional characteristics, 88% agreed with the statement "that a tool always goes through three steps: inputs, processing, and output". The 12% who disagreed with the statement indicated that there might exist variations or a need to focus on specific actions or require other intermediate steps.

Additionally, 87% agreed that "design for sustainability tools must be aligned with the needs of designers, the available resources, and the project objectives". The 13% who disagreed mostly believed that the tools also need to be aligned with the needs of clients and that designers must adjust to the characteristics of the tools.

The statement that "a design for sustainability tool should allow designers to use it autonomously without resorting to non-designer specialists" had the highest disagreement (22%). The reasons for the disagreement included the intrinsic need for collaboration with other areas of knowledge in the design process, the importance of dialogue with specialists and non-designers, the complexity of some projects, and the need for an external perspective. These reasons suggest that the statement was not understood by some designers, as it was not intended to imply that the development of a project should be exclusively the work of designers without the involvement of specialists from other fields.

4. Criteria for classification of DfS tools

In the literature it is possible to find several studies that classify DfS tools. In the authors' previous work (Vicente and Camocho, 2023) it was possible to analyze 33 of these studies, grouping them into 6 categories according to how the classification was made: C1-Scope; C2-Morphology; C3-Purpose; C4-Multi-Category; C5-Cross-Category; C6-Other/Mix. From this analysis it is possible to conclude that only 2 studies present the criteria used for classification (Bovea and Pérez-Belis, 2012; Byggeth and Hochschorner, 2006) and that only one study presents a classification according to the intended user (Varžinskas et al., 2020). It is also clear that the classifications that indicate the purpose and those that cross-reference this with other aspects relevant to designers are the most useful (C3 and C5).

However, there are few studies in the literature that systematically aggregate some information on the criteria used for classification, including the work by Rossi et al. (2016) which aggregates 6 types of criteria: 1) Product development context; 2) Functional aspects; 3) Stage

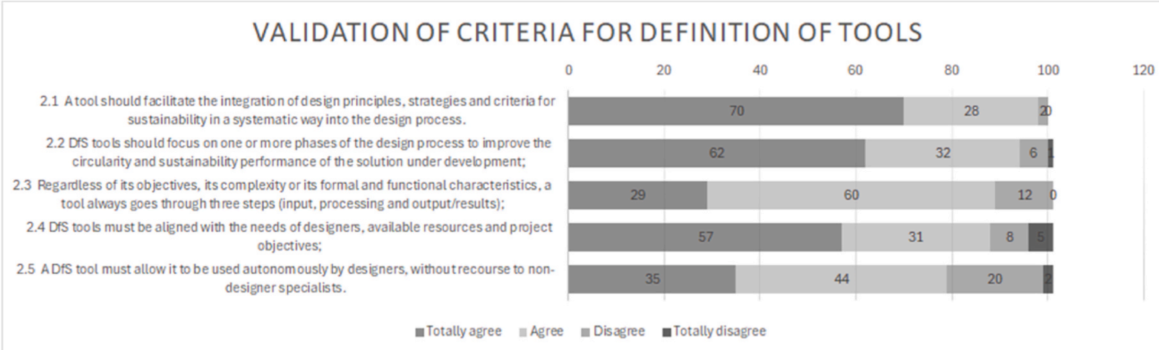

Fig. 2. Results of the validation survey on the new definition of DfS Tool.

of the development process and life cycle stage; 4) Tool characteristics; 5) Support for the user; 6) Level of integration in companies.

So, to respond to the need to systematically explain the criteria for classifying tools, the next step was to identify, list and organize the existing criteria that are referred to in the tool study literature, either directly or indirectly, and those that can be identified based on tool analysis. This list was completed and homogenized by the authors based on the known characteristics of the tools. This collection and systematization resulted in Table 3. In addition to establishing an identifier for each criterion, it was possible to develop a descriptor to help characterize each of the criteria and to group the 19 criteria into four types. The first group includes the basic classification criteria for the tools; the second group brings together the criteria that aim to define the operational characteristics of the tools; the third group brings together those that make it possible to define the tools according to their morphological characteristics; and finally, the fourth group includes the criteria that identify the objective and type of approach of the tools to the design process, sustainability and innovation. To clarify the intent of each criterion, a standardized set of parameters (right column) was defined, outlining the expected response for each criterion's assessment.

Bearing in mind that one of the final objectives of this research is to enable the identification of tools that are most useful and suitable for professional practice and specific projects, thus facilitating their choice and adoption, it is important to rank and value these criteria according to the importance that each one has for practical design work, i.e. the importance that designers perceive each criterion to have.

To achieve this, an analytical hierarchy process methodology, commonly applied in value analysis was used (Henriques et al., 2021; Catarino et al., 2007), in which each criterion is evaluated against each of the others, with a score from +3 to −3. Based on this methodology, a matrix to cross-reference the criteria (Fig. 3) was built. This matrix, along with Table 3, was pre-tested on a pilot by a designer-researcher in the field of design for sustainability who is external to this research but has experience in using the value analysis methodology. After refining the matrix in result of the pilot test, it was sent to national and European designers with experience in product development and/or sustainability. It was possible to obtain 15 valid results.

The results (Appendix 3) make it possible to determine the ratings for each criterion, taking into account a maximum rating of 3 points for each criterion, which means that, in theory, a criterion that was rated with the maximum rating in comparison with all the others and cumulatively by all the respondents could achieve a total rating of 810 points (3 points x 18 criteria x 15 ratings). It also enables to determine the average per type of criteria. The evaluation carried out by each designer also makes it possible, through the result obtained in each designer's evaluation of the criteria, to rank the various criteria in order of importance according to each person's perception (Appendix 4). These three types of results are expressed in Fig. 4.

Analyzing the results of the evaluation averages by type of criterion, the Base criteria group is the least valued by designers (113 pts on average) and, on the other hand, the Goal and Scope group is the most important for designers (391 pts on average), with 3 criteria having more than 400 pts.

The evaluation by criterion shows that the most important for designers is Innovation (464 pts), followed very closely by Purpose (448 pts) and Sustainability (440 pts). At the other extreme, Structure stands out as the least important criterion for designers (31 pts), followed by Country (47 pts).

The ranking of the criteria evaluated by the experts also presented in Fig. 4 is defined by the averages of the individual rankings defined by each expert. We can therefore see that despite there being different scores as demonstrated in the evaluation analysis, the "Purpose" criterion is the one that is considered the most important by various experts, followed by "Innovation" in second and "Sustainability" in third place. It should be noted that "Structure", a very relevant criterion for tool developers, was considered the least important criterion. Also, as least important, it is possible to find the "Origin" and "Country", which was an expected result.

5. Conclusions and further developments

The integration of sustainability approaches into the design process and practice is enhanced by the adoption of tools that facilitate and guide the process which is often complex. However, despite the existence of a broad diversity and quantity of DfS tools, they have not been widely used by designers and have not been applied systematically and effectively in product design projects. So, it is essential to encourage a higher use in the context of product development. To this end it was necessary to develop background research validated by designers on two fundamental aspects. One through the construction and validation of the definition of what a DfS tool is, associating it to the eligibility criteria that allow for the separation of instruments that are not DfS tools and, secondly, hierarchizing a group of classification criteria for the same tools which allow determining the importance that tool characteristics have for designers in an operational context.

The results of validating the parameters of the DfS Tool definition indicate that, despite disagreement regarding the need for designers' autonomy, the proposed definition is widely accepted by designers. The disagreement highlighted the importance of interdisciplinary collaboration in design for sustainability but does not invalidate the correct definition of these tools that, to be design tools, must be used by designers. The major parameters that structure this definition allow to determine eligibility criteria of what is or is not a DfS tool. Only after this selection will it be possible to organize the tools with the classification criteria defined in the second stage of the methodology.

The results of establishing the criteria and their ranking by designers demonstrate that, in line with some base criteria, which would be expected to be the least important, such as "Date", "Country" or "Origin", it is the "Structure" criterion that is considered the least important for those who use them. This is a very significant classification since this

Table 3
Criteria to classify DfS tools.

Ref	Type	Identifier	Description	Possible reply parameters
A	Base criteria	AUTHOR	The tool authorship, either individual or institutional	[-Name-]
B		DATE	The year of publication or distribution of the tool	[-Year-]
C		COUNTRY	The country of origin of the tool	[-Country-]
D		LANGUAGE	The language (s) in which the tool is available	[-Language-]
E		ORIGIN	The context in which the tool was developed	[Academic] [Professional]
F		COST	The business model of the tool	[Free] [Paid] [Mix] [User-dependent]
G	Operational criteria	COMPLEXITY	The level of complexity of the tool	[High] [Intermediate] [Low]
H		TIME	The time required to operate the tool and receive its outputs	[Low time-consuming] [Medium time-consuming] [High time-consuming]
I		INPUT	The type of information that the user must provide to operate the tool	[Quantitative] [Semi-quantitative] [Qualitative] [Mix]
J	Morphological criteria	OUTPUT	The format through which the results of the tool's utilization are presented	[Checklist] [Guidelines] [Graphic] [Prioritization] [Matrix] [Report] [Resource] [Strategy] [Score/Values] [Mix] [Other]
K		SUPPORT	The medium through which the tool is materialized and can be used by the user	[Digital] [Physical] [Hybrid] [Both]
L		DELIVERY	The mode through which the tool is rendered available to the user	[Stand-alone] [Part of a set] [Set] [Integrated into other tool/software]
M		STRUCTURE	The way through which the tool is organized and structured	[Matrix] [Diagram] [Checklist] [Data-set] [Game] [Mix] [Other]
N	Goal and scope criteria	PURPOSE	The objective for which the tool was designed	[Assessment] [Ideation support] [Prioritization] [Education] [Communication] [Multiple] [Coordination with other design criteria] [Other]
O		SECTOR	The coverage of the tool regarding if it is targeted to a specific sector of activity or if its general	[General] [Sector-specific]
P		DESIGN PROCESS	The design process phases in which the tool is used	[All-encompassing approach] [Specific phase approach]
Q		SUSTAINABILITY	The design approach to sustainability	[Part of Life Cycle] [Ecodesign] [Design for Circular Economy] [Design for Sustainability] [Other]
R		FOCUS	The design focus of the tool regarding the type of the intended outcome of the project	[Product] [Process] [Service] [System]
S		INNOVATION	The potential level of innovation	[Incremental/Product Redesign] [Disruptive/New solutions] [Both]

criterion is essential for academics and those who develop the tools. The most valued criteria are those that are oriented towards the potential/contributions of the tools, such as what their "Purpose" is (1st in the ranking), or the type of "Innovation" they allow to enhance (2nd), or about the scope of the relation with "Sustainability" (3rd). Criteria that have been referenced in the literature as very important and even as inhibitors of the use of tools are also identified as relevant, but with a lower degree of importance, as is the case with "Complexity" (6th) and the other two criteria that relate to it, which are "Time" (8th) and "Sector" (9th). One criterion that was not valued as much as one might expect was "Cost" (11th) and this may be since this survey was not targeted at senior or financial managers.

It is important to highlight that this study focused on validating the definition by designers and not by other professionals who have an active role in the product development process. Further analysis of the reasons for disagreement regarding designers' autonomy, as well as investigation of other aspects of the definition, such as the importance of each component, or the importance of tools for each phase of the design process, can provide valuable information for the development, selection and application of DfS tools more effectively.

The main contributions of this phase of the research - definition and criteria - serves as the basis for the creation of a common and harmonized language that allows better communication, identification and analysis of tools in response to the needs of designers and their projects, enhancing higher use of tools and better guidance in the development of new tools aimed at integrating sustainability aspects into the design process.

The results of this phase of the research allowed the definition of a

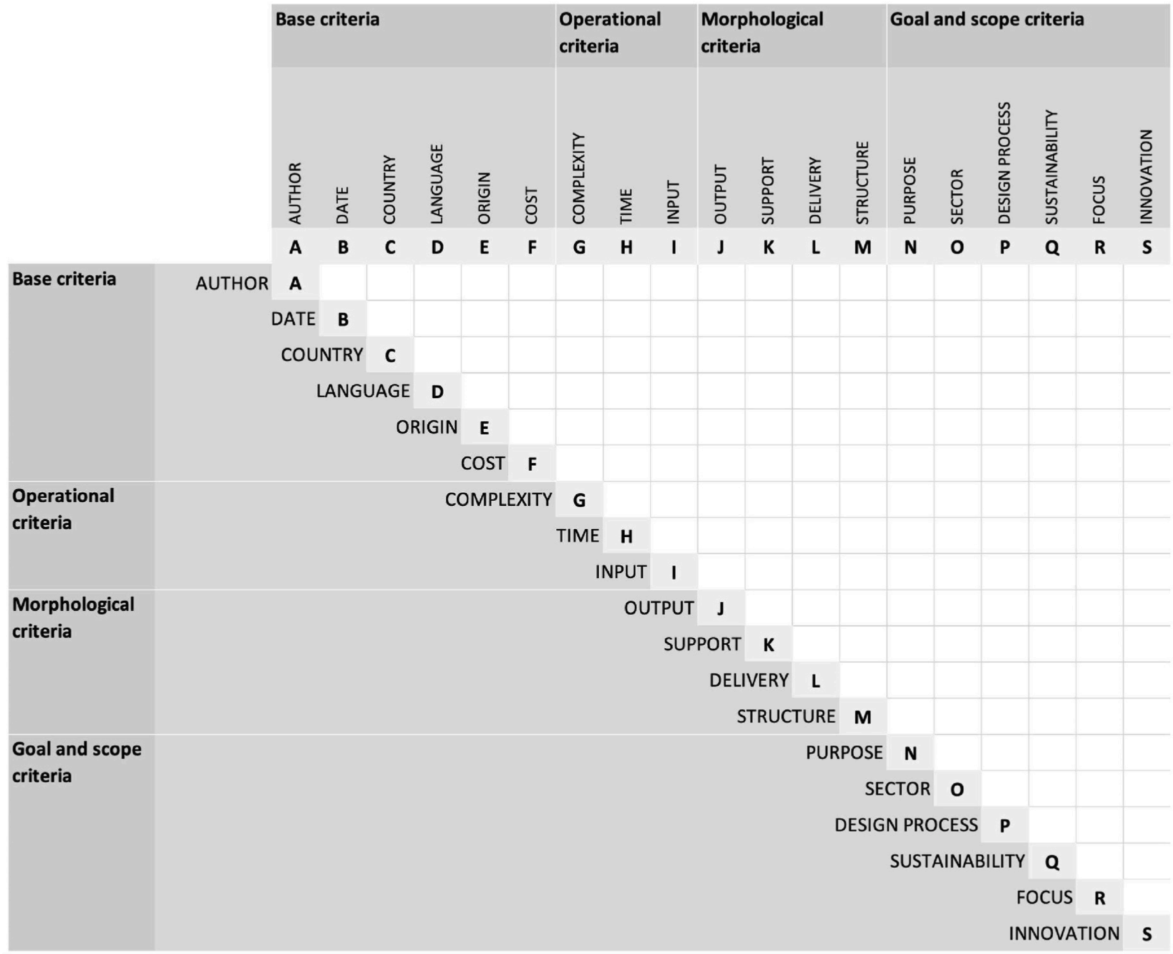

Fig. 3. Criteria evaluation matrix.

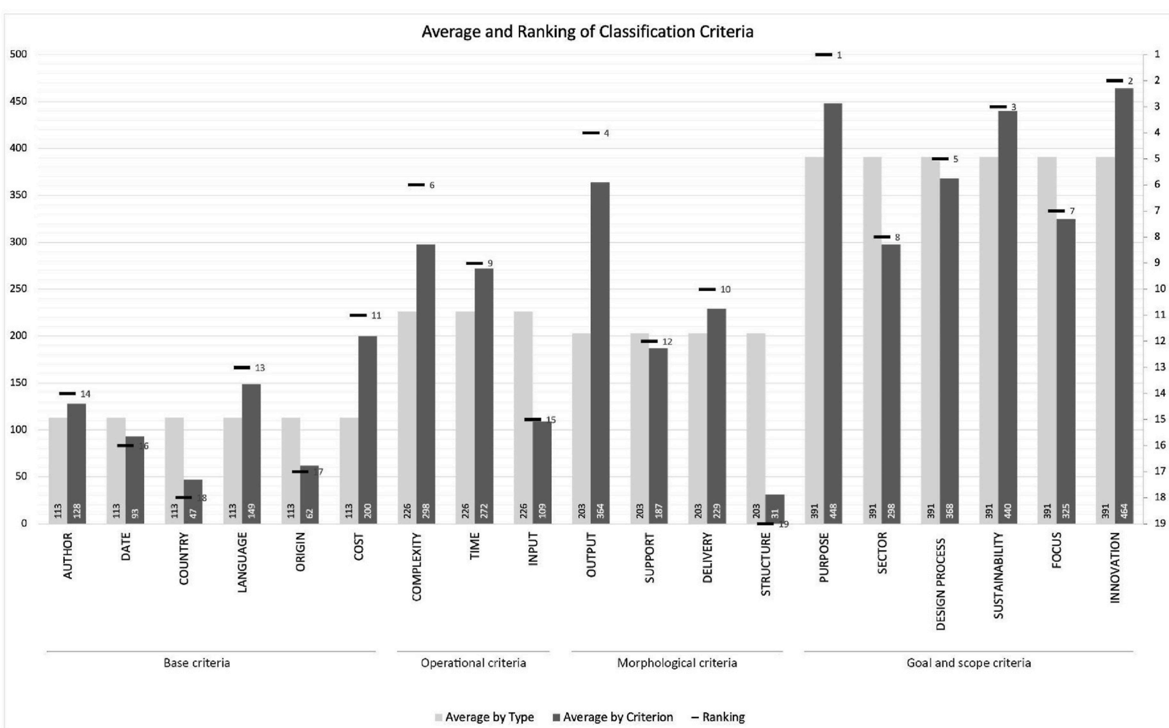

Fig. 4. Results of the evaluation of the classification criteria.

robust basis for the analysis and assessment of the tools that have been widely developed to support the design and development process. In this regard, the next phase in the scope of this ongoing research process will focus on collecting a vast number of tools that are developed and made available for the design community and their analysis and assessment in order to perceive the maturity of its use, identification of barriers and challenges to their adoption and identification of opportunities and guidelines for promoting the wider use of design tools for sustainability in the design process, thus contributing to the creation of more innovative and more sustainable solutions.

CRediT authorship contribution statement

José Vicente: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **David Camocho:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.144041.

Data availability

Data will be made available on request.

References

Bakker, C., 1995. Environmental Information for Industrial Designers. TU Delft, Delft. PhD Thesis. Faculty Industrial Design Engineering.
Baumann, H., Boons, F., Bragd, A., 2002. Mapping the green product development field: engineering, policy and business perspectives. J. Clean. Prod. (10), 409–425. https://doi.org/10.1016/S0959-6526(02)00015-X.
Beskow, C., Johansson, J., Norell, M., 1998. Implementation of QFD: Identifying Success Factors, International Conference on Engineering and Technology Management, IEMC '98. San Juan, Puerto Rico, USA, pp. 179–184. https://doi.org/10.1109/IEMC.1998.727757.
Bovea, M.D., Pérez-Belis, V., 2012. A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. J. Clean. Prod. 20 (1), 61–71. https://doi.org/10.1016/j.jclepro.2011.07.012.
Byggeth, S., Broman, G., Robèrt, K.-H., 2007. A method for sustainable product development based on a modular system of guiding questions. J. Clean. Prod. 15 (1), 1–11. https://doi.org/10.1016/j.jclepro.2006.02.007.
Byggeth, S., Hochschorner, E., 2006. Handling trade-offs in Ecodesign tools for sustainable development and procurement. J. Clean. Prod. (14), 1420–1430. https://doi.org/10.1016/j.jclepro.2005.03.024.
Bhamra, T., Lofthouse, V., 2003. Information/Inspiration: A Web Based Sustainable Design Tool. ICED 03 International Conference on Engineering Design, Stockholm.
Camocho, D., 2022. Transition to Circular and Sustainable Economy through Design. IADE. Universidade Europeia, Lisboa. PhD Thesis. https://comum.rcaap.pt/handle/10400.26/41842.
Catarino, J., Henriques, J., Maia, A., Alexandre, J., Camocho, D., Rodrigues, F., 2007. Manual Valor Sustentável, p. 120. INETI.
Ceschin, F., Gaziulusoy, I., 2019. Design for Sustainability: A Multi-Level Framework from Products to Socio-Technical Systems. Routledge, London. https://doi.org/10.4324/9780429456510.
Chrispim, M.C., Mattsson, M., Ulvenblad, P., 2022. The underrepresented key elements of Circular Economy: a critical review of assessment tools and a guide for action. Sustain. Prod. Consum. https://doi.org/10.1016/j.spc.2022.11.019.
Cross, N., 1989. Engineering Design Methods. Wiley, Essex.
D'Eusanio, M., Zamagni, A., Petti, L., 2019. Social sustainability and supply chain management: methods and tools. J. Clean. Prod. 235, 178–189. https://doi.org/10.1016/j.jclepro.2019.06.323.
De Fazio, F., Bakker, C., Flipsen, B., Balkenende, R., 2021. The Disassembly Map: a new method to enhance design for product repairability. J. Clean. Prod. 320. https://doi.org/10.1016/j.jclepro.2021.128552.
Duberly, H., 2004. How Do You Design? A Compendium of Models. Duberly Design Office, San Francisco.
Erlhoff, M., Marshal, T., 2008. Design Dictionary - Perspectives on Design Terminology. Brikhauser, Basel.
European Commission, 2019. The European green deal, COM(2019) 640 final. Brussels. Retrieved from. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640.
European Commission, 2020. A New Circular Economy Action Plan for a Cleaner and More Competitive Europe. COM/2020/98 final. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN.
European Parliament, 2022. 8th environment action programme - decision (EU) 2022/591 of the European parliament and of the council of 6 april 2022 on a general union environment action Programme to 2030, L 114/22. Retrieved from. http://data.europa.eu/eli/dec/2022/591/oj.
European Parliament, 2023. Proposal for a Regulation of the European Parliament and of the Council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC, COM/2022/142 final. Brussels. Retrieved from. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0142.
Faludi, J., Hoffenson, S., Kwok, S.Y., Saidani, M., Hallstedt, S.I., Telenko, C., Martinez, V., 2020. A research roadmap for sustainable design methods and tools. Sustainability 12 (19). https://doi.org/10.3390/su12198174.
Flipsen, B., Bakker, C.A., de Pauw, I.C., 2020. Hotspot Mapping for product disassembly: a circular product assessment method. In: Schneider-Ramelow, M. (Ed.), Electronics Goes Green 2020+ (EGG): the Story of Daisy, Alexa and Greta. Berlin, Germany.
Ghazilla, R.A.R., Taha, Z., Sakundarini, N., Iskandar, 2008. Eco design tools in product development: review and direction. In: 9th Asia Pacific Industrial Engineering & Management Systems Conference. APIEMS, Nusa Dua. Bali – INDONESIA.
Gómez-Navarro, T., Capuz-Rizo, S.F., Bastante-Ceca, M.J., Collado-Ruiz, D., 2005. Ecodesign function and form. Classification of Ecodesign tools according to their functional aspects. In: 15th International Conference on Engineering Design (ICED). Melbourne.
Gouveia, A., 2024. INDUSTRIAL DESIGN THINKING: Da génese à atualidade - a metodologia de design thinking. Faculdade de Belas-Artes. Universidade de Lisboa. PhD Thesis.
Hemel, C.V., Cramer, J., 2002. Barriers and stimuli for ecodesign in SMEs. J. Clean. Prod. 10 (5), 14. https://doi.org/10.1016/S0959-6526(02)00013-6.
Henriques, J., Catarino, J., Camocho, D., Alexandre, J., 2021. O que é o Valor Sustentável, Contributo para a sustentabilidade empresarial. Enterprise Europe Network, LNEG.
Hillary, R., 2004. Environmental management systems and the smaller enterprise. J. Clean. Prod. 12 (6), 561–569. https://doi.org/10.1016/j.jclepro.2003.08.006.
ILO, 2012. ISCO-08 International Standard Classification of Occupations - Volume 1: Structure, Group Definitions and Correspondence Tables. International Labour Office, Geneva.
ISO, 2010. Guidance on Social Responsibility (ISO Standard No. 26000:2010). International Organization for Standardization, Geneva.
ISO, 2015. Environmental Management Systems — Requirements with Guidance for Use (ISO Standard No. 14001:2015). International Organization for Standardization, Geneva.
ISO, 2024. Circular economy - Measuring and assessing circularity performance (ISO Standard No. 59020:2024). International Organization for Standardization, Geneva.
Jarzabkowski, P., Kaplan, S., 2015. Strategy tools-in-use: a framework for understanding "technologies of rationality" in practice. Strat. Manag. J. 36 (4), 537–558. https://doi.org/10.1002/smj.2270.
Kalita, H., Kumar, K., Davim, J.P., 2021. Current Tools and Methodology for a Sustainable Product Life Cycle and Design, Sustainable Manufacturing and Design, pp. 3–17. https://doi.org/10.1016/b978-0-12-822124-2.00001-9.
Kurt, A., 2021. Models and Tools for the Design, Assessment, and Evolution of Circular Supply Chains. Chemical and Process Engineering. Université Grenoble Alpes. PhD Thesis. https://theses.hal.science/tel-03615489.
Lindahl, M., Ekermann, S., 2013. Structure for Categorization of EcoDesign Methods and Tools. Springer Singapore, Singapore, pp. 117–122. https://doi.org/10.1007/978-981-4451-48-2_19.
Lindgreen, E.R., Salomone, R., Reyes, T., 2020. A critical review of academic approaches, methods and tools to assess circular economy at the micro level. Sustainability 12 (12). https://doi.org/10.3390/su12124973.
Lofthouse, V., 2006. Ecodesign tools for designers: defining the requirements. J. Clean. Prod. 14 (15–16), 1386–1395. https://doi.org/10.1016/j.jclepro.2005.11.013.
Luttropp, C., Lagerstedt, J., 2006. EcoDesign and the Ten Golden Rules: generic advice for merging environmental aspects into product development. J. Clean. Prod. 14 (15–16), 1396–1408. https://doi.org/10.1016/j.jclepro.2005.11.022.
Manzini, E., 2015. Design, when Everybody Designs - an Introduction to Design for Social Innovation. MIT Press, Cambridge.
Marseglia, M., 2017. Design process and sustainability. Method and tools. Des. J. 20 (Suppl. 1), S1725–S1737. https://doi.org/10.1080/14606925.2017.1352711.

Mkrttchian, V., Gamidullaeva, L., Panasenko, S., Sargsyan, A., 2019. Creating a research laboratory on big data and internet of things for the study and development of digital transformation. In: Kaur, G., Tomar, P. (Eds.), Handbook of Research on Big Data and the IoT. IGI Global, Hershey, PA, USA, pp. 339–358. https://doi.org/10.4018/978-1-5225-7432-3.ch019.

OLD, 2023a. Tool, Oxford Learner's Dictionaries. Oxford University Press, Oxford. Retrieved Mai 23, 2023 from. https://www.oxfordlearnersdictionaries.com/definition/english/tool_1.

OLD, 2023b. Method, Oxford Learner's Dictionaries. Oxford University Press, Oxford. Retrieved Mai 23, 2023 from. https://www.oxfordlearnersdictionaries.com/definition/english/method?q=method.

OLD, 2023c. Model, Oxford Learner's Dictionaries. Oxford University Press, Oxford. Retrieved Mai 23, 2023 from. https://www.oxfordlearnersdictionaries.com/definition/english/model_1?q=model.

Pahl, G., Beitz, W., 1992. Engineering Design. Springer-Verlag, Londres.

Patara, S., Dhalla, R., 2022. Sustainability reporting tools: examining the merits of sustainability rankings. J. Clean. Prod. 366. https://doi.org/10.1016/j.jclepro.2022.132960.

Penty, J., 2019. Product Design and Sustainability: Strategies, Tools and Practice. Routledge, New York.

Ritzen, S., 2000. Integrating Environmental Aspects into Product Development Proactive Measures. Royal Institute of Technology-KTH, Stockholm.

Rossi, M., Germani, M., Zamagni, A., 2016. Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. J. Clean. Prod. 129, 361–373. https://doi.org/10.1016/j.jclepro.2016.04.051.

Rousseaux, P., Gremy-Gros, C., Bonnin, M., Henriel-Ricordel, C., Bernard, P., Floury, L., Staigre, G., Vincent, P., 2017. "Eco-tool-seeker": a new and unique business guide for choosing ecodesign tools. J. Clean. Prod. 151, 546–577. https://doi.org/10.1016/j.jclepro.2017.03.089.

Royo, M., Chulvi, V., Mulet, E., Ruiz-Pastor, L., 2023. Analysis of parameters about useful life extension in 70 tools and methods related to eco-design and circular economy. J. Ind. Ecol. https://doi.org/10.1111/jiec.13378.

Schäfer, M., Löwer, M., 2020. Ecodesign—a review of reviews. Sustainability 13 (1). https://doi.org/10.3390/su13010315.

Schwartz, B., 2016. Paradox Choice: Why More Is Less. Harper Collins, New York.

Sherwin, C., 2000. Innovative Ecodesign - an Exploratory and Descriptive Study of Industrial Design Practice. The School of Industrial and Manufacturing Science. Cranfield University. PhD Thesis.

Varžinskas, V., Kazulytė, I., Grigolaitė, V., Daugėlaitė, V., Markevičiūtė, Z., 2020. Eco-design methods and tools: an overview and applicability to packaging. Environ. Res. Eng. Manag. 76 (4), 32–45. https://doi.org/10.5755/j01.erem.76.4.27448.

Vicente, J., 2012. Contributos para uma metodologia de design sustentável aplicada à indústria do mobiliário. PhD Thesis O Caso Português. Faculdade de Arquitectura. Universidade Técnica de Lisboa, Lisboa. http://hdl.handle.net/10400.5/5645.

Vicente, J., Camocho, D., 2023. Design for sustainability tools: categories of classification towards practical use. In: Ahram, T., Falcão, C. (Eds.), Human-Centered Design and User Experience AHFE (2023) International Conference. AHFE International, USA. https://doi.org/10.54941/ahfe1004220.

WDO, 2015. Definition of industrial design, WDO. Available at: https://wdo.org/about/definition. (Accessed 8 September 2024).

Witkowski, K., 2017. Internet of things, big data, industry 4.0 – innovative solutions in logistics and supply chains management. Procedia Eng. 182, 763–769. https://doi.org/10.1016/j.proeng.2017.03.197.