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Axiomatic Design and TRIZ: Deficiencies of their Integrated Use and Future Opportunities

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Abstract

The first decade of 2000s has observed the diffusion of several contributions illustrating methods that combined Axiomatic Design (AD) and the Theory of Inventive Problem Solving (TRIZ). Such a kind of methodological matching seemed to flourish in both reference communities. The strength of the connection was found in the complementary objectives AD and TRIZ pursue. The former faces design tasks with a holistic view, oriented to schematize and simplify the design brief. However, despite the correct employment of AD axioms, the decoupling is not ensured of Functional Requirements' and Design Parameters´ matrices. As a consequence, the powerful problem solving capabilities of TRIZ can be employed in order to overcome extant contradictions. With this vision, AD is supposed to analyze the problem and structure it in the most convenient way, whereas TRIZ should solve the minimum amount of design conflicts that are intrinsically present in a case study. Nevertheless, despite the promising match between AD and TRIZ, no conjoint application strategy has emerged as a reference, neither in academia, nor in industry. Conversely, the quantity has dropped of Scopus-indexed scientific papers contextually making reference to both methodologies. The authors have attempted to investigate the reasons of the unsatisfactory evolution of the matching hypotheses between AD and TRIZ. The paper puts particular attention on the sources that manifest skepticism with respect to the combination of the two techniques. The conducted research remarks that unsuitable modelling has been so far employed to represent conflicts arising with AD through TRIZ terms. To the scope, the authors point out the potential advantages of exploiting poorly known instruments developed within TRIZ field. These tools are capable of facing the problem with a wider perspective and guide the user to perform troubleshooting in a more efficient way, also in the perspective of the second AD axiom.

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1. Introduction

The present contribution aims at providing methodological support for the early stages of engineering design cycles. The interest for these initial phases arises from their claimed relevance with respect to the success of product development initiatives. In particular, the paper deals with methods that are viable to strengthen the definition of the technical solutions that better fit design objectives.

The creative development of new products and systems has to give rise to ideas that are both novel and appropriate in a given context according to posed constraints. These requirements constitute a fundamental set of criteria for selecting the alternative options that engineers and designers generate. They generally refer to the fundamental performances a product is expected to show in particular working conditions. However, it often happens that many emerging solutions are capable of fulfilling the most critical requirements, but fail to achieve a full consensus in the decision making team. Manifold reasons motivate this circumstance; we advance some of them, discussing aspects such as complexity, originality and versatility of technical solutions.

At first, emerging ideas and concepts might result overwhelmingly complex. Designers tend to adapt existing product platforms when asked to cope with new requirements. This provides readily available solutions and hence carrying out relatively short product development processes [1]. However, over time, accumulated changes on ingrained design concepts

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can give rise to disharmonious systems, which show tangled interrelations between components and characteristics. Drastic redesign efforts would give rise to simpler product configurations, by considering all the requirements from the very beginning of the problem analysis. In this sense, AD stands as a reference tool to perform a careful analysis of the design brief, guiding towards the generation of systems that overcome the above intricate interdependences. Indeed, the exploitation of AD axioms aims at improving technical solutions by leveraging designers' capability to isolate the carriers of each requested function. In this way, these solutions feature major controllability and versatility.

Shortcomings of generated designs may stand in poor novelty too. Although optimized solutions, and solutions built on established systems as well, are sometimes capable of fulfilling minimum requested performances, they seldom provide outstanding benefits for customers. Conversely, inventive steps in conceptual design allow to attain performances breaking extant boundaries. Besides, products characterized by major differentiation with respect to existing technical systems present further advantages, such as the potential for Intellectual Property protection, or, in a market perspective, increased success chances by being perceived as cutting-edge innovations. In order to hit the target, the framework proposed by AD is considered insufficient to support the creation of ingenious solutions. In this context, many scholars point out the potential of TRIZ [2], the theory developed in the former Soviet Union that proposes a sample of instruments to support designers' creativity by limiting their psychological inertia.

Matching the advantages of AD and TRIZ comes out as a prime opportunity. On the one hand, the former facilitates the analysis of technical problems and drives towards easily configurable and well-performing systems. On the other hand, the latter supports the ideation process suggesting inventive patterns, which bring out solutions characterized by originality and unprecedented advantages. These factors have motivated the choice of Shirwaiker and Okudan [3] to employ AD and TRIZ in a combined design framework, which fits industrial needs about problem solving by supporting both problem analysis and idea generation. From a slightly different viewpoint, Shai et al. [4] remark how AD offers a system-level perspective of the problem and TRIZ owns the means to provide synthesis assistance by addressing few functions at a time. Not surprisingly, the overall review of design methods performed by Tomiyama et al. [5] places AD among abstract mathematical-based tools and collocates TRIZ within the set of instruments concretely working on technical problems, thus revealing clearly paired functions. In addition, both the methods represent candidate design techniques enabling product development cycles relevant for agile manufacturing strategies [6].

More insightful methodological aspects, which the authors will illustrate in the next chapters, reveal the compatibility and the complementarity of the two techniques. However, the application of AD and TRIZ in concert has not produced the expected results and has not resulted in consolidated industrial practices. Section 2 lays bare how the research efforts are waning that concern the conjoint use of the mentioned strategies. The authors have thus surveyed the literature with the aim of elucidating the claimed strengths and weaknesses of this combination of tools, reporting them in sections 3 and 4, respectively. The results of this investigation are discussed in section 5, which, in addition, reports the authors' view. Eventually, section 6 concludes the paper and clarifies authors' intentions about future research activities.

The present paper takes for granted the fundamental concepts and tools that populate both AD and TRIZ. Abundant literature is available for any reader who requires major knowledge about both the theories for the scope of understanding the contents of this manuscript.

2. Intensity of the research about Axiomatic Design and TRIZ

The authors of the present paper have independently discerned that the scientific community is currently paying declining attention towards the combination between AD and TRIZ. In order to find confirmation or rejection of this perception, we have performed an investigation about the diffusion of papers treating themes regarding both techniques. In particular, we have considered Scopus-indexed articles that report in the title, abstract and keywords:

- "Axiomatic Design"
- TRIZ
- Both terms.

The results of the survey, which has been performed in April 2015, are reported in Table 1 and Fig. 1. The former summarizes the number of papers concerned with AD, TRIZ and both of them starting from 2002. This initial point was chosen, because, starting from this year, the two treated methodologies appear steadily in at least 10 Scopus-indexed publications.

Table 1. Scopus-indexed publications discussing AD, TRIZ and both.

Year	Axiomatic Design	TRIZ	Axiomatic Design and TRIZ
2002	15	15	0
2003	20	14	0
2004	32	30	1
2005	45	48	1
2006	37	81	3
2007	67	81	5
2008	61	87	6
2009	86	95	7
2010	79	135	6
2011	67	226	13
2012	72	177	5
2013	53	175	2
2014	59	161	2

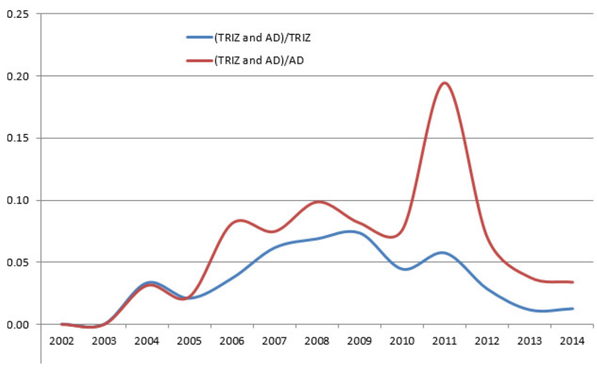

Fig. 1. Share of publications discussing Axiomatic Design and TRIZ simultaneously with respect to the total quantity of papers treating the two design methodologies.

The latter focuses on the rate of articles that include both AD and TRIZ as main topics with respect to the total quantity of papers discussing each of the two. More in detail, the red (blue) line describes the evolution over time of the fraction of AD (TRIZ) –related articles whose topics include TRIZ (AD).

The outcomes of the investigation show a peak of disseminations concerning both the design tools around the end of the first decade of 2000s, in terms of both absolute numbers and percentages. In this period, the literature about AD seems particularly concerned with TRIZ principles. On the other hand, publications about TRIZ slightly diverge from the reference topics of AD already few years before. Whereas we can observe a quite regular growth during the first observed years, a sharp decline follows the peak. This trend can be interpreted as a deadlock of the efforts paid to employ AD and TRIZ in concert for supporting engineering design and industrial problem solving. The sections that follow will try to identify the motivations underlying the initial rise and the abrupt drop.

3. Effectiveness of the integrated employment of Axiomatic Design and TRIZ

Section 1 has already remarked the different objectives pursued by AD and TRIZ in terms of supporting designers' activities. The present section, besides deepening the concepts that have been already outlined, focuses more insightfully on the findings that emerge from contributions that, with a more theoretical or practical approach, merge or compare the knowledge domains of AD and TRIZ.

3.1. Complementarity of objectives

AD is a valuable instrument for the scopes of structuring designers' thinking processes in the early design phases, while TRIZ is tailored to find solutions for conflicts taking place in existing systems [7]. By using the words of other scholars [8], the strength of AD lies in the problem identification and formulation, while the main strength of TRIZ consists in concept generation. Whereas both theories are devoted to aid decision making and problem solving in design, AD structures design problems and TRIZ is capable of solving them in a creative way, which avoids trial-and-error approaches [9].

From a slightly different angle, AD and TRIZ are committed to face different design tasks by focusing on distinct aspects of the product. Sarno et al. [10] compare the goals and the application domains of several design methodologies — AD's main output is the fulfillment of customer needs, while TRIZ aims at the improvement of the technical system.

In order to hit the target, AD clearly addresses technical and functional aspects of engineering design. TRIZ can be seen as a complementary support also from this viewpoint, by considering, within the concept of ideality, factors concerning aesthetics, resources and undesired effects too [7].

Additionally, classical TRIZ is supposed to have limited capabilities in terms of handling complex systems and multiple requirements. The individuation of the most relevant contradictions in complex systems is still insufficiently supported by TRIZ. Indeed, TRIZ commonly benefits from other techniques or design processes to define the conflicts to overcome [3]. In this sense, one of AD strengths stands in appropriately managing tangled situations.

Table 2 summarizes the above discussion by highlighting the design aspects for which AD and TRIZ result in being complementary or just partially overlapping.

Table 2. Complementary design aspects for AD and TRIZ.

Design issue	Axiomatic Design	TRIZ
Support of the design process	Analysis of current design and support to designers' thinking	Convergence towards devised ideas
Objectives within the design problem	Identification and formulation	Development of conceptual solutions
Output	Fulfilment of customer needs	Improvement of a technical system
Analyzed and processed design parameters	Functional requirements (see AD definition)	Any kind of (not) technical parameter, including undesired functions
Favorite application domain	Complex system	Simple system or simplified model of a complex system

3.2. Methodological synergies and results of practical applications

As emerged in the previous subsection, AD has the capability to provide a general vision of the problem and breakdown it, which should be followed by generating proper solutions. However, AD entrusts the search for solutions to designers' creativity, offering scarce methodological support. In this context, TRIZ can be exploited to engender innovative solutions, like in the examples that follow.

Yang and Zhang [9] show the possibility to apply contradiction-overcoming TRIZ principles to perform decoupling between functional requirements, which designers would otherwise carry out in a trial-and-error fashion. Their application in a case study concerning paper isolation mechanisms illustrates the usefulness of both inventive and separation principles. In particular, the latter can be advantageously employed when functional requirements need opposite effects brought on by the same element of the design. For instance, in the specific example, the friction between two elements should be large and small at the same time to fulfil two different functional requirements. In [11], TRIZ laws of systems evolution and the database of effects are additionally proposed to accomplish the decoupling task. An original methodology tailored to enhance reliability of designed systems, which is described in [10], recommends the forty inventive principles to face problems that directly arise in terms of contradictions both at functional requirements' and design parameters' level. Within this proposal, with the aim at achieving robust designs, multiple iterations are foreseen that alternate: a) the definition of the sets of functional requirements and design parameters that best embody the axioms and b) the application of problem solving patterns proposed by TRIZ. In this sense, the conceptual design phase observes cycles in which the system is transformed until a satisfying solution is devised.

In a more articulated way, Shin and Park [12] individuate the most beneficial TRIZ tools that allow to decouple and uncouple matrixes according to the kind of faced situation:

- A subset of TRIZ Standard Solutions is advised when the number of design parameters is lower than the quantity of functional requirements;
- The database of effects and other Standard Solutions are recommended when the design task consists in adding new functional requirements in a system that could be otherwise schematized by a decoupled or uncoupled matrix;
- Decoupled matrixes showing weak relationships in the dependencies represented by the diagonal require Standard Solutions that dictate the state transition of the system or a different hierarchical level of the system to fulfil certain functional requirements;
- When, in a decoupled matrix, the increase/decrease of a value of a design parameters has diverging effects on two functional requirements, the situation is clearly featured by a conflict typically described by TRIZ and the contradiction matrix represents a candidate heuristic to solve the problem;
- In a situation similar to the one above, by focusing on the different values that the design parameter should assume contextually, a physical contradiction is defined and separation principles are worthwhile of being applied;
- Coupled designs are the most troublesome situations and solutions could require multiple-step strategies; in this sense the Algorithm for the Solution of Inventive Problems (ARIZ) is suggested, which combines all the most reliable TRIZ tools.

The strength of using TRIZ Standards for the scope of obtaining uncoupled matrixes is widely discussed in [13]. In this contribution, however, TRIZ is employed as a reference framework and AD's principles help select the solution patterns leading to less complex systems.

A further combination option is described in [14], where the scholars successfully exploited the TRIZ list of engineering parameters to define new design parameters in AD, so as to facilitate the transformation of coupled and decoupled matrixes into uncoupled ones.

In a subsequent design step, thanks to the use of AD and principally to the Information Axiom, it is possible to assess the effectiveness of devised solutions [12, 13]. This is especially useful if a plurality of design concepts has been generated through the employment of TRIZ.

However, Kremer et al. [15] exploit AD to decompose complex problems into mutually independent sub-problems and TRIZ to find numerous solving concepts, but additional instruments are exploited to optimize the end solution. Therefore, in this case, the convergent design phase leading to the final concept requires other means than AD and TRIZ, because, still as claimed in [15], none of the methodologies tackles the quantitative issues of the problem. Thus, the scope of matching AD and TRIZ is limited to the management of design parameters and the subsequent overcoming of criticalities through the use of inventive principles.

3.3. Theoretical affinities

According to [16], the opportunity of building valuable techniques exploiting both AD and TRIZ descends from a philosophical assumption, i.e. both theories aim at explaining in an understandable way how to achieve excellence in design.

Moreover, theoretical insights support the parallelism between instruments belonging to both knowledge domains, i.e. axioms vs. ideality and zigzagging process vs. Su-Field model [7]. More diffusedly, the objective of decoupling functional requirements is seen as the other side of the coin of contradiction solving in TRIZ, as the previous subsection has documented by reporting practical examples. These and other theoretical affinities, whose widest overview is provided in [9], represent an actually overlooked driver in terms of potentially expanding the scope of supporting design tasks through tools conjointly benefitting from AD and TRIZ.

4. Problems concerning the combined use of Axiomatic Design and TRIZ

The previous section has reviewed the proposals about the synergistic use of AD and TRIZ, illustrating at the same time the benefits of this combination. Some of the cited references include however critical sparks with reference to the discussed methodological combination. The present section attempts to remark these criticalities, besides making reference to contributions specifically devoted to highlight possible pitfalls in matching AD and TRIZ.

Kim and Cochran [7] document how scholars do not agree about the usability of TRIZ for all the kinds of problems emerging from the application of AD. If TRIZ is supposed to overcome situations in which design parameters fail to meet constraints, it is not likely to work in case of functional coupling and especially when triangular matrixes come out from AD-driven analyses. Still with reference to [7], the compatibility between instruments belonging to the two theoretical frameworks requires major research. No evaluation has been carried out, e.g., with respect to the interplay of problem solving techniques belonging to TRIZ (e.g. inventive principles or ARIZ) and AD (e.g. theorems and corollaries).

Mann [16] recalls the attention on the different criteria that AD and TRIZ employ in evaluating a solution. In his view, the Independence Axiom contrasts with ideality concept. On the one hand, AD hunts functional independence, not unlikely through the introduction of new components. On the other hand, TRIZ-based solutions are expected to reach ideality through a system whose materiality vanishes, but is still able to deliver all the required functions. In other terms, AD aims at assigning each function to different carriers, while TRIZ pursues concentration of functions. Still with reference to [16], misalignment of objectives between AD and TRIZ can even take place. AD seeks to reduce the quantity of functional requirements to the minimum possible number that can however lead to a satisfying solution. TRIZ forecasting capabilities and trends urge designers to think about new opportunities for the systems under investigation, thus encouraging not focusing on strictly necessary requirements only. Said otherwise, TRIZ users tend to introduce a new function in a system if the new solution is sustainable, although it manifestly violates the Independence Axiom. Another not marginal aspect is raised in [16]. The focus of AD on customer needs might lead to acceptation of design compromises, if the optimization of certain parameters allows to fulfil the basic users' expectations. In a very different way, TRIZ aims, in any circumstance, at overcoming design trade-offs, so to maximize benefits that, otherwise, look mutually incompatible in the current structure of the studied technical system.

The work described in [17] faces hurdles in complementing AD and TRIZ at a more practical level. As widely explained in section 3, the most popular methodological connection is constituted by the use of TRIZ to the scope of finding new concepts for decoupling matrixes. The authors of the contribution lay bare that a formalized TRIZ contradiction does not directly descend from the outputs of AD applications in terms of critical functional requirements and design parameters. An abstraction process is indeed required in order to accomplish the task. On the one hand, problematic design parameters may not be defined in the formal terms of TRIZ engineering parameters, which are relevant when the problem solver wants to use the contradiction matrix. On the other hand, the identification of functional requirements to be decoupled does not comprise the whole information required to describe a contradiction.

5. Discussion and authors' point of view

The paper has attempted to produce a compendium of the most meaningful experiences and discussions about the opportunities to employ AD and TRIZ in a synergic way. Many scientific papers agree upon the beneficial integration between the two theories. However, after a period in which the literature has focused contextually on AD and TRIZ, a clear drop has followed of the attention dedicated to their use in concert. The motivations of this decline do not seem related to the development of an acknowledged model that benefits from both the knowledge domains. Indeed, the presented survey highlights that theoretical and methodological hindrances have not been removed.

More specifically, scholars have individuated the greatest synergy in terms of implementing TRIZ creative capabilities to fulfil the objectives posed by the Independence Axiom. In this sense, TRIZ has been merely interpreted as a brilliant problem solving approach, while its analytical body of knowledge has been largely disregarded. Therefore, the matching between AD and TRIZ has been meant as a practical measure to solve specific design problems arising after the analysis of involved functional requirements and design parameters. Hence, the destiny of the conjoint use of AD and TRIZ has been delegated to the success of this troubleshooting strategy. If this hypothesis is correct and we consider the tendencies illustrated in Fig. 1, the outcomes of the employment of TRIZ for the scope of decoupling matrixes are, at the very least, arguable. We can claim that insufficient research has been carried out to overcome methodological issues that complicate the task of translating the AD objective of decoupling into the expression of a TRIZ contradiction. The need of abstracting and reconfiguring the information emerging from AD analysis into a suitable TRIZ form are discussed in section 4. In juxtaposition with this aspect, the authors introduce additional considerations in the followings. To the scope, it is worth recalling the complete description of a TRIZ contradiction in order to make the situation clearer. If we make specific reference to a branch of TRIZ development oriented to powerful thinking, i.e. OTSM-TRIZ [18], contradictions are appropriately schematized as in [19]. Fig. 2 reports this kind of representation, exploiting the example described in [19].

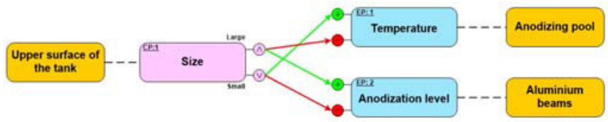

Fig. 2. Representation of a contradiction according to the formalities of OTSM-TRIZ.

This configuration requires indicating a control parameter (e.g. "size", pink box), which can assume at least two diverse values/conditions, and two evaluation parameters (e.g. "temperature", "anodizing level", blue boxes), among which just one is satisfied for a given state of the control parameter (e.g. small). AD schemas provide a network of design parameters and functional requirements. The former can be associated to control parameters, since the problem solver can leverage them in the design process, or, in another perspective, they represent dependent variables in a cause-effect function. Consequently, functional requirements are treated as evaluation parameters. The following circumstances can arise when a designer uses the AD framework and intends to exploit TRIZ for the creative stage of problem solving:

- A design parameter contextually influences two functional requirements; if the decrement or increment of the value of this parameter results in enhancing both functional requirements, the matrix is not uncoupled, but a proper contradiction cannot be formulated. Indeed, as in Fig. 2, a contradiction takes place if an assigned value of a control parameter gives rise to good outcomes in terms of an evaluation parameter, but a bad situation for the other one. In other terms, AD identifies troublesome situations whenever there is no separation between roles of functions' carriers, while TRIZ takes into consideration the way such relationships hold in order to discern if a conflict exists.

- More design parameters influence a functional requirement at the same time and their values do not impact on other performances of the system. Also in this case, no contradiction arises, because there is no inherent conflict between the values that the control parameter should mutually assume.

A further problem concerns the lack of knowledge about the dissemination of integrated AD/TRIZ design approaches. Preliminary experiences are described in [20] with reference to University education, while no information is available for industrial training. The cognitive load and the time dedicated to subsume the principles of design disciplines is absolutely noticeable, as confirmed by literature sources (especially with regards to TRIZ, as in [19]) and by hands-on experiences. The problem is even tougher when more design techniques have to be learnt and adopted contextually [21].

6. Final remarks and future activities

Despite the promising perspective of linking AD analysis capabilities and TRIZ potential in problem solving, we actually observe a vanishing interest of the design community with respect to their matched employment. The authors of the present paper support the reasons that have brought on the initial ferment. However, also in virtue of the presented investigation, they remark that some opportunities have been overlooked and that some methodological problems have not been suitably faced.

AD has been popularized thanks to the way it produces a holistic view of the design problem. Conversely, scholars have lingered with respect to the powerful means TRIZ offers to analyze more configurations of a given system and the resources it inherently possesses. We refer, e.g., to the System Operator and the Network of Contradictions. These instruments have demonstrated better problem-solving capabilities with respect to trivial heuristics, e.g. contradiction matrix, that have been diffusedly juxtaposed to AD in the reviewed literature. Hence, solutions are expected to be minor in number and to present better performances by benefitting from more efficient problem-solving patterns. This result can be seen as a support of the decisional phase of conceptual design, which could, as a result, simplify the use of the Information Axiom.

In this context, the authors' future activities have a twofold objective. On the one hand, they will investigate further barriers that prevent the display of benefits deriving from the matching of AD and TRIZ. Up to now, the analysis has been limited to literature sources describing both AD and TRIZ contextually. Other sources can potentially provide a major understanding about the versatility of both methods to fit various industrial contexts. A first attempt has been made in this sense: the reference work is quite dated and restricted to the manufacturing sector [3], while, for instance, AD and TRIZ are acquiring greater popularity in the service field with particular reference to healthcare [22, 23]. On the other hand, authors' work will concern more practical activities, by experiencing interfaces that allow to link the outputs of AD analysis and the inputs of powerful TRIZ-based instruments in a quick and intuitive way.

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