Lay the foundations for building a Robust eco-design methodology

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Abstract. This paper presents and discusses the possible theoretical bases of a comprehensive approach of robust eco-design to reduce the variations of the environmental impact of a product, compared to the baseline. The goal is to overcome the main limitations of contributions to the state of the art, i.e. the lack of a single approach to treat all possible causes, practical application and rigor in discussing the issues of environmental sustainability. The proposal is the intersection between eco-assessment, design theories and robust design. The eco-assessment provides the basis for an initial formulation of the environmental problems to be faced, which are correlated to the variation of the impacts. The design theories allow, through their ontology, to reformulate environmental problems in a more appropriate way to be addressed by the designer and at the same time provide, together with the robust design methods, suggestions to search the solutions. The analysis presented and the application proposal help to show the complexity and heterogeneity of the topic and reinforce the idea of introducing a systematic methodology to select the most appropriate method and favour its targeted use.

Keywords: Robust eco-design, Robust design, Design theories, Eco-design.

1 Introduction and State of the Art

The variations of the environmental impacts of a product or a process compared to the esteemed value, because of a sudden and unforeseen phenomenon, can also be very consistent and cause very serious problems on the eco-system. Consider, for example, the consequences of accidents in nuclear power plants or oil tankers.

It cannot be said that approaches, theories, methods and tools have not been proposed to improve products by making them more resistant to failures, e.g. Robust Design, Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), etc.

However, their focus is not to manage problems from a point of view strictly connected with environmental sustainability, unlike the reduction of environmental impacts which is instead supported by different specific Eco-design approaches.

Most of the methodological proposals that explicitly refer to the reduction of the variability of environmental impacts are substantially modifications of the more general methods of failure investigation.

Approaches dedicated to avoiding the environmental effects deriving from product failures are mainly based on FMEA (e.g. [1]; [2]; [3]), using it individually or within wider methodologies, such as Life Cycle Assessment and Lean Six Sigma. In them, the canonical modality of the FMEA is exploited to derive the failures, passing through the determination of the Failure Modes, which are typically obtained by brainstorming, starting from the list of product components or its functions. What changes, however, is the way in which the risk associated with certain failures is evaluated. Instead of using a purely numerical index, correlated to standardized severity factors for human health or for the realization of product requirements, in this case, the risk is assessed by using environmental impact indicators. Therefore, with problem solving activities, the possibility of occurrence of the most impacting failures is reduced or eliminated by improving the product. Some alternatives prefer other methods to the FMEA such as the FTA or the Analytical Hierarchy Process - AHP (e.g. [4]).

There are also other approaches that aim to reduce the variations in environmental impacts resulting from the influences of the external environment. Some of them provide suggestions obtained in an empirical way by analysing certain products (e.g. [5]; [6]). Others based on the Resilience theory (e.g. [7]; [8]) propose more qualitative and less specific suggestions. Still others considered Robust design (e.g. [9]), which can be considered the quantitative counterpart of the Resilience theory. Its main advantage in this field is the very broad analysis of many influencing factors that are also very different from each other and the analysis perspective extended to the entire life cycle of the product.

Finally, there are the approaches aiming to eliminate the environmental effects resulting from the misuse of the product caused by the user. This topic was particularly discussed in design theories and mainly concerns the design of the user-product interface (e.g. [10]) and the introduction of affordances [11], which are the qualities or properties of the product that define its possible uses or make clear how it can or should be used.

However, despite the many efforts spent and the many proposals, these methods still have some limitations.

- Robust design has been criticized for focusing mainly on the manufacturing phase and a certain difficulty at the application level, perceived above all by industry, due to the lack of pragmatism [9].
- In empirical approaches there is a strong relationship with a certain product, the surrounding conditions are rather stringent and the few environmental situations that have been tested make their results difficult to reuse and generalize.
- In general, the attention to environmental sustainability is rather marginal, often treated in an implicit, superficial, or totally neglected way. For these reasons, it is difficult for the designer to understand what to intervene on [12].
- Finally, in the literature there is no single approach to address all the possible causes of impact variations, but only some.

This paper discusses on a theoretical level how the integration of Eco-assessment, Design theories and Robust design should be integrated to build a structured methodology of robust eco-design, to reduce the variations of the environmental impacts, by overcoming the current limitations.

2 Proposal of integration: theoretical discussion

From the analysis of the proposals at the state of the art, no problems arise with current methods such that they must be modified or replaced.

However, to face the problem of reducing the variations of the environmental impacts in a pragmatic and comprehensive way, it is necessary to guide the designer in choosing the right method to use and to provide rigorous environmental considerations to allow their more targeted use of the methods.

For this reason, any application proposal should work at the intersection between eco-design, design theories and robust design (see Fig. 1). In it, the eco-assessment should provide the basis for the selection of design or robust design methods as appropriate, and their solutions.

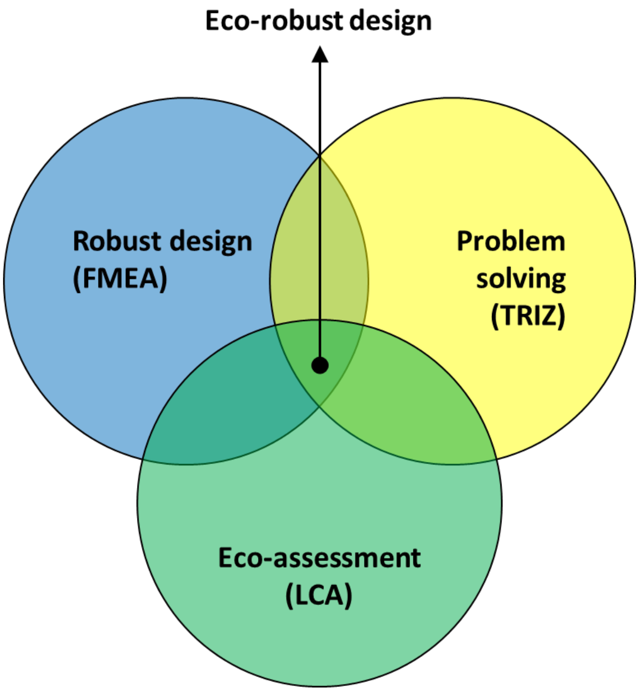

Fig. 1. The problem of the reduction of the variations of the environmental impacts should be solved considering eco-assessment, design theories and robust design.

Drawing contributions from each discipline, a three-step method for reducing variations in environmental impacts was developed:

1. Quantifying the environmental impact variations.
2. Defining what are the sources of impact, or the problems to be solved.
3. Solving the problems.

The following sections discuss the possible contributions that each discipline can bring to solve the problem of reducing the variability of the environmental impact of the product.

2.1 Quantifying the environmental impact variations.

The task of the eco-assessment could be to provide the initial criteria for selecting the right methodology to be applied according to the cause of variation in environmental impacts.

For this purpose, the organization of the Life Cycle Assessment (LCA) could be useful. It is unanimously considered one of the most useful for quantitatively evaluating the sustainability of the current technologies, to critically discuss the choices to implement during eco-design and to evaluate the environmental performances of the new developed technologies [13]. Furthermore, the LCA has already been used to show how the environmental impacts of a product can vary depending on the operating scenario and the different use modalities (e.g. [14], [15]).

To be able to express a sufficiently reliable estimate of its results, the LCA goes through several steps, which are regulated by the reference standards [16] and which may also be useful for classifying robust eco-design initial problems:

- The functional unit has the objective to reformulate and identify a reference unit to describe the standardized functioning modality of the product. When the product is used by a user, also ethnographic habits should be taken into account to properly identify the functional unit.
- The reference scenario is based on the definition of the system boundaries and it describe the standard condition of the working environment. It can include the description of the infrastructure, the climatic conditions, the geographical aspects.
- The inventory collects all the data about the environmental impacts arising from all the life cycle phases and they regard both the materials of the product and the energy consumptions.

Each of these steps can serve as a benchmark for identifying and solving the problems that cause the variations of the environmental impacts.

The problem of respecting the reference parameters of the functional unit, places us in front of the need to reduce the variability of the environmental impacts deriving from variations in the functioning of the product. Consequently, to solve this problem we should make sure that the product always behaves the same way, processing the inputs and obtaining the established outputs, throughout the operational life.

The second problem places us in front of the need to reduce the variability of the environmental impacts of the product following changes in the reference scenario. They can be different climatic characteristics (e.g. pressure, temperature, humidity), geographical (e.g. the type of route in which a car travels) or infrastructural (e.g. electricity mix).

Finally, the third problem concerns the reduction of the variability of the structural characteristics of the product, such as masses, geometries, and types of materials.

2.2 Defining the sources of impact

The object of this second step is to reformulate the variations of the environmental impacts in a more suitable manner to be faced during problem-solving activity. For this purpose, the simplified approach of FMEA-TRIZ proposed by [17] was considered.

The core of this approach is the determination of the failure modes, i.e. the modified elements of the system, due to external influences, causing the variations of the environmental impacts. For instance, a rod with a reduced diameter (failure mode) caused by corrosion (external influence) early breaks causing the reduction of its operative life (from which it derives the variation of the environmental impact).

ENV model from TRIZ theory is a useful tool to be adopted to determine the possible failure mode in the modified version proposed by the authors (see Table 1). According to this approach, the components of the technical system (Column 1 – "Element") are described through their parameters (Column 2 – "Name") and for each parameter, the effects deriving from an arbitrary variation of the parameters (Column 3 - Value) are determined (Column 4) and evaluated according to their risk occurrence by using the Risk Priority Number (Column 5 - RPN). In this table, a failure mode results from the conjunction of an Element, a Name, and a Value.

Table 1. ENV model used to determine the failure modes and their effects from [17].

Failure modes

Element	Name	Value (vs. design)	Effect	RPN
El. energy	Current intensity	Higher	Electrocution	20
		Lower	Engine and resistance fail	12
Max temp. allowed	Temperature	Higher	Overheating of hairdryer	14
		Lower	Useless shut down of hairdryer	10
	…	…	…	
Engine	Rotation speed	Higher	Overheating	18
			Mechanical failure	24
		Lower	Poor performance	8
		Absent	Hairdryer fails	12
	Noise	Higher	Acoustic discomfort	8
	Vibration	Higher	User's perceived value	8
	…	…	…	
Fan	Rotation speed	Higher	Increased noise	8
		Absent	Air is not moved	10
	…	…	…	

2.3 Solving the problems

TRIZ method [18] is applied to solve the identified problems, by: (1) providing the ontological tools to reformulate the problems defined in Section 2.2, and (2) providing the tools to solve it.

TRIZ method can be defined at the same time as a heuristic method and a collection of tools to systematically solve a technical problem in a creative way, following a path divided into three main steps:

1. General problem formulation: starting from a specific problem, you gather all the information, and you reformulate it in an abstract way, using some of the tools of the theory (top model or small model, ENV model, Ideal Final Result). The final reformulation is in terms of contradictions or a kind of functional analysis called Su-Field model.
2. Concept/General solution definition: Contradictions and other problem models can be translated into conceptual solutions by means of TRIZ techniques (ARIZ, separation principles, contradiction matrix, 40 Inventive Principles, 76 Standard Solutions). In this way the designer works with a finite number of general suggestions.
3. Specific solutions definition: the designer must translate the conceptual identikit of a solution into a real and working solution by using resources already present in the product itself or in its environment.

The typical TRIZ path comprising the three described steps is presented in Figure 2.

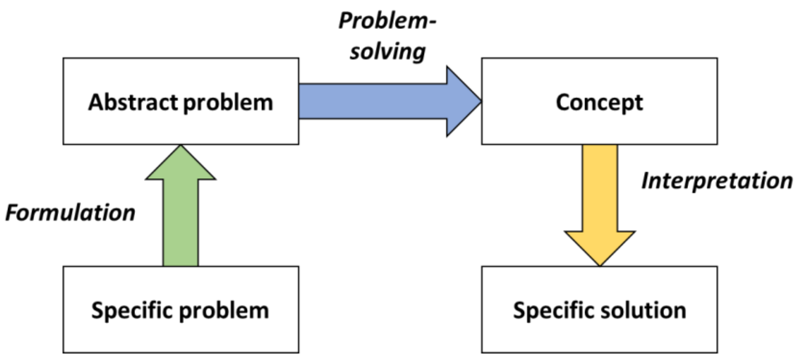

Fig. 2. Typical TRIZ path.

The reformulation of the initial problem, in TRIZ method is supported by the Minimal Technical System model. It is used to describe the Technical system and its functioning by only including a minimum number of ontological elements presented in Table 2.

Table 2. Some elements of TRIZ ontology.

Ontological elements	Definitions

Function	The action performed by the Technical system
Object	The entity over which the Technical system performs the Function
Product	The transformed Object after the Function has been performed
Tool	The part of the Technical system that is in direct contact with the Object during the performance of the Function. The contact can be mechanical, acoustical, thermal, chemical, electrical, magnetic, intermolecular, or biological
Other elements of the Technical system	• Supply: the part generating the energy. • Transmission: the part transmitting the energy generated by the Supply to the Tool. • Control: the part interacting with Supply, Transmission and Tool to regulate the execution of the Function on the Object
Resource	• Any substance, including waste, available in the Technical System or in the working environment. • An energy reserve, free time, unoccupied space, information. • Physical, chemical, geometric properties of the substances

By applying these definitions, it is possible to reformulate the initial problems in a more congenial way for their resolution. Then the reformulated problem can be approached by using the TRIZ path with its main tools (i.e. Step 2 and Step 3). The use of these tools cab be effectively able to solve the initial problems or to reduce the environmental impacts or their variations as qualitatively showed in in [19], [20] and [21] and quantitatively demonstrated through the eco-assessment of the proposed solutions in [22].

2.4 Case study

To demonstrate how can the approach be used, a case study about a compressed air dryer is proposed. This system is used where it is required to remove moisture from a continuous and massive flow of compressed air, typically in oil and gas applications or downstream of a compressor feeding an industrial plant. The main requirements are the quality of the function and the continuity of operation since the presence of moisture in the compressed air can cause serious problems of wear and reduced efficiency of the powered components. This system is installed after a compressor and it includes two column tanks placed in parallel containing the alumina. The two columns work in an alternating way: during phase 1, in one tank the compressed air is dried and in the other the alumina is hot regenerated, and vice versa during phase 2. To regenerate the alumina, it is heated with a stream of hot air that is drawn from the same flow rate of compressed air just produced by the compressor and heated by a heater. The hot, moist air exiting this tank is then dehumidified by means of a chiller with a condensate separator and combined with the main flow of compressed air before entering the drying column.

Figure 3 depicts a schematic representation of the functioning (one of the two phases) and CAD model of the considered Technical system.

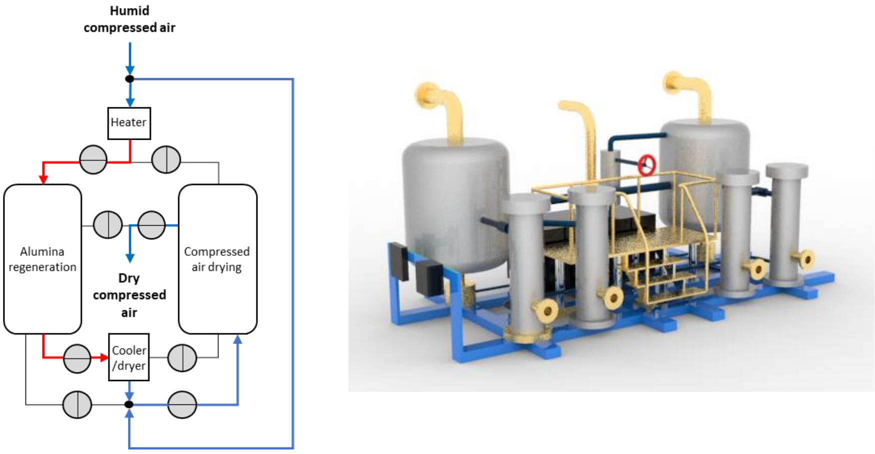

Fig. 3. Schematic representation of the functioning and CAD model of the Technical system.

One of the causes of the variation of the environmental impacts depends by the variation of the flow rate of air that is dehumidified. This flow is in fact one of the main parameters to be considered when defining the functional unit in a LCA study of this product. Consequently, the environmental problem to be faced is: “How can the effects of the variability of the technical system functioning be reduced?”.

One of the most obvious strategy is to reason about the possible inefficiencies during dryer operation.

Reformulating the problem in order to identify the failure mode, we can state that there is a variability in the characteristics of the Product (i.e. the dried compressed air) compared to what it is expected, or the ideal value in the ENV model. Otherwise, if the compressor elaborates a higher flow of compressed air, it means that the dryer cannot produce as much dry air as is required downstream. Consequently, the problem to be solved is to prevent flow losses inside the dryer.

Reformulating the problem according to the MTS model, the objective become: “How can the Technical system continue to perform the Function during use, always as designed?”.

Then, we can search only those components of the air dryer that might break or degrade during use, as prescribed by step 2 of the proposed methodology. Consequently, we can determine which parts or components of the Technical system should not break so as not to affect the realization of Function, as prescribed by step 3 of the proposed methodology. After this reformulation, the problem becomes: “How to reduce the pressure drop inside the tank where the drying takes place”.

A Possible solution to this problem, which was obtained by using TRIZ Inventive Principle N.15 “Dynamicity”, regards the introduction of a mobile membrane. The objective of this device is to modify the internal volume of the tank, by moving exactly when required, or during the malfunction. After the malfunction is terminated, the mobile membrane returns to the initial position, by restoring the initial volume of the tank and the standard functioning of the system. TRIZ method is also strategic as a suggestion of resources to be used to make the identified solutions work. In this case, the most obvious resource to be used to move the membrane is the difference of pressure of the gas within the plant, which is caused by the variation of the fluid dynamic parameters after the pressure drop inside the tank. In turn the restoring of the parameter also provide the return of the membrane to its initial position.

3 Conclusions

This paper has helped to show how the problem of reducing variations in environmental impacts can be tackled in different ways, although the literature still lacks a single, shared, pragmatic, and rigorous approach to environmental aspects.

To fill this gap, the proposal concerns the integration of eco-assessment, design theories and robust design, to reformulate the initial problem in a more suitable way to be solved by a designer and more aware of the environmental aspects.

The results obtained, also through the provided case study, although the result of theoretical speculation, are useful in showing the variety of aspects to be considered and the heterogeneity of the topic, which can be addressed in many ways.

The approach followed, however, allows them to be compared and linked together. For this reason, it could constitute the basis of a structured case-based reasoning methodology, which is the main future development planned for this work.

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