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Linking TRIZ to Conceptual Design Engineering Approaches

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Abstract

During the last decades, product design has yielded several interest by scholars, leading to a great amount of contributions concerning design methodology. Some of them, beyond modeling the whole design process, propose their model of the early design activities devoted to the development of the product concept, i.e. the conceptual design phase. These design approaches are widely diffused in academia. However, some uncertainties appear in literature, concerning their efficacy in performing innovative design. This observation forms the basis of this work, which aims at improving classical design processes by integrating their procedure with the TRIZ base of knowledge. To achieve such an objective, authors' approach consists in considering generally valid steps of the conceptual design process, and then in identifying most suitable TRIZ tools for each of them. A structured list of suggestions concerning the proposed integration is finally presented, together with an explanatory case study application of the proposed improvements.

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Keywords: *TRIZ; Conceptual design; Design methods, Design models*

1. Introduction

Product planning phase (PP) and early design activities are acknowledged in literature to play a critical role for the success of the product [1]. Indeed both the development stages, although in different ways, are devoted to the

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definition of the fundamentals of the system, strongly influencing performance, production technologies, and in general all the characteristics of the final product. The main outcome of PP is the definition of a first product requirements list that constitutes the starting point of the design process. Considering well known literature models of the design process [2, 3], the first phase is the so- called "conceptual design" (CD), which produces the definition of functionalities, working principles and a rough layout of the system structure.

The most acknowledged CD methods put their bases into functional decomposition and morphological composition of the concept, in order to define respectively the function structure of the product and the set of partial solutions which, combined together, constitute the building blocks of the system. Critics on these methods have been raised in literature, some of them concerning the real capability of such approaches in developing innovative design [4]. In order to overcome such a critical limitation, attempts devoted to upgrade classical CD processes can be found in literature, and some of them consider the TRIZ base of knowledge [5, 6] as a potential resource. Such literature contributions constitute a valid reference for this research activity; however, their general validity has not been comprehensively demonstrated.

Here arises the objective of the present work, i.e. to propose a generally valid improvement of functional decomposition and morphology based CD processes, focused on increasing their capability in developing innovative design. In order to achieve such an objective, this work points toward the identification of a set of specific TRIZ tools to be used in the main general phases of the concept development.

Section 2 proposes a short introduction to the most acknowledged CD methods with the aim of highlighting the general steps to be improved with TRIZ. Section 3 describes the research methodology and the list of identified TRIZ tools for CD. In order to validate the results, a case study application is depicted in Section 4, while discussions about the results are provided in Section 5. Eventually, concluding remarks constitute the contents of Section 6.

Nomenclature

PP	Product planning
CD	Conceptual Design
SAPB	Systematic approach of Pahl and Beitz
LESE	Laws of Engineering Systems Evolution
NoP	Network of Problems
EMS	Energy – Material – Signal
SO	System Operator
IFR	Ideal Final Result
TOP	Tool – Object – Product
UP	Useful Product
SLP	Smart Little People
STC	Space – Time – Cost

2. Conceptual design: classical approaches

Among the plurality of models acknowledged by the scientific community, several of them divide the design process into three sub phases [2, 3], namely conceptual design, embodiment design and detail design (figure 1).

As introduced in Section 1, the conceptual design phase defines the fundamental traits of the product. Subsequently, the embodiment design phase develops the layout of the system by considering issues related to geometrical features, materials, and physical properties. Finally, the detail design produces a complete description of the product, so as to produce production documents.

Designing a product is not a straightforward process, indeed. As shown in figure 1, when proceeding from the abstract level of the requirement lists to the concreteness of the technical documents, any type of problem may arise by the way, leading to modifications of previous design steps. These are the well- known iterations characterizing any design process. However, the iterative trait of the design activities is intrinsic of the whole product development process.

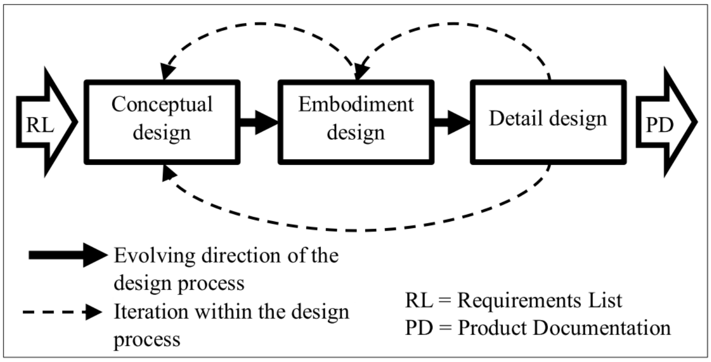

Fig. 1. Main steps of the engineering design process [2].

For this paper, three well acknowledged literature contributions have been considered for investigations, i.e. the models by Pahl and Beitz [2], Ulrich and Eppinger [5] and Ullman [6]. At a glance, the three models appear quite different in terms of number of phases and/or tasks to be performed in each of them. Moreover, the design activities are described with different levels of detail. However, for what concerns PP activities, a more in-deep analysis shows that the models share the same traits and consist of the followings:

- Identification of needs and opportunities
- Resource assessment
- Definition of a first product requirement list to be updated during the design process.

Furthermore, also CD presents significant analogies and it is worth of a more detailed discussion. Table 1 lists the main steps of the design models considered for this study.

Table 1. Reference CD processes and related activities.

Pahl and Beitz [2]	Ulrich and Eppinger [7]	Ullman [6]
1 Abstract to identify essential problems	1 Identify customer needs	1 Generate concepts
2 Establish function structures	2 Establish target specifications	2 Evaluate concepts
3 Search for working principles	3 Generate product concepts	3 Make concept decisions
4 Combine working principles	4 Select product concepts	4 Document and communicate
5 Select suitable combinations	5 Test product concepts	5 Refine plan
6 Firm up into principle solution variants	6 Set final specifications	6 Approve concepts
7 Evaluate variants against technical and economic criteria	7 Plan downstream development	

Also in this case, at a first sight the three models appear quite different, but anyhow it is possible to identify a common path, i.e. starting from the requirement list, a set of concept variants is generated and then a selection of the preferred ones is performed by means of evaluation parameters.

More in detail, it is possible to observe that in order to "generate concepts variants", all the three models propose substantially the same procedure:

- Formulation and decomposition of the design problem (by means of functional analysis and decomposition)
- Definition of the solutions related to single sub-functions
- Combination of the solutions related to single functions.

For the definition of a functional solution, or more generally for generating ideas, the three approaches take into consideration many creative methods and tools, among which also TRIZ is mentioned. However, none of them provides a comprehensive description about "how" to use TRIZ tools. Actually, some contributions can be found in literature, suggesting the adoption of TRIZ as a means to improve CD [7, 8]. Nevertheless, it is still possible to observe some gaps to be filled. Malmqvist et al. [7] perform a comparison devoted to find differences and analogies between the systematic approach of Pahl and Beitz (SAPB) [2] and TRIZ. They proposed some merging tips, but missed to provide any case study application to show their factual implementation. A more recent attempt by Dietz et al. [8] proposes a hybrid model for CD characterized by a modification of SAPB through some ARIZ [9] steps.

The work is focused on designing across multiples-scale domains (product and materials), i.e. belonging both to the macro and micro levels. However, it is not clarified what is the range of applications deserving such a multi-scale approach, i.e. it is not showed how to behave when there is no need to consider the macro and micro levels concurrently. Furthermore, both these literature contributions were constructed strictly around the logical schema of SAPB.

Diversely, the present work aims at considering the general steps shared by the main CD approaches based on functional decomposition and morphology.

3. Improving the conceptual design process

As introduced in Section 1, the aim of the paper is to improve classical CD approaches. In particular, the authors focused their attention on the observation raised by Tomiyama et al. [4] according to which the design methods considered here belong to a group characterized by some inefficiencies in producing truly innovative design outcomes. Besides, it should be noticed that innovation implies not just novelty, but also the success of a product. Therefore, the innovativeness of a solution can't be really assessed at the end of the conceptual stage. However, it is possible to claim that the inventiveness is fundamental to pursue innovation, and it can be evaluated at the conceptual level. Starting from this observation, the authors assumed that TRIZ can provide a significant contribution to overcome the limitations of established engineering design methods and as such it is worth embedding a selection of TRIZ tools into the accepted CD scheme. It should be highlighted that the main purpose of the activity is not defining a hybridization between classical CD and TRIZ, but providing a structured list of indications compatible with CD approaches, in order to help engineers in achieving inventive solutions.

3.1. How to reach the objective

According to the authors' experience, classical CDs processes introduced in Section 2 present some interesting compatibilities with TRIZ. This observation also complies with the attempts to improve systematic design approaches with TRIZ mentioned in the previous section.

This study mainly consisted of analyzing the detailed features of both CD methods and TRIZ, in order to identify TRIZ tools and models compatible with the general CD steps identified in section 2. Then, starting from the authors' professional experience in applying those methodologies, a list of tools has been selected for each of the three CD steps. As expected, most of them suit the second step of CD, i.e. where creativity has to be stimulated and psychological barriers have to be destroyed (see Table 2).

Furthermore, also the phase of requirements definition, which is more typically assigned to the PP stage rather than to CD, was here investigated in terms of possibilities to embed TRIZ items. This makes sense both for the impact of requirements definition on CD activities and for the suitability of some TRIZ models for supporting it.

The first outcomes of this research activity are reported hereafter. Besides, only a single industrial case study has been so far performed with the specific objective to compare CD activities of traditional systematic design methods and a TRIZ- enriched approach. Thus, in order to check the effectiveness of the complete set of suggested tools, and to check if some others can be added to the list, further tests are foreseen for future refinements.

3.2. Identified tools

As discussed in Section 2, CD processes can be subdivided into three leading phases: main problem decomposition, solutions identification for each single function and solutions combination. Table 2 summarizes the selected TRIZ tools suggested as suitable for supporting CD activities.

Table 2. TRIZ tools proposed for integration in PP and CD activities.

Process step	Tools from Classical TRIZ	Tools derived from TRIZ
Requirementsdefinition	- Laws of Engineering Systems Evolution (LESE)	
Main problem decomposition	- Functional Modelling - System Operator	- OTSM-TRIZ Network of Problems
Solutions identification for each single function	- Laws of Engineering Systems Evolution (LESE) - Su-field modelling and Standard Solutions - Ideal Final Result - Pointer to Effects - Smart Little People - STC Operator - Contradiction approach: Inventive and Separation principles	- Guided Brainstorming inspired by the System Operator - TOP TRIZ
Solution combination	- Contradiction modelling and Inventive Principles	OTSM-TRIZ-ENV model

As already suggested by Malmqvist et al., LESE [10] can be adopted in order to improve requirements definition. For such task, two of the three engineering design methodologies considered for this study, namely those proposed by Ulrich and Eppinger and by Ulmann, suggest the use of the S-curves in order to assess the maturity level of the product. The introduction of the LESE at this step supports the definition of particular requirements concerning the specific level of evolution of the considered system. For instance, a technical system that implies the involvement of the user in the delivery of its main function, i.e. a system that is still not completed according to the first Law (Completeness of Technical Systems), is likely to evolve in the direction of increasing its automation degree. In the PP phase, specific requirements can be formulated to orient the following CD activities in that direction. Similarly, to add a further example, according to the fourth Law of Evolution (the Law of increasing the degree of Ideality), a system in its maturity stage should be characterized by a lower consumption of resources in a shorter-term perspective. Besides, a long-term vision would suggest more radical shifts, as suggested by Laws six and seven (the Law of Transition to Super-system and the Law of Transition from Macro to Micro Level). A more detailed discussion about the interpretation of the TRIZ Laws of Evolution in the context of new product definition is available on [14].

Moving to the CD stage, the first activity is the main problem decomposition. For such a step, TRIZ offers several valuable tools. Among the others, the authors recommend three of them. The first is the OTSM-TRIZ Network of Problem (NoP) [11]. This tool allows visualizing in an efficient way the decomposition of the main problem into a set of sub-problems and their logical links. The network suitably represents the complexity of the system, but also allows working on simpler problems approached one by one. Once completed, the NoP appears as a graph composed by problems and partial solutions, where at the top there is the main problem, and every branch of the network represents the development of the solutions for each sub-problem. Moreover, the NoP can be built also without starting from an existing system (as it usually happens with most TRIZ modelling tools), but only from the description of the main function to implement. It also offers the opportunity of highlighting possible conflicts among the different branches of the network. This can be considered the main advantage of the NoP, if compared with the functional modelling approach typically used in systematic design methods, i.e. the EMS (Energy Material Signal) model.

The second tool that can be used in the first phase of the CD is Functional Modelling. Such modelling technique lets to decompose a system into its basic elements and highlights the functional relationships among them. If compared with EMS flows, TRIZ Functional Modelling produces a richer description of the system, by highlighting harmful interactions and insufficiently delivered benefits. Such classification allows the designer to better identify the core of the problem to solve.

The last TRIZ tool usable in the first step of CD is the System Operator (SO). By means of the SO it is possible to search for bypass problems, i.e. alternative design problems to address that still allow to satisfy the product requirements, addressing them from a different perspective. Sometimes, the initial task is not the most convenient to address. For such a reason, SO is an effective tool to investigate other problems to deal with. Overall, the systematic search of by-pass approaches can be significantly beneficial for the whole CD activity.

For the solutions identification step, TRIZ clearly provide plenty of alternative tools, as reported in table 2. Among them, the LESE suggest directions of evolution that could inspire modifications of the current system. Su-Field modelling extracts specific problems from a function model, while the Standard Solutions trigger inventive ideas by analogy with abstract models of effective solutions. The Ideal Final Result (IFR) greatly helps overcoming psychological barriers.

According to authors' experience, the System Operator can be used also as a guide for generating ideas in a brainstorming like session, starting from the different roundabout problems. In each cell of the SO, a question represents an alternative problem that could be solved and, as such, it can trigger the generation of new ideas.

Once the function is defined, the next step consists in identifying the so called working principle. In order to accomplish this task, the pointer to the effects is a suitable tool to explore physical, chemical and geometrical effects that can be used to deliver the given function. With the same aim, also the TOP (Tool Object Product) TRIZ approach, developed by Zinovy Roizen [12], is a valid help. It suggests starting from the object and the definition of the useful product (UP), that is the modified object after the effect of the function. Then, the field able to obtain the UP has to be identified, and finally the tool capable to use the selected field has to be chosen among the available resources.

The Smart Little People, is a further tool conceived by Altshuller to overcome the psychological inertia. It is an effective tool to identify possible structures and physical principles usable to deliver the requested function. Another instrument that allows overcoming the psychological barrier is the Space-Time-Cost (STC) Operator. By envisioning drastic changes in space, time and available resources of the scenario in the context where the function should be delivered, the designer is stimulated to produce out-of-the-box solutions.

Contradiction modelling and the Inventive Principles are the last tool here taken into consideration for aiding the idea generation phase. According to the second postulate of TRIZ, as reported in OTSM research, good solutions reject trade-offs and overcome occurring contradictions. For such a reason, if in the development of the conceptual solution, some conflicts arise, Inventive and Separation Principles are the best way to solve them.

When all the sub problems, or all the sub identified functions are fulfilled, the designer has to combine them in order to obtain the final conceptual solution. In such step, it is possible to highlight other contradictions by means of the ENV model solvable with the already mentioned Separation Principles.

4. Case study

The case study where the proposed approach has been tested concerns a glass block produced by a company with the headquarters nearby Florence. The need they wanted to address was to reduce the thermal transmittance of the blocks, so as to increase their insulating efficacy. The glass block consists of two glass made hollow shells welded together. Within the block, a certain volume of air remains, and it is warmed up to 450°C before welding, so as to avoid the formation of condensate. The commercialized standard block has a heat transfer coefficient of 2.8 W/m2K, while the aims of the firm is to lower it to less than 1 W/m2K. Two main aspects must be considered as design constraints, as imposed by the firm: the transparency of the glass block, and the structural stiffness. To reduce the thermal transmittance, the first solution adopted by the company consisted in introducing a thin glass plate with a reflective surface between the two shells.

Page limit restrictions preclude a detailed presentation of the performed activity. On the other hand, the purpose of this paper is to enable a discussion about the differences between ordinary industrial practices, conceptual design activities carried out with the support of systematic design methods and the latter with TRIZ embedded.

With such objective, it is useful to dedicate more space to the results of the design process. In detail, the outcomes are grouped into three sets: the first contains the solutions generated by the designers of the firm with their usual approach working on their own. The second set is the result of the application of classical systematic design methods for CD, generated by the same team of designers with the support of a first engineering design expert. Finally, the solutions obtained by embedding TRIZ tools within CD complete the overview. Such results have been obtained by the same team working together with a TRIZ expert.

Starting from their own experience, the technicians of the firm proposed a solution to improve the current design: instead of a single glass plate between the shells, which halves the internal air volume, they suggested to insert another plate in order to divide even more the volume of air so as to reduce its convection phenomena (figure 2).

The structured conceptual design approach brought, instead, to a very different model of solution. Due to the deeper investigation of the problem, the authors proposed to modify the structure of the glass block in order to reduce the heat transfer for conduction from one side of the block to the other. The proposed solution consists in modifying the structure of the perimetric sides of the block, changing them from solid glass to cellular glass, and spraying all the internal faces of the shells with the reflective coating (figure 3). Cellular glass is a kind of glass foam that contains a huge number of micro air bubbles. Such a foam enormously reduces the heat transfer.

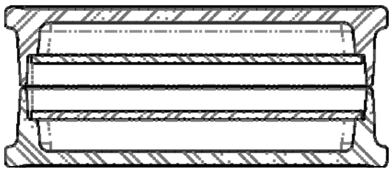

Fig. 2. Solution proposed by the company: subdividing the internal air volume in three parts by means of two glass plates.

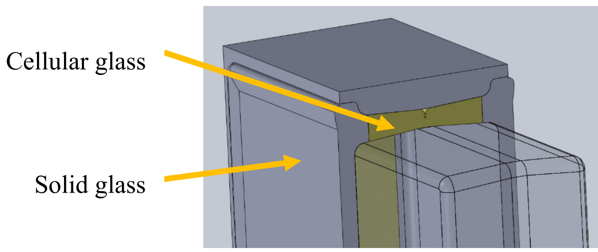

Fig. 3. Solution derived from CD: some parts of the solid glass block substituted by cellular glass

The last set of proposed solutions derives from the application of the above mentioned TRIZ tools within the steps of the classical CD methodologies. Then, instead of the EMS map of the system, the TRIZ functional model has been realized. It led to the identification of critical interactions between system elements. For the identified harmful functions, Su-Field models were built: in fact, the first two solutions come from the application of the Inventive Standard 1.2.2. According to such suggestion, hot air and the front face of the block, a modification of one of them, has to be interposed. So the authors proposed to realize that face as a kind of honeycomb in order to create an external air cushion able to reduce the heat transfer (figure 4-a).

Another interpretation of the same solution consists in realizing on the surface a set of horizontal grooves with the same function of the honeycomb.

The analysis of the current system suggested by classical CDs brings only to its functional decomposition, without giving any suggestions about its potential evolution. By using the suggestions of TRIZ, instead, some solutions can be generated just considering different layouts of an existing system. Indeed, starting from original structure of the glass block, composed only by the two shells, passing from the solution with the internal reflective plate, and considering also the solution with two glass plates proposed by the firm, one can recognize the trend of segmentation of the internal volume (one cavity, two cavities, multiple cavities…).

The next step of the trend suggests incrementing the degree of fragmentation. Thus, another air chamber could be added in front of the external faces in order to exploit the resource of air as insulating mean. The same evolutionary trend applied to the solution of the honeycomb suggests increasing the degree of segmentation of the frontal face. A glass foam can be used for replacing the solid glass. Although such solution is expected to improve the heat transfer behavior of the system, it could be disregarded because it infringes the constraint of transparency. All the suggestions of CD concerning the ideas generation are focused on the solution of the core problem. Conversely, the System Operator leads to consider also different aspects of the problematic situation changing completely the task to work with simply shifting the column taken into account. The use of the SO, indeed, as a guide to generate ideas brought to very interesting solutions. The starting cell (System Present) could contain the initial formulation of the problem: "how to reduce the heat transfer from the hot face of the block to the cold one?".

(a) (b)

Fig. 4. (a) honeycomb on the front face of the block. (b) metal thread to conduce heat from the glass structure to internal air volume

The Future column brings to consider the effect in case the problem is not solved in the Present column: the heat passes through the structure of the block, but it is not a problem. How could it possible? A possible answer is to direct the heat flux toward a less conductive zone of the block different from the solid glass of the structure. Such an answer is likely to be interpreted as a set of very thin metal threads, which conduce heat from glass to the internal air volume of the block (figure 4-b). Such a solution is in accordance also with the second Law of Evolution (about Energy Conductivity).

5. Discussion of the results

The selection of tools reported in Table 2 can be considered a structured list of TRIZ tools suitable for being embedded in systematic design methods during conceptual design activities. A comprehensive description of the tools and their application rules lies outside the scope of this paper, however, a few practical indications can be found in Section 4.

Concerning the considered case study, when analyzing the generated solutions it is possible to observe that the proposal of the firm, i.e. two internal glass plates, is the most conservative one, and then the less inventive. Indeed, they kept their focus only towards the insulating effect of air chambers. Diversely, by using the classical CD approach it was possible to abstract the problem by modeling it from a functional point of view, thus allowing the designer to highlight the key problem, and then to consider different directions of solution. In fact, after a deep analysis performed before the generation of ideas, it emerged that the chamber subdivision was not so important if considered as the only design parameter to act upon. More in detail, the concurrent effect of the reflective coating and the thermal conductivity of the glass was predominant. Indeed, the proposed solution aims at reducing conductivity of the block walls and at improving reflective properties, keeping into considerations economic and technological constraints imposed by the firm.

Despite the evident advantages reached in using the classical approach, however the reader can observe that the obtained solution is not characterize by high creativity, since the same fundamental principles of the original solution were still used. Differently, by assisting the CD process with the TRIZ tools indicated in Section 3, many other different and somehow “revolutionary” solutions have been found. It is worth to notice that since the results of the conceptual design phase are constituted by early sketches or rough CAD models, it is impossible to quantitatively assess the real efficiency of solutions and then to assess the product success for all of them. Consequently, it is not possible to assess the expected innovativeness of the solutions. However, among the possible future developments, beyond the application of the research to a more extended set of case studies, it would be interesting to refine the research by assessing creativity of solutions by using acknowledged literature metrics [13]. What can be stated here is that in order to reach design efficiency, the adoption of a systematic CD process is fundamental, and moreover, the case study demonstrates that by using TRIZ with the indications provided in Section 3 it is possible to increase the range of potential solutions.

6. Conclusions

The work described in this paper concerns the improvement of classical conceptual design approaches by means of an integration with specific TRIZ tools. Such an improvement aims at increasing the capability of these methods in reaching innovative results. More in particular, a sample of three acknowledged models based on functional decomposition and morphology has been considered. They have been analyzed and their main steps have been summarized in a small number of generally valid design phases. Subsequently, for each of these general phases, a set of specific TRIZ tools has been identified and selected. Such an identification activity has been performed starting from the authors’ professional experience in both conceptual design processes and systematic problem solving, which has been acquired in years of academic and industrial applications.

After the description of the identified toolset, an explanatory case study application has been reported in the paper, in order to support with concrete arguments the first results of this activity. The outcomes of the case study application have been also reported, and a comparison of them has been performed in order to highlight the improvements of the conceptual design process after the application of the selected TRIZ tools.

Furthermore, future developments of the research activity have been proposed, specifically concerning the application of creativity metrics to evaluate the generated concepts.

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