DESIGN OPTIMIZATION FOR ENVIRONMENTAL SUSTAINABILITY: A FRAMEWORK TO SELECT THE BEST ECO-DESIGN STRATEGY

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ABSTRACT

Environmental sustainability represents an unavoidable design driver. The consciousness of the importance of tackle the topic of environmental sustainability since the first stages of the product lifecycle is slowly spreading through enterprises. However, although they reach this grade of awareness, it is hard to introduce additional considerations to the traditional drivers of functionality, manufacturability, assembly, cost, etc. Therefore, it is crucial to identify methods and tools to support companies in efficiently integrating environmental sustainability issues in their design process. This paper proposes an approach to identify the inputs, functionality and outputs suitable to each industrial reality. Its core is the eco-design tool matrix, that estimates the tool implementation time and suggests proper outputs; from this the necessary inputs and functional blocks are derived. The approach is applied to the cases of two Italian industries, very different one another. This proves the wide applicability of the approach. The definition of a validation procedure represents the next steps to identify the benefits of the approach.

Keywords: Ecodesign, Design process, Design management, Design methodology

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1 INTRODUCTION

The development of eco-design methods and tools allows for satisfying quite heterogeneous issues of the design process (Cappelletti et al., 2022a), from the acquisition of preventive information about environmental or circular performance to the intersection of value chains for the sake of sustainability (Cappelletti et al., 2022b). There are multiple solutions for designers in the literature, even though it is reported a lack of benchmarks to evaluate the performances of methods and tools (Ghandi et al., 2015). A tool can be either simple guidelines (Favi et al., 2016; De los Rios et al., 2017) or a software tool (Stavropoulos et al., 2010); some implement mathematical models (Steeneck and Sarin, 2018), others fuzzy graph approaches (Li et al., 2008) Multi-Criteria Decision-Making (MCDM) or Knowledge Based Engineer (KBE) (Talents et al., 2019). Among the benefits of having eco-design tools available, there is the chance for designers to acquire lifecycle thinking directly by applying its principles. Although a lack of integration and standardization among existing tools is claimed (Arnette et al., 2014; Williams, 2014), it is very common to encounter new, customized tools showing up.
The present paper proposes a process to support companies in defining the main features and functionalities of a customized eco-design tool to use inside their design departments with the objective of analysing and improve product environmental performance.

1.1 Tailored tools

The widespread need for eco-design tools means that the importance of the decision made at the design stage is confirmed and has become a consistent awareness in the industrial sector. In addition, several reasons make environmental sustainability a driver that urges to be accounted for in the design process. Unfortunately, the need for eco-design is mainly triggered by external factors (policies, customers, competition) and enterprises struggle to introduce and apply eco-design strategies (Dekoninck et al., 2016; Pigosso et al., 2016).
For the time being, no tool is widely chosen and preferred compared to other eco-design tools.
In this context, organizations prefer having a tool tailored to their need, instead of making a significant investment and having to accomplish the existing features of commercial tools.
Three are the main reasons behind the choice of a custom tool instead of buying one:

- Initial investment and upgrade costs;
- Compatibility and integrability with the industrial (design) process;
- Grade of customization.

In fact, the quantification of environmental burden influences design choices (Züst et al., 2016), as assessing potential environmental impacts (EI) during the early stages of development, it may help designers to integrate environmental considerations against other product requirements (Parolin et al., 2012). The following factors set themselves naturally as what empowers a customized tool against a commercial one:

- the opportunity to align datasets to the specific process instead of relying on general, mean process data;
- the tailored tool structure, both related to the main functionalities and the integration with other tools employed in the design process;
- the higher usability for the user, as functionalities are customed and similarly is the User Interface (UI).

1.2 Eco-design tools

A tool developed in-house (with or without the support of environmental and Information Technology (IT) experts), even if the main goal is to apply the Circular Economy (CE) principles and/or to increase the attitude of designers towards lifecycle thinking, has a specific objective when developing an eco-design tool. The outputs that eco-design tools may generate can be classified into five main categories:

- Values, when punctual information is provided (i.e., when environmental impacts for specific impact indicators are given);
- Index; when project data are arranged to obtain summary indicators;
- Guidelines, when according to the product features, and indications are given;

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- Differential, percentage indications, when any complete analysis is carried out, instead only for specific critical parameters is evaluated whether an improvement or worsening is registered;
- Similar to the guideline, feedback shows whether what has been designed accomplishes certain set standards and thresholds. Differently from the guideline, feedback is an advisory on what has been already decided and negative feedback requires a revision of choice; instead, the guideline is advice that the designer can choose to follow or not before making a decision. A guideline has a more general validity and a more preventive attitude to avoid uneco-friendly choices.

The scalable design for costing platform proposed by Mengoni et al. (2016) presents a practical case of applying a robust Knowledge-Based (KB) system that can estimate costs from feature-based 3D CAD models. In doing so, KB rules mapping manufacturing processes and modeling features are at the base of the guidelines provided to the user, such as *Avid sharp internal corners in milling operations or Guarantee alignment of hole axes in assembly operations.* The platform checks the CAD features and the rules; whenever those are not respected, the guidelines provide alternatives or corrective actions. Feedback instead outlines what is discovered during the analysis that presents criticalities. For example, *Harlè et al. (2021)*, in their model to design new rules and create a heritage for industry, provide feedback to the designer: in the case of a sanbox that presents leakages, the feedback says that *the sanbox lets the water pass:* this doesn't provide alternatives to the user; however, outlines criticalities in the analyzed system. Conversely, the results from the simulation of the framework for predicting potential product impact during product design shown by *Mabey et al. (2021)* provides indexes that summarize the specific results (i.e., Mean and σ are given).

Table 1 shows five examples of eco-design tools in-house developed by companies; academies supported some enterprises in developing the tool, especially in building the knowledge behind it.

Table 1. Eco-design tools description and output classification.

Ref	Tool description	Output
Cappelletti et al., 2022b	Tool to establish synergies for Industrial symbiosis and find sustainable EoL alternatives to (composite) materials	Differential, % indications Value Feedback
Parolin et al., 2012	AEco: fast and versatile tool for assessing aircraft EI. Streamlined LCA algorithm implemented to assess cradle-to-grave life cycle impacts quickly and to compare different aircraft configurations and scenarios	Value
Harlé et al., 2021	*Model to design new rules and create a heritage for the industry*	Feedback
Mengoni et al., 2016	Scalable design for costing platform	Guidelines
Tao et al., 2018	Feature extractor from CAD, calculates EI for multiple scenarios	Value
Cappelletti et al., 2022 c	Analytical Tool to Support Decision Making in building design (Greenbuild)	Value, Differential, % indications
Mabey et al., 2021	Framework for predicting potential product impact during product design	Index
Rossi et al., 2022	Tool for conceptual eco-design	Differential, % indications

1.3 How to define the good tool

A commercial tool may require relatively low effort in the first stages of introduction in the design process, but in the second place may not accomplish the user needs. Oppositely, when developing an in-house tool, most difficulties are faced first, as countless tools may have any architecture and provide different outputs. The tool structure and main features definition can be a bottleneck for the enterprises if they are not supported by a mixed team of software developers and environment experts, that may guide them through the compromise that best fits their requirements.

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In this context, this paper proposes an approach based on the eco-design tool matrix. The presented approach is based on two main steps: I. the eco-design matrix support; II. The functionalities blocks identify. It is willing to support the decision-making process in the first stages of tool features and functionalities characteristics (Section 2). The approach is then applied to two different case studies in Section 3.

2 APPROACH

The definition of an eco-design tool's main functionalities can be very challenging for enterprises whose core activities consist in designing, producing and commercializing products (of different natures). Nevertheless, the policies and customer requirements make the eco-design tools necessary to accomplish environmental product requirements and the willingness to have available a tool that best fits the organization’s need makes it necessary to develop it in-house.

This section describes an approach able to guide the process of defining the main features and functionalities of the eco-design tool. The approach rises from the eco-design tool matrix, shown in Table 2. The matrix has the purpose of rationalizing the multiple aspects that are important but come from different demands. Those are clustered into 7 main categories, each further detailed in 3 or 4 sub-categories that may describe a real condition more accurately. Each category will be further explained in the next paragraph.

Different roles can be in charge of following the approach, even from different backgrounds. Likely a team goes through the matrix. The team's composition may vary and can involve designers, product and project managers, marketing managers, tool developers; also outsourced resources may be involved.

Besides their role in and outside the organization, the first step that the team carries out is the analysis of the eco-design matrix. The matrix is symmetric; however, its content may be read in two different directions, described in the upper left cell:

- Output: if the matrix is read from lines to columns; the output is above the diagonal and cells are filled in light yellow. The matrix relates the line and column elements and suggests the preferable output for the case. In addition, the matrix considers the classification of output previously presented in paragraph 1.2.
- Implementation time: if the matrix is read from columns to lines; the originating information is below the diagonal, and cells are filled in light blue; the outcome is an estimation of the time that may take to develop the tool: short (S) term when it takes days or few weeks, Medium (M) when several weeks up to 2/3 months are needed and Long (L) term when up to one year of more is needed.

The team should go through every horizontal matrix category and identify the intersecting cell per every vertical category. Every intersecting cell contains an output of the matrix related to the output type of the implementation time. While retrieving each line, the main categories and the sub-categories are encountered: at least one sub-category must be applied to the team case; per one topic, more than a single sub-category may apply. The numerosity of acronyms obtained by intersecting the sub-categories that apply to the case should be counted.

In the end, those with higher numbers reveal the type of output the tool should obtain and an estimation of the time needed to develop the tool. In accordance with the suggested outputs, certain functional blocks should be investigated, as shown in Figure 1 and further described.

A simplified example is provided, where only a few categories are analyzed to show the workflow. The company is willing to provide customers with a tool that supports them in choices the material for their customized product by introducing tips about the environmental sustainability of the available materials. The sub-categories that apply to the case are e*nvironmental impact, material choice, sale* and *custom;* the first two refer to the *objective* category, and the remaining to *when, user and product structure,* respectively. When entering the matrix from raws, the intersection between the sub-category fall in cells containing 1V, 7 %, 7 F, 5 G, 4 I; therefore, the suggested output are percentages that compare materials and feedback. This complies with the role of the user, who might not have a technical background and may not be an expert in the field of sustainability. Reading the matrix in the opposite direction is expected to have a medium-term to develop the tool (7 intersecting cells for M, against 3 S and 1 L). The eco-design matrix is intended to be used when there is the need to develop an eco-design tool for which the main objectives are identified, but it is not yet clear how outputs

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should be chosen, per the case peculiarities. The outputs of the eco-design matrix are then employed to scout the functionalities and input that would characterize the tool.

Table 2. Eco-design tool matrix

Eco desgign matrix		Objective			When			User			Company			Product Structure			Product complexity		SW integration			
Outout / Implementation time		Environmental impact	EoL strategies eval.	Material choice	Sale	Conceptual design	Virtual prototyping	Environmental expert	Engineer/designer	Customer	Worldwide located	Single, big	Single, small	Standard	Custom	Modular	Simple	Complex	None	LCA	CAD	ERP/MES
Objective	Environmental impact	-	All	V, %, F, G	I, %, F	I, G, F	V, %, F	V, I	V, I, G, %	I, %, F		N/A		V, %	V, %	V	V, I, F	I, %, G	I, G	V, I, F	V, I	I, %, F
	EoL strategies evaluation	M	-	I, G, % F	I, %, F	I, G	I, G, %	V, I	V, I, G, %,	I, %, F	I, G, %	V, %, F	V, %, F	G, %	I, G, F	G, F	N/A		N/A	V, %	I, G, F	I, %
	Material choice	M	S	-	G, %, F	G, %, F	V, I, F	V, I, F	V, I, G, %,	I, %, F	I, G, %	V, %, F	V, %, F		G, %, F		V, I, G, F	I, %, G, F	V, I,	V, I, F	V, I, F	N/A
When	Sale	M	S	M	-	I, %, G	N/A	N/A	V, %, G, F	%, G, F		N/A		V, %	G, %, F	G, %, F	G, %, F	G, F		N/A		
	Conceptual design	M	M	S	S	-	All	G, %, F		%, G, F		N/A			G, %, F		G, %, F		G	V, G	N/A	N/A
	Virtual prototyping	M/L	L	M/L	N/A	S/M	-	V, I, F	V, I, %, F	N/A		N/A		V, G, F	I, G, F	G, %, F	V, G, F	G, %, F	I, G	V, F	V, %, F	V, %
User	Environmental expert				N/A	S/M	M/L	-	V, %, F	I, G, %, F		N/A			V, %, F		V, F	I, G, %	I, G	V, I, F	V, %, F	V, %
	Engineer/designer						L	L	-	N/A		N/A		V, G	I, %, F		V	I, G	I, G	V, F	V, G, F	V, %
	Customer	S/M	S	S	N/A	S/M	N/A			-		N/A		N/A	I, G, %		N/A		G, F	V, F	N/A	
Company	Worldwide located				N/A	M	L	M/L	L		-	N/A		G	I, %, G	I, %, F	I, G, %	G, %, F	G, F	V, F	I, V, F	I, V, F
	Single, big	S/M	M	M/L							N/A	-	N/A	G	I, %, G	I, %, F	I, G, %	G, %, F	G, F	V, F	I, V, F	I, V, F
	Single, small	S/M	M	M/L							N/A		-	G	I, %, G	I, %, F	I, G, %	G, %, F	G, F	V, F	I, V, F	I, F
Product Structure	Standard	M	S	S	S	S	M				M/L	M/L	M	-	N/A	I, %, F	V, F	I, G	G, F	V, F	V, I, F	V, I, F
	Custom	M/L	M/L	M				L	M/L	S/M	M/L	M/L	M/L	N/A	-	I, %, F	V, G, F	G, %, F	G	V, %, F	V, %, F	G, %
	Modular	S/M	M/L	S				S	M/L	S/M	M	M	S	N/A		-	V, G, F	G, %, F	G, %	V, %, F	V, I, %, F	G, %
Product complexity	Simple	S/M	S/M	S/M	S	S/M	M		M/L	S/M	M	M	S	S	M	M	-	N/A	I, G, %	V, %, F	V, %, F	G, %
	Complex	M/L	M/L	M/L	M	M	L	M/L	L		L	M/L	S/M	M	L	M/L	N/A	-	G	I, %, F	V, I, %, F	G, %
SW integration	None	M	M	S	S	S/M	M	S	S/M	S/M	N/A					S	S/M	S/M	-		N/A	
	LCA	M	M	M	S/M	S/M	L	M/L	M/L	M	L	M/L	M/L	M	M/L	M	M	M/L	N/A	-	N/A	
	CAD	M	M	M	N/A	N/A	M/L		M/L			M/L		M	L	M/L		L	N/A		-	N/A
	ERP/MES													S/M	M/L	M	M	M		N/A		-

2.1 Matrix categories

In the following, the main features that pave the way to the tool development are described:

- The objective includes the primary purposes the tool is needed for; in fact, although the matrix is intended for an eco-design tool, there are differentiations. Some enterprises focused on revealing in advance, since the design phase, the product lifecycle environmental impacts; while some others are more interested in evaluating whether their choice enables proper management of the product EoL (EoL strategy evaluation); a third class wants to join the material properties and their environmental performances, to choose the best compromise (material choice).
- The category "when" refers to when the tool is expected to be used in the design process. They may be used together with the customer, during the negotiation, or product functionalities definition (if the good is customized as in the case of Greenbuild (Cappelletti et al., 2022c), after the order is received, or when the product is sketched (Conceptual design). By sale, it is not just meant the distribution of the product, but also the negotiation phase, when customizations are evaluated by the customer. In this case, the final user is directly involved in making choices, not just relying on his aesthetic preferences or functional features but also paving the way to a less impacting product lifecycle. The earlier the tool supports the product design, the easier it is to make changes to the project; unfortunately, in the early stages, there is not much information: if more accurate data are desired, the tool should be used during the product Virtual Prototyping.

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- The user is one of the most critical aspects that highly influence the tool's outcome. Whether the user is an environmental expert, a technician (engineer/designer) or a customer, the tool may provide very different output: punctual values and guidelines may be helpful for the firsts, but customers and the less specialized users should receive comparative or qualitative information; otherwise, they would not be able to interpret and adequately use the outcomes. If the tool is intended for an expert on environmental sustainability, detailed data should likely be retrieved; this may lead to longer development time, as the information acquisition (i.e., effort in populating database).
- How the company is organized may have an important role in the tool features definition; sometimes, this is also related to the product's nature and structure. In a small, single-located company, a single division is likely responsible for the product design, while in a bigger one, the design process may include multiple roles, also from different backgrounds. Multinational companies worldwide located, may even require a single tool that would accomplish the needs of all the realities that belong to the group.
- If a product is quite standard and not customized, it is easier to obtain values, and similarly it can be said for modular products, where outcomes may come from the linear addition of modules' contribution; differently, for personalized products is more difficult to obtain single values, as results cannot be retrieved from previous versions. These features are considered in the product structure class.
- The product complexity is willing to discern whether the product is perceived as complex (high numbers of components, multiple suppliers. multiple assemblies with different functions), or not; the simpler the product is, the more likely it is to get punctual information.
- Ultimately, a critical point is a desire to integrate the tool with others or to make it stand alone. The integration may largely elongate the implementation time but can also reduce the use time (i.e., lower data to gather). The main common integrations are with LCA software (to retrieve EI),
  with Computer Aided Design (CAD) systems to automatically retrieve geometrical information, or with management software to get information about the supply chain or further product life cycle phases. Enterprise Resource Planning (ERP) and Manufacturing Execution System (MES) are IT structures that allow the control and management of the production processes; thus, their role would consist of a data lake from where live or processed data can be retrieved.

When N/A is filled in cells, there is no relation between the two sub-categories; for instance, no iteration happens between the customer and designers during the virtual prototyping phase, as this is a technical step and the customer has already set his features. Moreover, the information that is useful to them is different, as different are their background. For example, although they would need basic data about environmental sustainability because they are not experts in this field, the engineer may need feedback highlighting the hotspot the designer can impact. At the same time, the user should be pervaded with information and tips related impacted by his behavior. Also, the size of the company and its location don't force any specific output according to who the user is and when the tool is used. Differently, empty cells, that can be found in the matrix side dedicated to the implementation time, mean that the relation between the sub-categories in the raw and column does not elongate nor guarantee short timing.

2.2 Functional blocks

Figure 1 shows the main input and functions that each kind of tool expects. The outputs are shown above the line of each output; the main possible functionalities are below. Necessarily, a single tool may provide more than a single kind of output, thus functional blocks should be implemented. The inputs and functionalities listed in the picture have been selected by analyzing the tools retrieved in two previous reviews by Rossi et al. (2016) and Cappelletti et al. (2022). Figure 1 may not provide the full range of existing eco-design tools; nevertheless, the two sources provided a high number of tailored-made eco-design tools. Besides potential implementation obstacles, defining a set of useful functionalities is important, as when designing software, an increased functionality can negatively affect usability as the software becomes more complex to use (Farzaneh and Neuner, 2019).

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3 BUSINESS CASES

This section deals with the description of the application of the approach to two industrial cases. Those were chosen for their big differences. The focus is not much on the tools that have been developed after employing the eco-design matrix, rather the main goal is to highlight its potentialities in discerning different needs and leading the user toward the solution that best fits the case.
Both companies produce mechatronics components. The first one is further addressed as Company 1 and produces electrospindles. It is located in the center of Italy. The design and production site are placed in a single plant. The Original Equipment Manufacturer (OEM) relies on a few additional branches; however, they are only responsible for the commercialization of the electrospindle.
The second, further addressed as Company 2, is a multinational group located in Germany; it has a plant in the center of Italy, however the enterprises that belong to the group produce machines for multiple purposes, from the pharmaceutical sector to the personal hygiene sector.

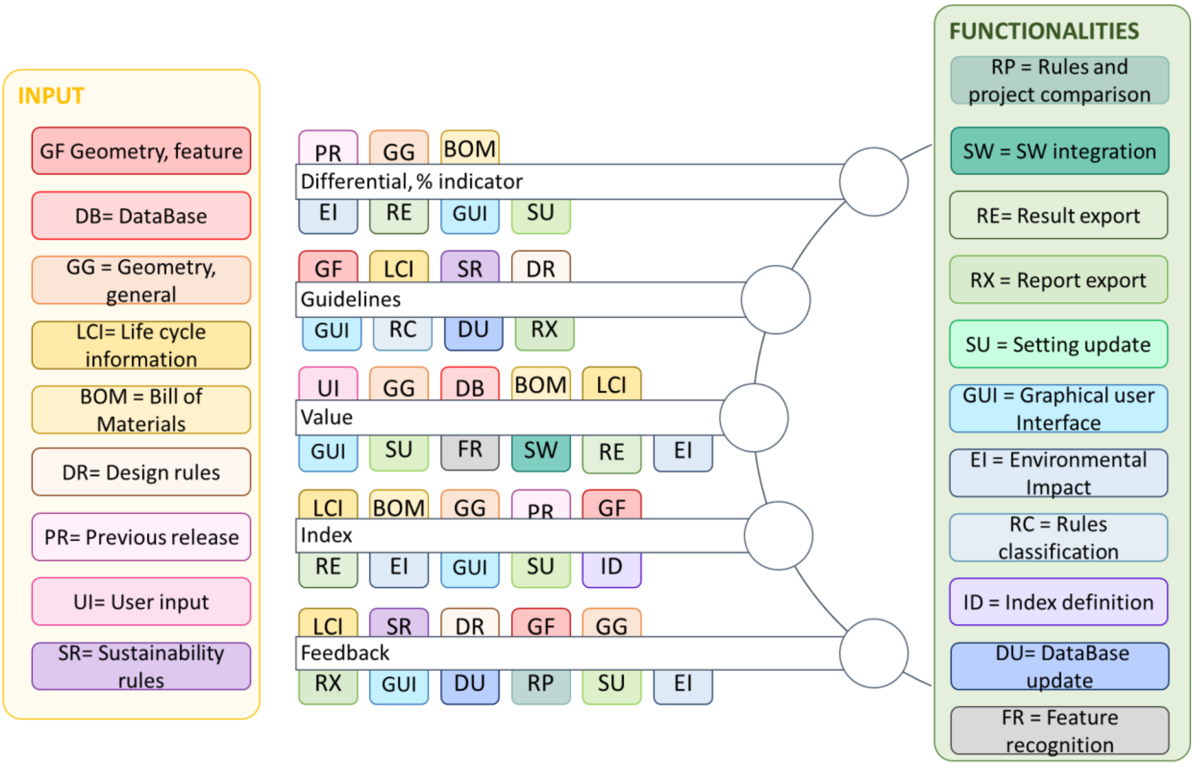

Figure 1. Tool input and functions definition, according to the output

Starting from the information relating to the organization structure, is it possible to affirm that the sub-category single-small applies to Company 1 and *Worldwide located* to Company 2. Furthermore, it can be stated that the electrospindle is a relatively *standard* product and *simple* in its structure. The sub-category *standard* does not mean that it is a mass product; instead, it depicts a product with certain recurrent modules or assemblies. The categories and sub-categories are assigned from the direct contact between the academy and the two industrial realities: unstructured interviews investigate the companies' dimensions, locations and business models. Moreover, the products they commercialize were also analyzed to discern whether they are standard products, how many parts are made of, if the customer commits a project behind their production, or if the company offers a completed solution to the market. As far as Company 2 is concerned, the vastness and variety of served sectors lead to the choice of *custom*, *modular* and *complex* sub-categories. Table 3 summarizes all the categories of the eco-design tool matrix that describe the two companies; those are the lines and columns considered when using the eco-design matrix. The cells that intersect the lines and columns of the sub-categories contain indication of output (superior diagonal) or expected implantation time (inferior diagonal). The numbers indicate the time the intersecting cells contain those values and indication of time. For example, *V* appears in all intersecting cells but *single small* sub-category. From the intersecting cells of the remaining sub-categories that comply with Company 1, 19 times is obtained overall. The bolded values are the highest and thus represent what should characterize the upcoming eco-design tool. The

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outputs are also inputs for identifying the main inputs and functionalities (retrievable in Figure 1). Both enterprises are willing to develop tools for machine designers; the objective is to support the designers in the design phase introducing the environmental drivers next to the functional, and economic. By doing so, they would have support in evaluating the goodness of their choices from the environmental perspective and integrating the tool with the CAD system. However, further different aspects lead Company 1 to obtain values of EI, to calculate sustainability indexes and to get feedback from the analysis; instead, according to the approach, Company 2 should focus more on obtaining comparisons among modules or versions of the machines instead of punctual values. This is mainly due to Company 1's product simplicity (an electrospindle) and the complexity and inhomogeneity of Company 2's machines; in addition, the wish to build a tool that would fit all the design processes of the subsidiary companies. As the implementation time is concerned, this is longer in the case of Company 1, although the development process in Company 2 is expected to last more than half a year.

Table 3. Eco-design tool matrix results for Company 1 and Company 2

		Company 1	Company 2
Sub-categories		Environmental impact	Environmental impact
		EoL strategies evaluation	Conceptual design
		Virtual prototyping	Virtual prototyping
		Engineer/designer	Engineer/designer
		Single, small	Worldwide located
		Standard	Custom
		Simple	Modular
		CAD	Complex
			CAD
Output	V	**19**	12
	%	12	**18**
	F	**16**	**18**
	G	12	12
	I	**14**	14
Implementation Time	S	6	2
	M	**15**	12
	L	9	**14**

Figure 2 shows the workflow for the tool developed in company 1, whose main functionalities have been identified by applying the eco-design matrix. More insight into the tool currently investigated in Company 1 can be found in Cappelletti et al. (2022d).

The developing process in company 2 is currently under definition. Following the input and functional blocks suggested in Figure 1, the Bill of Materials (BOM) is an input; however, since the integration with the CAD system is also desired, the BOM will be substituted with the information retrieved from the virtual model of the product that is being designed. This is a convenient solution, as the BOM may not be available before the design phase is done.

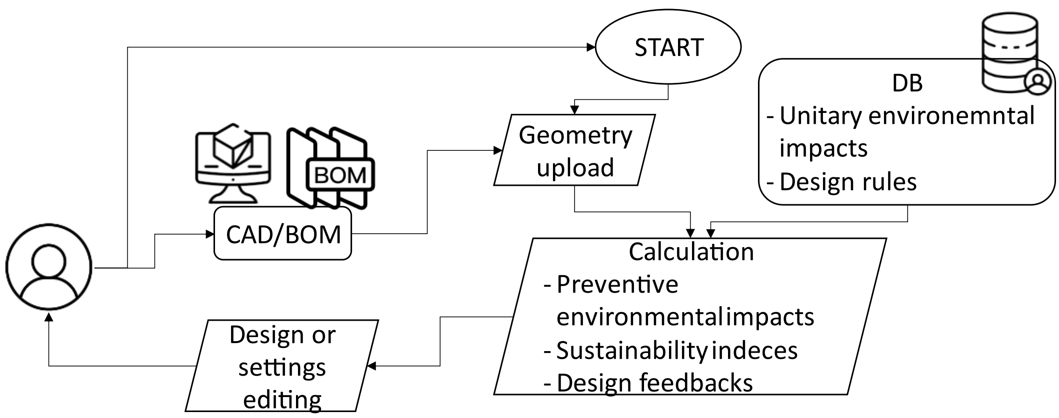

Figure 2. Workflow of the tool developed in Company 1.

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4 RESULTS AND DISCUSSION

Based on the eco-design tool matrix, the paper suggests an approach for assisting the decision-making process in the early phases of tool features and functionality characteristics The approach aims to help companies find the compromise that best satisfies their needs, the tool structure and major feature definition. Because when it comes to designing an internal tool, the most significant challenges are encountered early on because the tool may theoretically have any architecture and produce different output, whereas a commercial product initially requires relatively little effort but fails to meet user expectations later. The case studies presented were introduced to verify the effectiveness of the proposed approach. This approach is valid for different business realities with different requests and needs, as well as The primary goal of the business case is to highlight the tool's potential for identifying various needs and guiding the user toward the best possible answer. This allowed both cases to understand the needs and systematically arrive at an optimal solution. The eco-design matrix is an offline tool; thus, it does not require much effort to update or upgrade. Entities that use it are those willing to develop a customized tool. It is well known that those required much effort in upgrading and maintenance activities. As the functionalities suggested by the eco-design matrix may highly differ, additional categories may be added, to discern their differences. For example, the maintenance category could encompass the sub-categories of updating, upgrade, and scalability, as a tool linked with CAD software needs more dedication in keeping the link working as new versions are released. The maintainability of a software is a critical issue because the risk of working on outdated data can lead to analysis and incorrect forecasts. A limitation of this tool that can also be interpreted as a potential is the possibility of expanding the requests, based on market demands and functionalities, based on future technological developments.

5 CONCLUSION

This work presents an approach to guide the definition of features and functionalities of eco-design customized tools. The presented approach is based on two main steps. The eco-design matrix supports the first: the team that is willing to develop the tool enters the matrix by knowing the organization's structure, the nature of the product, the user and the objective the tool is intended to be developed for. The output of the matrix is reported in the cells of the matrix. The content of intersections of lines and rows of the sub-categories that apply to the case should be highlighted or reported. Even though the matrix is symmetric two different outputs are retrieved. The second step aims at identifying the main functionalities (blocks) to develop and the potentially needed input. The approach is applied to two industrial cases; this highlights the wide applicability of the approach, as the two industrial realities are very different from one another.

The present approach overcomes the present obstacles enterprises encounter in introducing the environmental sustainability driver in their design processes. The eco-design matrix leads industrial teams in the first steps of eco-design tool development, when the functionalities, the input and the functional blocks have to be chosen. The eco-design tool matrix, in accordance with the company and product structure and the tool's purpose, suggests the most appropriate output the tool should provide and qualitatively estimates the time to develop and implement the eco-design tool. Validation of the approach will be possible after the development of software tools for the selected company. The definition of a validation procedure represents the next steps.

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