Enhancing functional decomposition and morphology with TRIZ: Literature review

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Abstract

One of most acknowledged approaches for conceptual design is the so-called "Functional Decomposition and Morphology" (FDM), which provides a systematic framework for transforming a set of technical requirements in a product concept. However, as observed by some scholars, this particular procedure acknowledges some flaws, also concerning a non-comprehensive support in generating creative ideas. Accordingly, literature suggests to combine creativity-enhancer tools or methods with the FDM process. The TRIZ base of knowledge appears to be one of the viable options, as shown in the fragmental indications reported in well-acknowledged design textbooks. Accordingly, other contributions can be found in literature, which are focused on more structured ways for enhancing FDM approaches with TRIZ. In such a context, the objectives of this paper is to collect the literature contributions focused on the TRIZ-FDM integration, with the aim of providing a first comprehensive classification and discussing about observable differences and lacks.

Keywords	TRIZ; systematic design; conceptual design; problem solving; design methods

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RESUBMISSION OF THE PAPER:

“Enhancing Functional Decomposition and Morphology with TRIZ: Literature Review”

Contents

COVER LETTER

This is a resubmission of the previously submitted paper COMIND-2017-2

Dear Editor, dear Reviewers,

First, we would like to thank you for the valuable efforts and suggestions, which in our opinion resulted very useful to improve the quality of the manuscript.

According to the received comments, we did our best to amend the paper and clarify the doubts risen by reviewers.
In particular, Abstract and Introduction have been partially modified to better explain the actual objectives of the work. Discussions section has been completely reformulated, better highlighting the flaws characterizing the reviewed literature and proposing potential hints for future research activities on TRIZ-FDM integration. Moreover, new important literature contributions have been cited, especially thanks to reviewers' observations.
Furthermore, other minor modifications and integrations have been carried out throughout the entire document, in order to improve the readability where possible.

Eventually, also the Conclusions section has been partially reformulated according to the operated integrations and modifications.

Therefore, we hope that our effort is sufficient for successfully overcoming the flaws arose in the first version of the paper.

Here in the following, a detailed list of answers to reviewers is reported.

Kind regards.

The authors.

ANSWERS TO REVIEWERS COMMENTS

NOTE:

Within the following answers we do not explicitly indicate the additional corrections and modification performed to cut the paper's length and or improve readability. Nevertheless, each performed modification or integration has been highlighted in the main document.

REVIEWER 1

COMMENT 1

The very first one is that the paper lacks of a clearly stated and claimed contribution. It is true that a paper could present a survey, but surveys of TRIZ, of FDM, of TRIZ and FDM have already been published (they are cited here) and this particular proposal is not bringing enough added elements to disserve a so long article. I would advise authors to rebuild the paper in order to introduce a case study based on their own way of merging TRIZ and FDM and justify what this new association is bringing as "new" to users/researchers.

Answer:

According to the first point mentioned by the reviewer (*the paper lacks of a clearly stated and claimed contribution*) we now better highlight the objectives in the introduction section, and a complete reformulation of Discussions (Section 5) have been carried out.

Now we hope it could be more evident that the paper is the first literature review focused on TRIZ-FDM integration, aiming at highlighting similarities, differences and lacks of the reviewed contributions, and providing suggestions for future research activities on the argument.

Accordingly, in the new Discussion section, we now present a clear list of the observed lacks (five), where also potential research hints are suggested accordingly. Consequently, besides being a first ever-performed literature review on the TRIZ-FDM integrations, this is now (after the performed revision) also the first paper that highlights the actual lacks characterizing the related literature contributions.

Therefore, we hope that, in light of the above-mentioned modifications and integrations, the originality and contribution of the paper are more evident and can be considered sufficient, according to the article category (i.e. a literature review).

Concerning the possibility to introduce our personal proposal, we kindly ask the reviewer to reconsider his/her suggestion. We intentionally aimed at presenting a review article because our study is currently limited to a literature review, and then we are not ready for submitting a new original proposal here. Of course, the contents of the paper constitute the starting point for our future researches, but we also hope that it could be useful to share the outcomes with other scholars interested in the same (or similar) arguments.

COMMENT 2

The second is that authors have submitted a proposal to Computers in Industry. I don't recall having red any perspective, vision, summary about a numerical, axiomatic, computed vision on their work making their contribution aside the core aims and scopes of the journal in which they intend to publish. I am convinced that the paper's topic would disserve such a discussion.

Answer:

According to the reviewer observation, among the lacks highlighted in Section 5 we now mention that concerning the implementation of the proposals into CAI tools. In the same section, a discussion about the recalled argument is reported. We hope it can be considered sufficient.

Moreover, we kindly inform the reviewer that before submitting the manuscript to Computers in Industry, we asked the Editor to perform a preliminary assessment of its suitability. The answer of the Editor was positive, without mentioning the need of inserting computational/algorithmic/axiomatic visions or perspectives or other issues related to the relevance of the content with respect to aims and scope of the journal.

Nevertheless, we have done our best to add such a kind of arguments, but it is worth to notice that the reviewed contributions and the paper type do not allow to extract more information in that sense.

COMMENT 3

The third one is linked with the discussable "up-to-date" vision of TRIZ authors present in the paper. TRIZ is now widely diffuse both in academia, in research labs and in acknowledged international journals. Recent researches, especially through Computers in Industry (but not only), have shown a more accurate and detailed description of TRIZ body of knowledge and its developments through its Ontology. These accepted and published papers, about TRIZ and IDM-TRIZ ontology are totally absent from authors' very long (and to be honest sometimes over-abundant) reference list. More, these (absent) papers are present in Computers in Industry, the journal in which authors intend to be published. Their absence from the reference list is truly questionable, especially when authors are directly addressing TRIZ community to build "univocal and non-ambiguous interpretations of the TRIZ tools" which is the aim of an ontology.

Answer:

According to the reviewer suggestion, we added the requested references in Section 5.

COMMENT 4

Some further remarks to take into consideration: "a physical contradiction arises when the same parameter is desired to be at two different levels (e.g. of big and 15 small)" is an example of an old an imprecise vision of TRIZ, even coming from Altshuller. Another paper in Computers in Industry, fully dedicated to the axiomatization of the contradiction (and also not cited) is fully describing it and advocates that as an engineer (and not a researcher) Altshuller didn't went deep into contradiction disambiguation like saying that things are contradictory only when there is a full opposition (Va and V opposite of a) therefore "big" and "small" is correct but not "levels" (like V1 and V2).

Answer:

According to the reviewer suggestion, we added the requested reference (in Section 5) and modified the wrong sentence highlighted by the reviewer.

REVIEWER 2

COMMENT 1

- I feel that the paper contributes no new knowledge to this well researched field. It correctly identifies the need for more standardization and understanding of each of the areas considered, but makes no attempt to suggest how this may be achieved. I would draw your attention to the (correct) citation for your reference 81; the conference held in 2015 on TRIZ and knowledge based innovation in Science and Industry. This publication contains 116 papers which could add to the progression of the ideas identified in this review.

Answer:

Thanks to the reviewer comment we noticed that a more comprehensive and detailed identification of the flaws related to the reviewed contributions was needed. Accordingly, we have now reformulated the Discussions section, by highlighting five different lacks that need to be addressed in future research activities.

It should be now more clear that the FDM-TRIZ integration is still an open researched field, since some important and critical investigations and research activities are still needed.

Concerning Standardization, we have now reformulated the suggestion. Indeed, thanks to the observation of the reviewers, we found that some recent efforts have been made in the TRIZ literature. Therefore, besides citing the existing contributions, we now focused our attention on the actual topic of the paper (i.e. TRIZ-FDM integration), suggesting to consider recent standardization efforts for future research activities on the TRIZ-FDM argument.

Concerning the reference 81 (now 90), we have corrected the data. Actually, since indexed as practitioner paper within the conference proceedings, it is not present in the Elsevier Procedia Engineering. It was a mere archiving error in my personal database, which automatically extracts formatted references for MS word.

Concerning the conference indicated by the reviewer (i.e. the TRIZ Future Conference TFC 2015) we kindly observe that it does not contain 116 contributions. Indeed, the papers from the recalled conference have been published in the Volume 39 of Procedia CIRP 2016, which contains only 38 articles. Nevertheless, we already analyzed such a set of contributions, but we didn't found articles with information focused on the TRIZ-FDM argument. Actually, two papers in the recalled set mention the Pahl and Beitz process (i.e. that of Manami et al. and that of Li et al.). But the first is an extension of the contribution already cited in our paper, where no additional information concerning the fundamentals of the TRIZ-FDM integration (TRIZ-SDA in the recalled paper) is reported. The second contribution is focused on the FDM functional modeling, but the involvement of TRIZ is unclear.

Maybe the reviewer is referring to Volume 131 of the Elsevier Procedia Engineering, where actually 116 contributions (a collection of TFC papers from 2012 to 2014) are present. In this case, we kindly note that some of the reviewed contributions already come from that set, which have been analyzed in deep by searching for contributions focused on TRIZ-FDM integration.

With the above mentioned integrations and observations, we hope that our effort could be appreciated by this reviewer, leading him/her to a better consideration of the proposed paper.

Enhancing Functional Decomposition and Morphology with TRIZ: Literature Review

ABSTRACT

One of most acknowledged approaches for conceptual design is the so-called "Functional Decomposition and Morphology" (FDM), which provides a systematic framework for transforming a set of technical requirements in a product concept. However, as observed by some scholars, this particular procedure acknowledges some flaws, also concerning a non-comprehensive support in generating creative ideas. Accordingly, literature suggests to combine creativity-enhancer tools or methods with the FDM process. The TRIZ base of knowledge appears to be one of the viable options, as shown in the fragmental indications reported in well-acknowledged design textbooks. Accordingly, other contributions can be found in literature, which are focused on more structured ways for enhancing FDM approaches with TRIZ. In such a context, the objectives of this paper is to collect the literature contributions focused on the TRIZ-FDM integration, with the aim of providing a first comprehensive classification and discussing about observable differences and lacks.

1. INTRODUCTION

The design process is a complex activity aimed at conceiving and developing product ideas, and providing the information needed for their physical realization. Several scholars deeply investigated such a fascinating process, leading to methods, models and theoretical discussions about designing. Among the design models acknowledged by literature [1]–[3], the so called "German systematic design" is one of the most taught and robust, grounding its historical roots on two centuries of engineering experiences [4]. In particular, concerning conceptual design activities, the recalled model adopts the well-known Functional Decomposition and Morphology (FDM) approach.

Unfortunately, despite their academic success, systematic approaches suffer a poor industrial diffusion, as well as other contributions coming from academia. Literature infers several possible reasons behind this lack and, among the others, a non-comprehensive support to (or even the hindering of) creativity (i.e. the ability to generate novel and useful ideas [5]) has been often pointed out as one of the most impacting ones. In order to overcome the recalled limitation, some scholars suggested the application of specific methods and/or tools to support idea generation activities (e.g. Pahl et al. [6]). One of these "aids" can be provided by TRIZ [7], which is considered in some textbooks (e.g. [8], [9]) as a suitable support for designers in generating creative solutions. However, the cited contributions only report very short introductions to the TRIZ body of knowledge, neglecting a comprehensive description about the use of the related tools within the FDM framework. Nevertheless, among the literature references concerning TRIZ, some of them propose different combinations with FDM aimed at exploiting the positive characteristics of both the approaches. In such a context, this paper argues about the current scientific proposals that explicitly try to enhance FDM with TRIZ. More precisely, the relevant contributions available in literature are collected and analyzed to understand how TRIZ tools are exploited in the fuzzy front-end phases of systematic design processes. Indeed, literature reviews focused on TRIZ are certainly present, but none of them contemplates the combined use with FDM. For instance, in [10] the authors performed an analysis of successful and unsuccessful cases in order to collect information about people who tried to apply and understand TRIZ methodology. Such a survey was aimed at indicating to beginners the tools of TRIZ toolkit useful to learn first, based on their observed degree of usage by the survey respondents. More recently, Chechurin at al. [11] presented a literature review of 100 most cited contributions about TRIZ to verify its diffusion and application fields. Furthermore, the literature presents publications that review the proposals aimed at integrating TRIZ with other methods like Axiomatic Design (AD) [12], or with other ideation tools and processes diffused in industry [13]. Hence, due to the absence of literature reviews focused on the FDM/TRIZ combination, this paper provides a first comprehensive state of the art on the recalled topic, with the aim of:

- Highlighting the main similarities and differences between the reviewed contributions.
- Discussing about their observable lacks.
- Providing suggestions for future research activities on the argument.

The following section reports a brief overview of TRIZ, introducing the fundamentals, the historical roots and information about its dissemination. In Section 3, the systematic conceptual design approach is introduced, together with a discussion about the possible causes that hinder its industrial uptake. In Section 4, the current literature contributions concerning possible links between FDM and TRIZ are reviewed and discussed. Section 5 reports a discussion on the outcomes of this work and the relevant research issues concerning the integration of FDM with TRIZ. Eventually, in the last section conclusions are presented, while the Appendix shortly introduces the TRIZ tools considered in the reviewed contributions.

2. SHORT INTRODUCTION TO TRIZ

TRIZ is the Russian acronym for "Teoriya Resheniya Izobretatelskikh Zadach", i.e. the "theory of the resolution of inventive problems" that was formerly developed by Genrich Altshuller, a Soviet engineer, inventor and science fiction writer [14]. The first publication ("On the psychology of inventive creation" [15]) dates back 1956 and argues about how to solve thousands of different technical contradictions by means of a limited number of "Inventive Principles" (see Appendix for a short introduction to the tool). In 1969, Altshuller published "The Innovation Algorithm" [16], a milestone where the well-known 40 Inventive Principles and the first version of the so-called "ARIZ" (Russian acronym for the "algorithm for the solution of inventive problems") were presented. The three main observations made by Altshuller as a consequence of his noticeable research effort, can be summarized as it follows [17]:

- Technical systems evolve according to objective laws, toward an increasing degree of ideality (i.e. the ratio between benefits and the sum of costs and harmful effects).

- Any specific technical problem can be converted into a more general one through an abstraction process. Thanks to the abstraction, Altshuller observed that similar problems arise in very different fields, allowing to group the related solving processes in a finite number of “solving principles”.
- Given a finite number of standardized problems and solving principles, solutions based on similar concepts can be used for solving apparently different technical problems. Consequently, it has been possible to build the invention theory, aimed at finding the most effective conceptual path for the generation of a solution.

According to the above-mentioned considerations, many inventive tools have been developed (part of them shortly introduced in Appendix), now constituting the TRIZ toolset. TRIZ actually supports problem solving and innovative solutions development, troubleshooting and failure prevention, incident management, new products-services-business concepts definition and administrative/management conflict resolution [18]. Therefore, it looks like a toolbox containing a set of tools to be conveniently selected, according to the specific needs. However, it is worth to notice that the selection of the tools is currently guided only by the experience of the user; therefore, he/she should be well trained for ensuring a correct application.

Moreover, several Classical TRIZ developments and/or alternatives arose during the years (e.g. SIT [19], USIT [20], CROST [21], etc.), but giving a thorough description of all these contributions is out of the scope of this paper. Nevertheless, two of them, i.e. the so called OTSM-TRIZ [22] and TOP-TRIZ [23] (where “OTSM” is the Russian acronym for “general theory of powerful thinking” and “TOP” stands for “Tool-Object-Product”) have been considered in some of the contributions reviewed in this paper. The two recalled TRIZ evolutions are mentioned in Section 4, and a short description of some related tools is reported in Appendix.

Concerning the diffusion of TRIZ, the fall of the Soviet regime allowed it to spread outward the Russian countries, especially thanks to some Altshuller's collaborators who transferred in North America, Europe and East Asia. Effectively, since the nineties of the last century, TRIZ is taught in universities and adopted by well-known companies across 35 countries [10]. Big multinational corporations immediately recognized its benefits [24] and maybe, Samsung represents one of the best experiences of TRIZ adoption in industry [25], [26]. Differently, academic world initially struggled in recognizing the TRIZ potentialities. Perhaps, the causes of this initial negative impact reside in the heuristic and not completely scientific origins of TRIZ basis, as well as in the non-academic origin of the teachers [27]. Moreover, the English translation of the Russian literature also played a crucial role in TRIZ dissemination. Indeed, only a minimal part of the original Russian contributions was initially translated [14], neglecting a comprehensive understating of Altshuller findings.

Nevertheless, the positive effects of TRIZ have been scientifically observed by performing evaluations and tests on samples formed by academic students (e.g. Hernandez et al. [28], Borgianni et al. [29]). Moreover, some scholars have performed investigations on the actual use of TRIZ tools within industry (Moherle [30], Ilevbare et al. [10]), substantially observing that only a limited and not univocally defined set of the available TRIZ tools is usually considered by practitioners. These evidences show that, despite the potentialities, the actual use and understanding of TRIZ tools is far to be standardized.

3. THE SYSTEMATIC APPROACH FOR CONCEPTUAL DESIGN, LIMITATIONS AND ATTEMPTS OF IMPROVEMENT

3.1. Fundamentals

The so-called German systematic design approach actually started to evolve from the second half of the last century [4], as for the related design guidelines [31] that have been proposed and successively updated, up to the current VDI Guideline 2221 [32]. Nevertheless, the model proposed by G. Pahl and W. Beitz [6] still represents one of the most acknowledged versions of the recalled approach. It is constituted by four key phases, i.e. the clarification of the design task, the conceptual design, the embodiment design and the detail design [6]. During task clarification, the designer has to focus on “what” he/she has to design, by defining design objectives and constraints. Starting from the outcome of the first phase (i.e. a requirement list), the conceptual design phase aims at modeling the functionalities of the system, selecting the working principles and schematically representing and selecting overall solution variants. At the end of this step, preliminary information about the system and the related production process is available, allowing to perform first evaluations and undertake decisions. Moreover, the fundamentals for the subsequent design phases are defined, enabling the development of the system details, up to the realization of production documents. For such a reason, conceptualizing is well acknowledged to be a crucial step in the design process, influencing the 60-80% of the overall product design costs [33], [34] and the likelihood of product success [8].

Well-known classical design models (e.g. those reported in [6], [8], [9], [35]), consider FDM-based approaches for performing conceptual design tasks. More precisely, the overall function of the product is identified according to the set of available requirements, and is decomposed in various levels of sub-functions, depending on the related complexity [6]. The considered functional model follows the well-known Energy-Material-Signal (EMS) formalism [6], where functions are graphically represented by boxes, and specific flows of energy, material and signals (represented by different arrowed lines), constitute inputs and outputs of functions. Once a function structure is generated, it constitutes a sort of “base” for generating overall concepts. More specifically, different possible solutions are identified for the implementation of each sub-function, and schematic representations of them are listed in a graphical tool, i.e. the “morphological chart” [6] or “morphological box” [36], derived from the so called morphological approach [37]. In this way, different combinations can be evaluated, within the variety of solutions found for implementing each single sub-function. Finally, after the realization of sketches representing the preferred solution variants, a selection process is performed by means of specific tools, e.g. the “Concept selection matrix” [38], “Selection charts” [6] or QFD-like matrices [39].

In order to provide a generalization among the various FDM-based models (e.g.[6], [8], [9], [35]), we identify four main steps to represent the activities performed by the designer in the fuzzy front-end of the systematic design process. The recalled steps are reported and described in Table 1, and constitutes the reference framework for the scopes of this paper.

Table 1 The four main steps representing the design activities in the fuzzy front-end of the design process.

MAIN STEPS	DESCRIPTION
Generation of a requirement list.	It is the outcome of the "planning and task clarification" phase in the Pahl and Beitz model [6], but also in the other ones, the setting up of a set of requirements (or specifications) constitutes the starting point for succeeding conceptual design activities.
Formulation of the functional problems to be solved.	A function structure, in the form of the EMS-based functional model, is a graphical representation of the functionalities of the system and their interactions (through the EMS flows). However, once the functions have been defined, it is necessary to generate (or simply to find) specific solutions for their implementations (working principles [6]). This is why we consider the function structure also as a "list" of functional problems.
Definition of the solutions related to the formulated problems.	This is the step associated with the setting-up of morphological charts [6]or concept combination tables [8].
Selection of the preferred concept variants.	This is the last step of any systematic conceptual design approach, where the different concepts are evaluated and selected by means of different processes and tools.

3.2. FDM flaws

Despite some issues raised by scholars (e.g. [40]–[42]), FDM reached a great success in academia, as a part of one of the most taught design models [27]. However, a non-negligible gap has been observed, between the recalled academic diffusion and the actual industrial uptake. Indeed, industrial practitioners rarely follow FDM, even where the recalled systematic approach is traditionally diffused (e.g. Germany) [43]. As reported in the introduction of this paper, this is a common issue for academic methods [44]–[49], and the reasons of such a gap have been investigated also through ethnographic surveys (e.g. in UK, USA, Germany). As a result, some hypotheses have been inferred, together with some potential suggestions for a successful knowledge transfer. Considering the contributions quoted above [44]–[49], main emerged aspects concern the perceived laboriousness, the poor training, which lead to incorrect use of methods, the need to adapt methods to the modern designer's exigencies, the need of software tools implementing design processes and the need of paramount importance, i.e. that of a comprehensive information exchange between academia and industry.

Additionally, generating functional descriptions is acknowledged to be a difficult task [50], where the presence of several different definitions also worsens the problem [51]. Indeed, the existence of very different meanings of the term “function” generates uncertainties and difficulties in mutual communications between different functional modeling approaches [52], or even between designers with different native languages [53]. Accordingly, Pahl and Beitz report some practical experiences in applying their systematic approach [6], highlighting that one of the main difficulties faced by designers, is to think in terms of functions.

However, Birkhofer [54] reports that frequent objections to the systematic approach concern a limited support to creativity and, accordingly, Tomiyama et al. [27] assert that one of the reasons of the poor industrial application of systematic approaches is that they do not sufficiently support innovative design. Leenders et al. [55] (as quoted in [41]) state that an excessive use of the functional decomposition limits designer’s freedom and consequently limits her/his creativity. It is probably from these considerations that some scholars tried to enhance creativity in the early phases of the systematic design process, by considering the support of specific methodological tools. For example, Pahl et al. [6] suggest the use of several methods for supporting the generation of creative solutions (e.g. Brainstorming, 6-3-5, Synectics, etc.), while in other textbooks it is possible to find TRIZ as potential support [8], [9]. However, on the one hand, the recalled textbooks [8], [9] neglect a comprehensive description about how to apply the TRIZ toolset within FDM steps, implying the impossibility of a complete exploitation of the related potentialities. On the other hand, some literature contributions can be found about TRIZ/FDM combination proposals, but they are characterized by non-negligible differences that need to be analyzed and discussed.

4. CURRENT LINK BETWEEN FDM AND TRIZ

In this section a review is reported, concerning the proposals aimed at combining FDM with TRIZ. The set of reviewed contributions has been identified by searching within literature databases like (but not limited to) Scopus, Google Scholar, Web of Science and Procedia Engineering Elsevier. The latter, has been considered since periodically publishes the scientific contributions of the ETRIA (European TRIZ Association) TRIZ Future Conferences (TFC). More specifically, many different search queries have been formulated by matching a list of terms within different document fields. Such terms were “TRIZ” or “TIPS (Theory of Inventive Problem Solving)”, in combination with “SAPB (Systematic Approach of Pahl and Beitz)”, “FDM”, “Morphological Analysis”, or simply “Pahl and/or Beitz”. Therefore, we iteratively analyzed search results and deepened the research with new information gathered from them, e.g. from their reference lists.

More specifically, the literature review considers only the contributions that explicitly mention FDM and TRIZ; therefore, the reader may found other similar proposals in literature, not considered here. For example, Franke and Deimel [56] proposed a combination of various methods for supporting FDM where TRIZ was marginally used, leading us to not consider the contribution in this survey. Under certain aspects, also the so called Unified Structured Inventive Thinking (USIT) [20], [57] could be considered a hybrid approach where some inventive tools are structured in a design process that has some similarities with the systematic one

[58]. However, such a method has not been considered in this review, since neither the original TRIZ nor FDM are explicitly involved. Then, excluding contributions like those mentioned above, the considered set is the one shown in the following paragraphs.

4.1. Short introduction to the literature contributions

4.1.1. The unification proposal of Malmqvist et al.

The unification proposal of Malmqvist et al. [59] puts its basis upon a comparison aimed at identifying similarities and differences between TRIZ and SAPB. As a result, the FDM phases related to task clarification, problem decomposition and search for solution principles have been modified as it follows. In the task clarification phase, they substantially modify the original Pahl and Beitz model by adding a new sub step devoted to the application of the Laws of Engineering System Evolution (LESE) tool (see Appendix) for performing technological forecasting. For the problem formulation phase, they suggest to follow an alternative path, by using the Ideal Final Result (IFR) (that they call "Ideal Solution"), Physical Contradictions and some ARIZ steps (see Table 2). Then, the authors suggest to continue by using the TRIZ Standard Solutions, the Pointer to Effects and the Inventive Principles when searching for SAPB working principles. Unfortunately, no detailed indications have been provided about how to apply the proposed method in practice.

Furthermore, it is worth to highlight that an ambiguous definition of technical contradiction has been used in the paper. Indeed, they report *"… physical contradictions arise when a certain parameter cannot be improved without causing another to deteriorate"*, which is not correct, because a physical contradiction arises when the same parameter should assume two mutually opposed values (e.g. of big and small) [7]. Actually, the recalled definition refers to a technical contradiction, but later in the same article, a correct definition of the physical contradiction appears. Therefore, we are not sure about the correctness of the term “physical contradiction” used in the unification proposal.

4.1.2. The QTC approach of León-Rovira

León-Rovira [60] proposes an approach called QTC (QFD-TRIZ-CAD) where TRIZ is exploited to enrich the contents of a pre-compiled morphological chart, obtained by following the classic systematic procedure. More precisely, the first part of the proposed process starts with the QFD House of quality (HoQ) [39] to identify product parameters to be changed or preserved, and ends with the realization of a first morphological chart. After that, León-Rovira proposes to formulate the IFR for identifying contradictions on the roof of the HoQ, and to solve them by means of the TRIZ inventive principles and the contradiction matrix. In this way, the designer is supposed to enrich the preliminary morphological chart with new creative solutions. Moreover, Léon-Rovira suggests to convert technical contradictions in physical contradictions, and to work on their resolution. However, although the proposal considers only a very limited set of TRIZ tools, a comprehensive guideline for its practical use is missing.

4.1.3. The new functional model of Ogot

Another attempt to exploit the advantages of both TRIZ and SAPB is that of Ogot [61], where the black-box model of the systematic approach is considered as a possible mean to improve the diffusion of TRIZ in industry and academia. More precisely, he conceived a new EMS-based black-box model where, instead of functions, boxes represent parts of the systems. In addition to the classical EMS flows [6], other formalisms have been introduced to highlight harmful and not sufficient flows according to the TRIZ functional modeling. In this way, a condensed version of the TRIZ standard solutions (called “condensed standards”), composed by 27 solutions (instead of 76), is used to modify the original system whereas the proposed model highlights inefficiencies.

4.1.4. The use of contradictions suggested by Liu et al.

Liu et al. [62] propose a new enhanced conceptual design approach strongly based on the Pahl and Beitz one, where the working principles generated for functions are analyzed in order to find contradictions. Then, if technical or physical contradictions are detected, the authors propose to use the classic TRIZ procedure for solving them. More precisely, in case of technical contradictions, they suggest to use the 39 parameters, the 40 inventive principles and the contradiction matrix. Instead, in case of physical contradictions, they suggest to apply the four separation principles together with inventive principles. Indeed, it is possible to link separation principles to the 40 inventive principles, in order to use them as a further aid to solve physical contradictions [63].

4.1.5. The integration proposed by Dietz and Mistree.

Dietz and Mistree [64] consider the Pahl and Beitz model as the base for obtaining a new augmented approach, where TRIZ is used with the aim to improve the effectiveness of the conceptual design process, in term of design space exploration and information transfer between different domains. The authors propose a procedural model where some TRIZ tools are involved in different conceptual design steps. In particular, similarly to Malmqvist et al. [59] they suggest the use of the LESE for performing technology forecasting during the task clarification phase but excludes the use of this tool for simplistic design problems. The majority of TRIZ tools has been suggested for the other conceptual design phases, structuring them also by referring to ARIZ. More precisely, the same ARIZ steps considered by Malmqvist et al. [59] appear in the proposed problem formulation phase, after the functional modeling of SAPB. Then, IFR, physical contradictions and "Substance-Field" (S-Field or Su-Field) modeling are considered for avoiding design fixation when formulating (functional) problems. In particular, the authors claim that Su-Field modeling allows a more concrete representation of the design problem, if compared with classical EMS-based function structures. For the subsequent SAPB phase, i.e. the solution finding, authors suggest the use of Separation Principles, Standard Solutions, Pointers to Effect (that they call "Effect & Phenomena") and the 40 Inventive Principles together with other tools not belonging to the TRIZ base of knowledge. The remaining SAPB steps are unaltered.

4.1.6. The FB-Matrix of Nix et al.

The proposal of Nix et al. [65] aims at merging the functional modeling philosophy of SAPB with the inventive problem solving of TRIZ. In particular, a functional basis [66] and the inventive principles of TRIZ are used together to obtain the so called FB-TRIZ Matrix. More precisely, the authors extracted functions involved in the definitions of the 40 inventive principles, which constitute the rows of the above mentioned matrix. Instead, the three columns represent the three EMS flows of the Pahl and Beitz functional model. Then, the selected inventive principles are placed in each box of the matrix, to be consulted during the design process. More precisely, a certain box contains those inventive principles whose definitions contain the function of the related row, and that can be applied to a specific flow of the EMS model. The logic of the proposal consists in using the FB-TRIZ matrix after a first realization of the EMS functional model of the concept, for exploiting the potentialities of the TRIZ inventive principles when searching for additional solutions. However the approach substantially modifies the fundamentals of TRIZ, because foresees the use of the inventive principles without extracting contradictions.

4.1.7. Deimel and the Braunschweiger design model

Deimel [67] proposes the use of some TRIZ tools for specific phases of a systematic design approach called “Braunschweiger” design model [67]. Such a model is very similar to SAPB, especially for the first phases. For each of these phases the author proposed to support the process with TRIZ and other classical methods, not mentioned in this paper. The design phase with the higher number of suggested TRIZ tools is that related to the finding of principle solutions (see Table 2). Morevorer, these authors are the sole suggesting the use of the “Innovation-Situation-Questionnaire” (ISQ), the “Resources Checklist” and the “S-shaped curve” (S-Curve) (See appendix for a short introduction to the recalled tools).

4.1.8. The integration proposal of Mayda and Börklü

Another contribution considered in this survey is that of Mayda and R. Börklü [68]. The aim of their work is namely to enhance conceptual design by reducing the time consumption and increasing the chances to find innovative solutions. They take the Pahl and Beitz model as reference and suggest the use of a limited set of TRIZ tools. More specifically, they assert that it is possible to find contradictions (physical and technical) between the formulated functional problems. Therefore, they suggest to use classical TRIZ tools for solving contradictions during the problem formulation phase, and to formulate new problems based on inventive principles or separation principles. In this way, i.e. by resolving contradictions in advance, the authors claim a possible reduction of the iterations within the design process.

Inventive principles are also considered in the solution-finding phase. More precisely, for each sub function, the authors suggest to check each of the 40 inventive principles and to select the most suitable ones for the development of the implementing solutions. Finally, after the concept selection phase, they propose to apply S-fields and the standard solutions to strengthen the weak points of the preferred solutions. The latter suggestion has not been considered in this paper, since it operates on the results of the conceptual design phase, and not within the development process of the first versions of the concepts.

4.1.9. The list of Frillici et al.

The aim of such contribution [69] is not to modify the logic of functional decomposition and morphology, but only to indicate most suitable TRIZ tools for enhancing each of the main, generally valid, conceptual design phases. Most of the tools were selected from the classical TRIZ base of knowledge, while others were selected from some new developments of the classical theory of Altshuller, i.e. OTSM-TRIZ and TOP-TRIZ.

More precisely, they suggest one tool for supporting the definition of the requirement list, three for supporting the main problem decomposition, thirteen for supporting the generation of solutions, and five for supporting solution combination. Among the suggest tools it is possible to find the operator “Size-Time-Cost” (STC), the “Smart-Little-People” (SLP), the OTSM-TRIZ “Element-Name-Value” (ENV) model and the “Network of Problems” (NoP).

4.1.10. The TRIZ-SDA approach of Manami et al.

Eventually, Manami et al. [70] propose a new approach called TRIZ-SDA, where SDA stands for Systematic Design Approach. The proposal mainly aims at considering safety issues during the conceptual design process, referring to the Pahl and Beitz framework. The TRIZ 40 Inventive Principles are grouped underneath their correlation with literature safety principles [6], in order to be selected for solving the related contradictions. The authors suggest the use of the TRIZ functional modeling instead of the FDM one, to improve the understanding of product characteristics. Technical Contradictions identification is performed during the composition of the concept variants. In such step, the 39 parameters used for formulating contradictions are selected in terms of compatibility with the most appropriate safety principle. Then, a limited set of inventive principles is selected coherently to the chosen safety principle. Also physical contradictions are considered, and the inventive principles related to the separation ones are used to find solutions, according to the relationship with the safety principles.

4.2. Positioning TRIZ tools in the FDM systematic framework

On the base of the information available in the contributions surveyed above, the different attempts aimed at exploiting the advantages of TRIZ and FDM together are here examined more in deep. Due to the non-negligible heterogeneity that characterizes the logic of the reviewed proposals, identifying general traits among them is a difficult task. Nevertheless, it is possible to note that some of the considered contributions aim at modifying the original FDM model, creating a sort of hybrid with TRIZ. The contributions that fall into this “merging-type” category are those of Malmqvist et al. [59], Léon-Rovira [60], Ogot [61], Dietz and Mistree [64], Nix et al. [65] and Manami [70]. However, by following this way, a non-negligible drawback exists. Indeed, the fundamentals of FDM and TRIZ are not completely preserved. It implies that applicability and robustness of the new resulting methods have to be assessed more comprehensively, e.g. through several case study applications.

Differently, the other contributions do not aim at obtaining a new methodological proposal, since they only indicate a selection of TRIZ tools suitable for supporting specific conceptual design phases. For these "support-type" contributions, the applicability of both the theories is preserved, and the effectiveness of the proposals strongly depends on the user expertise in using the selected tools.

Moreover, the schematization of the design process given by the German systematic approach is often used as a reference framework for selecting and/or implementing TRIZ tools suitable for the engineering design context. Accordingly, the generalized FDM phases listed in Table 1 are considered here to provide a shared framework for clustering and classifying the different TRIZ tools in reference to the conceptual design process. However, since TRIZ has not been exploited for supporting concept selection, such a phase is not considered here for classifying and analyzing the reviewed contributions.

Therefore, the suggested TRIZ tools are listed in Table 2 according to the framework introduced in Section 3 (basic information about the mentioned TRIZ tools is reported in Appendix), and grouped in terms of their integration strategy (merging-type vs support-type). Here in the following, the suggestions listed in each column of Table 2 are analyzed more in deep, according to the information available in the reviewed literature. Moreover, in Figure 1 we report the count of the occurrences of the identified tools across the different design phases and across the two groups (i.e. merging and supporting).

4.2.1. Generation of a requirement list.

For this phase of the conceptual design process, Table 2 and Figure 1 show that only five different tools have been proposed, i.e. LESE, ISQ (“Innovation Situation Questionnaire” or also called “Innovation Checklist”), Resources Checklist, System Operator and Evolutionary trends.

The use of LESE has been considered by two “merging-type” contributions, suggesting to use them for technology forecasting purposes, and then, for supporting the definition of the requirement list. Accordingly, despite the different group type (i.e. support-type), also Frillici et al. [69] indicate LESE as a valid tool for supporting the same phase. More precisely, they assert that the tool may support in defining requirements and in orienting the conceptual design process (according to TRIZ laws of evolution). Differently, Deimel [67] suggests two different tools, i.e. the ISQ and the Resources checklist. No information about the detailed use of these tools is provided, except for a general indication (without details) concerning the possibility to use the ISQ in addition to the Search Matrix of Franke [71]. It is also worth to highlight that Deimel originally called the ISQ with another name, i.e. “Innovation checklist”, as for many German users of TRIZ [72].

Finally, Mayda and Börklü [68] do not explicitly consider any tool for this specific phase, but mention the System Operator and the eight Evolutionary trends (or simply Trends) as possible support for the task clarification phase. However, no further indications are provided.

Table 2 TRIZ tools involved in the considered proposals, grouped by the affected conceptual design step (in order to ease the understanding of the contents we adopted our “unified” names for the tools.).

		SYSTEMATIC CONCEPTUAL DESIGN STEPS			
		Generation of a requirement list	***Formulation of problems***	***Solution identification for each single problem***	***Solution combination***
MERGING –TYPE CONTRIBUTIONS	Malmqvist et al. [59], 1996.	*LESE*	*IFR* *Technical Contradictions* *Physical Contradictions* *Some ARIZ steps*	*Standard Solutions* *Pointers to Effects* *Inventive Principles*	-
	Léon-Rovira [60], 2002.	-	-	*IFR* *Contradiction Matrix* *Inventive Principles* *Technical Contradictions* *Physical Contradictions*	-
	Ogot [61], 2004.	-	*Functional Modeling*	*Standard Solutions*	-
	Dietz and Mistree [64], 2009.	*LESE*	*IFR* *Technical Contradictions* *Physical Contradictions* *Su-Field model* *Some ARIZ steps*	*Separation Principles* *Standard Solutions* *Pointers to Effect* *Inventive Principles*	-
	Nix et al. [65], 2011.	-	-	*Inventive Principles*	-
	Manami et al. [70], 2015.	-	*Functional Modeling*	-	*Technical contradictions* *Inventive Principles* *Physical contradictions* *Separation principles*
SUPPORT-TYPE CONTRIBUTIONS	Liu et al. [62], 2008.	-	-	*Technical contradictions* *Inventive Principles* *Physical contradictions* *Separation Principles*	-
	Deimel [67], 2011.	*ISQ* *Resources Checklist*	*Functional Modeling* *Problem Formulation Process*	*Trimming* *IFR* *Operator STC* *SLP* *Technical Contradictions* *Inventive Principles* *Physical Contradictions* *Separation Principles* *Su-Field Model* *Evolutionary Trends* *S-Curve* *Anticipated Error Determination*	-
	Mayda and R. Börklü [68], 2014.	*System Operator* *Evolutionary Trends*	*Technical Contradictions* *Contradictions Matrix* *Inventive Principles* *Physical Contradictions* *Separation principles*	*Inventive Principles*	-
	Frillici et al. [69], 2015.	*LESE*	*Functional Modeling* *System Operator* *OTSM-TRIZ NoP*	*LESE* *Su-Field model* *Standard Solutions* *IFR* *Pointers to Effects* *SLP* *Operator STC* *Technical Contradictions* *Physical Contradictions* *Inventive Principles* *Separation Principles* *System Operator* *TOP TRIZ*	*Technical Contradictions* *Physical Contradictions* *Inventive Principles* *OTSM-TRIZ ENV model* *Separation Principles*

Tools	Generation of a req. list – Merging	Generation of a req. list – Supporting	Formulation of problems – Merging	Formulation of problems – Supporting	Solution identification – Merging	Solution identification – Supporting	Solution combination – Merging	Solution combination – Supporting	Total count – Merging	Total count – Supporting	Total count – Overall
Inventive principles				1	4	4	1	1	5	6	11
Physical Contradictions			2	1	1	3	1	1	4	5	9
Technical Contradictions			2	1	1	3	1	1	4	5	9
Separation principles				1	1	3	1	1	2	5	7
IFR			2		1	2			3	2	5
Functional modeling			2	2					2	2	4
LESE	2	1			1				3	1	4
Standard solutions					3	1			3	1	4
Pointers to effects					2	1			2	1	3
Su-field model			1			2			1	2	3
System operator		1		1		1			0	3	3
ARIZ steps			2						2	0	2
Contradiction matrix				1	1				1	1	2
SLP						2			0	2	2
STC						2			0	2	2
Trends of evolutions		1				1			0	2	2
Anticipated error determination						1			0	1	1
ENV model								1	0	1	1
ISQ		1							0	1	1
NoP				1					0	1	1
Problem formulation process				1					0	1	1
Resources Checklist		1							0	1	1
S-curve						1			0	1	1
TOP TRIZ								1	0	1	1
Trimming						1			0	1	1

Figure 1. Distribution of the tools occurrences observed across the general design phases listed in Table 1, and across the two identified groups.

Even in this case, we are not sure about the tool suggested. Indeed, the same authors wrongly assert that Malmqvist et al. [59] suggested the use of the Trends, while they actually mentioned the Laws of Evolution (LESE). It is important to highlight that Trends and LESE are not the same tool, although the former comes from the latter [21], [73].

4.2.2. Formulation of problems.

The use of both contradiction types (Technical and Physical) is quite common across the two types of contributions. Malmqvist et al. [59], and similarly Dietz and Mistree [64], considered the contradictions in a well-defined sequence of steps for formulating the problems, without any attempt to solve them in this specific conceptual design phase. Differently, Mayda and Börklü [68] use the 40 inventive principles, the contradiction matrix and the four separation principles for solving contradictions between problems, with the aim of defining other more ideal ones.

Functional modelling is another tool that has been commonly used across the two types of contributions. Ogot [61] tried to merge the classic EMS-based model with indications about harmful, useful and insufficient functions provided by the TRIZ functional model, while Manami et al. [70] suggest to use the latter instead of the original EMS one. Deimel [67] suggests two different models concerning functions, i.e. what they call the “Object modelling” and the “Functional modelling”. In this case, we found some difficulties in understanding which tools were actually indicated by the authors. Indeed, we found that in the German TRIZ literature, the “object modelling” term often refers to what we usually call as “TRIZ functional modelling” [74], [75] (i.e. the graphical tool where the nodes constitute the system elements, and the connections are the functions amongst elements). Instead, what Deimel calls “Functional modelling” seems to be what we usually call “Problem Formulation Process” [76]. Unfortunately, the author provides no further information about the use of the tools. Eventually, Frillici et al. [69] state that the TRIZ functional model can be used for supporting the problem formulation phase thanks to the rich description of the system if compared with the classical EMS-based functional model. However, even in this case, a more comprehensive description is missing.

Dietz and Mistree [64] (similarly to Malmqvist et al. [59]) propose the use of IFR in this phase, asserting that it constitutes the goal of the design activity, and could also be used along the requirement list as a measure of the final design performance and for concept selection. The same authors propose the use of the tool together with other ARIZ steps, merged with other ones belonging to SAPB. Moreover, the Su-Field modelling is considered for a graphical and more abstract representation of the problems.

Frillici et al. [69] have suggested the System Operator as a valid help for searching alternative problems for satisfying requirements, and for addressing them by different perspectives. They also assert that the tool can be useful for discussing about the correctness of the design task. The same authors suggest the use of the OTSM Network of Problems (NoP) [77] for managing the decomposition of the design problems and the possible logical interactions between them.

4.2.3. Solution identification for each single function.

This phase is the most populated by suggestions concerning potentially exploitable TRIZ tools, among which, inventive principles and separation principles. Some differences can be observed amongst who applies them as a consequence of the contradiction modelling performed in the preceding phase (e.g. Dietz and Mistree [64]) and who extracts contradictions and applies principles in the same phase [67], [69].

Mayda and Börklü [68] proposed a particular use of inventive principles without the contradiction matrix, asserting that in this phase the designer has not to solve contradictions but to find inventive solutions. But, maybe the most alternative use of inventive principles is that proposed by Nix et al. [65], with their FB-Matrix. Indeed, as previously mentioned, inventive principles are supposed to be used without explicitly extract contradictions.

Another tool often considered in this phase is the “Standard Solutions”, explicitly considered by three merging-type contributions and by a support-type one. For Dietz and Mistree [64], similarly to Malmqvist et al. [59], Standard Solutions are supposed to support the designer in solving the problems, and then in finding solutions. Frillici et al. [69] suggest the use of both Su-Field modelling and the Standard Solutions to extract problems from the functional models and to find solutions by analogy with abstract models of effective solutions. Differently, Ogot [61] considers a condensed set of 27 standard solutions, for being used with his modified version of the EMS-based functional model.

Pointers to Effects is another tool that can contribute in solution finding activities, i.e. in searching for suitable physical, chemical and geometrical effects, for developing specific working principles. However, as reported in Table 2, some other tools have been suggested, especially by Deimel [67] and Frillici et al. [69], but in the first case, the available information does not allow to better specify how these tools are supposed to be used. In the second case, available information allows to assert that SLP, STC and the System Operator are intended to help the designer in overcoming psychological barriers, while LESE are now supposed to inspire possible modifications of initial versions of the system. Finally, the TOP-TRIZ “sufficient function building” is considered for helping designers in finding suitable behaviors and structures for implementing previously defined functions.

4.2.4. Solution combination

For this phase, only two of the considered contributions proposed some tools, i.e. Frillici et al. [69] and Manami et al. [70]. Despite the differed affinity with considered groups (i.e. supporting and merging), both the contributions contemplate contradiction modelling and related principles as potentially valid tools. However, it is worth to notice that Manami et al. [70] propose a particular use of inventive and separation principles, focused on facing safety issues, and grouped according to the Pahl and Beitz safety principles [6].

Finally, Frillici et al. [69] suggest the use of the OTSM-TRIZ ENV model, for giving more support in finding additional contradictions.

4.3. Commonalities and differences between the reviewed approaches

As can be seen in Figure 1, the reviewed contributions show a non-negligible level of heterogeneity in how TRIZ can be exploited in classical FDM-based approaches. Therefore, it is not possible to identify any apparent trend in the selection and the implementation of the inventive tools. However, according to the few indications provided by the well-acknowledged contributions of Ullman [9] and Ulrich and Eppinger [8], Figure 1 shows that most of the TRIZ tools are intended to support solution generation activities. More precisely, the two types of proposals (merging-type and support-type) have equally considered IP for the recalled phase, while, beyond the others, some differences can be observed about the use of Contradictions (Figure 1).

Nevertheless, reviewed contributions reveal that TRIZ is expected to provide a comprehensive support for FDM approaches. Indeed, except for the selection phase, almost the entire conceptual design process has been supposed to benefit of different inventive tools. This is partially in accord with Leon Rovira and Terninko (TRIZ experts consulted by Carvalho et al. [78]), who stated that TRIZ can be used for removing contradictions and for solving problems, independently on the specific design phase.

5. Considering the specific objectives that the authors claim in their works, we found an almost totally shared intention, i.e. to improve the FDM approach. More precisely, in reference to the FDM flaws introduced in Section 3, the performed review highlights that the contributions available in literature explicitly face the drawbacks/limitations related to the generation of creative or innovative solutions, while the other issues are not explicitly tackled.

DISCUSSIONS ON THE CURRENT LINK BETWEEN TRIZ AND FDM

Besides commonalities and differences reported in the previous section, the performed review highlights five important lacks, which should be faced in future research activities concerning the integration between TRIZ and FDM:

- The absence of a standard vision about TRIZ tools.
- The industry perspective is totally neglected, especially for what industry practitioners actually expect from a conceptual design method.
- The effectiveness of the proposals has not been assessed comprehensively.
- TRIZ and FDM are based on the notion of "function" but, unfortunately, the underpinning concepts are not equivalent.
- Issues concerning the implementation of the proposed TRIZ-FDM integrations in computerized tools have sometimes been considered in the reviewed contributions, but neglecting comprehensive indications or information.

In the following paragraphs, the recalled issues are discussed more in detail.

5.1. About the importance of a standard for TRIZ

We found that for a single tool, many different names are used in the reviewed contributions, leading to uncertainties when performing a simple comparison among the different available suggestions. For instance, what we usually call "technical contradiction", is also defined as "system conflict" (e.g. in [59]) or even as "engineering contradiction" [70]. Another example is that concerning the "Operator MZK" [67] that we call "Operator STC", or even that concerning "object modelling" often identified as "function modelling". This is certainly not a critical problem, but ambiguous names could lead non-expert users to uncertainties and, then, to a waste of time when trying to apply TRIZ. In Table 3, we report all the translations of the TRIZ tools performed in this paper, on the names of the original versions encountered in some of the reviewed contributions.

Table 3 Translations and/or disambiguation performed on original versions of the tools names found in some reviewed contributions.

TOOL	ORIGINAL VERSIONS			
	Malmqvist et al. [59]	Dietz and Mistree [64]	Deimel [67]	Frillici et al. [69]
Functional modeling [74]	-	-	Object modeling	-
IFR [79]	-	-	Ideality	-
ISQ [14]	-	-	Innovation checklist	-
Operator STC [80]	-	-	Operator MZK	-
Physical contradictions [7]	-	-	-	Contradiction modeling
Pointer to effects [74]	Effects	Effect and phenomena	-	-
Problem formulation process [14]	-	-	Functional modeling	-
Standard solutions [24]	Standards	-	-	-
Su-field model [81]	-	S-field	-	-
Technical contradictions [82]	System conflict	-	-	Contradiction modeling
Evolutionary trends [74]	-	-	Evolution principles	-

Obviously, we do not want to assert that the names we propose are the right ones, but we only want to emphasize the importance of a "unification" effort from the TRIZ community. Accordingly, some recent contributions tries to provide specific answers to the recalled issue. For instance, a German normative has been published [83], which reports a glossary. Furthermore another comprehensive list of definitions is reported in [84], which summarizes various synonyms for TRIZ tools. Nevertheless, a universally shared list of definitions is still missing.

Moreover, this literature review highlights that beyond the presence of possible synonyms, sometimes the same TRIZ tools are used in different phases of the FDM process. However, this is not necessarily an evidence of a mistake, but an evidence of the different possible interpretations of TRIZ tools. For example, the IFR has been considered both for “solution identification for each single function” and for “formulating functional problems”. However, both the proposals could be correct, because in the first case, the formulation of the IFR is considered for focusing the attention on more ideal solutions, while in the second case, it is considered in the identification of a more ideal task, and then for formulating problems. Other cases can be observed in Table 2 and Figure 1.

Such an observation implies that it is currently necessary to accept a certain subjectivity in interpreting the proposals reviewed in this work, partially explaining the reasons under the criticisms claimed in the work of Ilevbare et al. [10], concerning the lack of a framework for guiding users in selecting and applying TRIZ tools. In reference to this issue, the present review highlighted that support-type contributions could provide useful indications to designers interested in directly applying TRIZ for design purposes. Indeed, the outcomes of the performed analysis, presented in Table 2 and Figure 1, might constitute preliminary criteria for choosing the suitable TRIZ tools according to the design task. The proposed selection framework may represent a contribution to the important effort of developing guidelines for the selection of TRIZ tools for design purposes , such as the cited German VDI 4521 [83].

Furthermore, it is worth to notice that the reviewed contributions are almost totally based on a classical view of TRIZ (except for rare cases). Currently, some specific research works exist about TRIZ, focusing the attention on the development of a shared ontological basis [85], [86] and also on the formalization of the concept of “contradiction” [87]. Therefore, under certain aspects, the reviewed contributions are based on a up-to-date vision of TRIZ, neglecting the latest developments in terms of standardization. Consequently, future research activities on this argument should consider the information reported in this review about previous attempts, but should also necessarily take into consideration the recalled recent standardization efforts concerning TRIZ.

5.2. About the need of an industrial perspective

The limited information available in the reviewed contributions together with the reasons explained in the previous paragraph do not allow to assess if the considered proposals effectively meet the objective of overcoming the FDM flaws related to creativity. Moreover, as stated in Section 2, creativity is just one of the possible reasons that hinder the industrial diffusion of FDM, while other drawbacks have been inferred by literature. Therefore, in our opinion, without a thorough investigation on the FDM deficiencies actually perceived by industry, any attempt for their overcoming by employing TRIZ tools becomes a scattershot. More precisely, even assuming that FDM can actually benefit from TRIZ in terms of creativity perhaps other aspects can worsen. For instance, the learning time of FDM is sometimes considered a possible obstacle [6] that hinders the adoption in industry, but TRIZ in this case does not bring any improvement, on the contrary, the learning time can even become higher. In fact, Malmqvist et al. [59] associated a “long time to learn” characteristic to TRIZ and a “short time to learn” for SAPB.

Therefore, future research activities should investigate about the FDM flaws actually perceived by industry, for example by means of interviews or questionnaires to be submitted to industry engineers with a knowledge background on FDM. Moreover, since different industrial sectors certainly have different needs, also information concerning commercial and/or production profiles should be stored for more focused analysis.

The information gathered from the recalled investigation could be used for classifying the proposals listed in Table 2 in terms of “adequacy” of the proposed tool (for example, if a specific step of FDM is perceived as too complex, a TRIZ tool capable of lowering the complexity of the considered step is expected to be suggested by the examined proposal). Moreover, the same information could also be used for developing new integration proposals between TRIZ and FDM approaches, more focused on actual industrial needs.

5.3. About the need of comprehensive assessments

Besides the lack of an industrial perspective, it is also unclear if the shared main objective of the proposals has been attained. Indeed, although the reviewed contributions generally aim at improving FDM especially in terms of creativity, their effectiveness has not been assessed comprehensively, avoiding the possibility of objective evaluations.

Therefore, in order to understand if the proposals actually bring some of the claimed improvements/benefits, comprehensive testing sessions should be performed. Literature currently acknowledges metrics concerning creativity [5] and ideation effectiveness [88] that could be successfully used for that purpose, allowing to assess and compare design outcomes of the different methods. Moreover, other comprehensive literature procedures (e.g. [89]) can be considered for the recalled purposes. For the above mentioned experimentations it is certainly preferable to exploit a sample of industrial engineers, but first evaluations could be performed also by involving engineering design students opportunely trained.

In any case, a more detailed information should be retrieved from the considered contributions, about the practical application of the proposals.

5.4. About the different concepts of function between FDM and TRIZ

Any integration of TRIZ with FDM requires to deal with the different definitions of "function", belonging to the body of knowledge of the two approaches. Indeed, it is worth to notice that the definition of "function" in TRIZ [50], [74], [75] differs from that usually adopted in FDM approaches, being also contradictory under certain aspects [87]. Moreover, different definitions of functions can be observed also within the TRIZ community, which make often difficult the application of some inventive tools [90]. Consequently, concerning the difficulties related to the FDM functional nature, both supporting and merging contributions do not help in overcoming them, but can even contribute to their worsening.

Therefore, future activities aimed at exploiting the advantages of both FDM and TRIZ, should work on a reduction of the mental effort currently needed for reasoning with two different notions of function. Moreover, recent literature contributions about the "functional issue" should be taken into consideration [50]–[53], [91], [92].

5.5. Computational implementation of the reviewed approaches

Designing or redesigning a product very often implies to face complex activities where several aspects have to be taken into account and, especially when searching for substantial innovation, the conceptual design stage plays a crucial role. In order to support designers in early design phases of innovative products, computer aided tools have been developed during years [86], [93], [94]. Such a new category of tools known as Computer Aided Innovation (CAI) is emerging among computer-aided technologies, as a response of a strong industrial demand [93]. Accordingly, it is possible to find different computerized tools about TRIZ (e.g. Invention Machine's Goldfire [95] and STEPS [96]) .

Coming back to the reviewed contributions, some of them actually take into considerations the computational aspects of their proposals, but only in a marginal way. For example, Dietz and Mistree [64] mention the possible advantages that could be achieved by exploiting computerized functional structures, design repositories and computerized Su-Field with SS. Accordingly, Nix et al. [65] mention that the adoption of a shared functional basis could allow the adoption of computational tools. Moreover, even the work of Malmqvist et al. [59], which dates back to 1996, shortly considers the computational implementations of both TRIZ and SAPB.

The proposals surveyed in this review do not bring sufficient information about their actual implementations in computerized tools, and therefore, it is not possible to assess their impact from this point of view. However, the software implementation of academic methods can be useful for several aspects, among which, that of reducing efforts for iterative and formal tasks [47], potentially increasing their industrial acceptance. Therefore, future research activities focused on TRIZ-FDM integration should take into consideration implementation issues related to the development of CAI tools.

6. CONCLUSIONS

The work described in this paper concerned a literature review of the contributions aimed at combining TRIZ with the German systematic approach for conceptual design. More precisely, the main objective was to extract the current state of the literature concerning proposals aimed at enhancing FDM by means of the potentialities of TRIZ. We found a total amount of ten contributions, that we split into two distinct groups representing the related different strategies of integration between the two approaches. Indeed, a group of contributions marginally modifies the two original methods in order to obtain new original proposals, leading us to call them as “merging-type” contributions. Diversely, the other proposals simply aim at suggesting suitable TRIZ tools for supporting specific phases of the classical FDM (support-type group).

However, we found out that when talking about TRIZ, a lack of a standard in tools definitions led to a certain subjectivity, also when using them within FDM. Therefore, as useful palliative for a more rapid understanding of the contents, we considered the unified definitions in Table 3, according to some widespread TRIZ references. Moreover, the Appendix reports a short introduction to each TRIZ tool involved in the reviewed contributions, allowing an univocal understanding of the contents of the paper.

Concerning the effectiveness of the methods, the surveyed literature does not provide sufficient information for performing assessments and systematic comparisons. However, literature surely highlighted that comprehensive information concerning "what has to be actually improved" in FDM is actually missing.

Moreover, we observed that the different concepts of functions that underpin the two approaches are potentially conflicting. Unfortunately, the reviewed contributions do not face this problem comprehensively, thus leaving us with several uncertainties about the actual difficulties that a designer should face when approaching the related proposals.

Eventually, we also observed that some of the reviewed contributions do not consider computational aspects in a comprehensive manner, neglecting detailed indications about the implementation of the proposals into computer-aided design tools.

Besides the observed criticalities, there is also a fruitful outcome from this review, i.e. a structured list of TRIZ tools suitable for conceptual design purposes. Such a list provides useful indications for guiding practitioners among the selection of suitable TRIZ tools for specific conceptual design phases. Moreover, considering all the recalled observations, many different research hints can be extracted from our work. More precisely, researchers aimed at exploiting the benefits of TRIZ and Systematic Design will find here a comprehensive review of past attempts, with important considerations about standardization, industrial needs, methods effectiveness, functional concepts and computational implementation.

APPENDIX

Table A1 TRIZ tools mentioned in this paper (see Table A2 for references)

Tool	Short description
ARIZ	ARIZ is the Russian acronym for the "Algorithm for Solving Inventive Problems". It is the main analytical instrument of TRIZ and provides specific sequential steps for developing a solution for complex problems. Over the years, it has been refined in its structure, becoming a powerful tool for solving a wide variety of technical problems. The most used version, ARIZ- 85C, was published in 1985 and contains nine main steps, each of them composed by other sub steps [97]. To use ARIZ, the problem has to be described as a technical contradiction that can be solved by taking into account several TRIZ tools.
Contradiction Matrix	It is a 39x39 matrix where the rows and the columns contain the so-called 39 Engineering Parameters [74]. Any Technical Contradiction can be represented as a combination of two of these parameters after a broad interpretation of them. The parameter to improve has to be chosen among those reported in column, while the parameter that worsens has to be found among those in row. The cell identified by the intersection of the selected row and column, contains the numbers of recommended Inventive Principles to use for overcoming the contradiction.
ENV Model	OTSM-TRIZ ENV Model is an instrument for the description of problematic situation and is focused on formalizing the description of elements [24]. More precisely, in order to overcome mental inertia and to resolve problems, any feature is split into "Name" of a parameter and its "Value". Therefore, the "apple" could be described by a set of important parameters: kind of plants; hardness; colour; level of sweetness; shape; etc. Each of these parameters could have a specific value: kind of plant has value - fruit; hardness has value - hard enough; colour could have several values - green, yellow or red; level of sweetness has a value - sweet enough but not too much; parameter shape has a value - round or oval.
Evolutionary Trends	Evolutionary trends, or Trends (or Pattern) of Evolution, are a direct consequence of the Laws of System Evolution. Many different numbers of patterns of evolution are acknowledged in different TRIZ books and articles (e.g. 8, 10, 20 or even 30) but the right consensus seems to be that there are only 8 trends [74]. Altshuller's studies demonstrated that if a system starts following one of such trends, during its evolutions it would arrive to the predicted end. Therefore, analysing the current state of a system and its history it is possible to identify which trend(s) has been undertaken and so how the system can evolve in the next future.
Function Modeling	The Functional Modelling or Functional Analysis is a tool, which allows to decompose the technical system into its components and to represent the functional relationship between them. The output is a map that slices the system into small simple units composing a delivered function created by a subject/action/object triad [74]. The subject is the function provider, the object is the receiver and one of its parameter is modified by means of the action developed by the subject. The interactions between subjects and objects can assume different values (useful and sufficient, useful but insufficient or harmful) according to the satisfaction of the modification of the object parameter.
IFR (Ideal Final Result)	A basic principle of TRIZ is that systems evolve towards increased ideality, where ideality is defined as the ratio between benefits and the sum of harms and costs. Evolution is in the direction of increasing benefits, decreasing costs, and/or decreasing harm [79]. The extreme result of this evolution is the Ideal Final Result, where all the benefits (even just one) are present, but harms and costs are not. It is worth to highlight that costs are not intended only in economic terms, but more generally they are all those related to any resource consumption. Therefore, the Ideal Final Result describes the ideal solution to a technical problem.
Inventive principles	From the analysis of hundreds of thousands of patents, Altshuller extracted a list of 40 methods for overcoming Technical Contradictions: the so-called Inventive Principles (IP) [7]. Such methods have been used by inventors for generating their ideas, independently on the technical field of the problem. They appear as a short title, followed by a list of simple examples for their explanation. During the years, a great number of other patents have been analysed in order to look for further ways for solving problems, but no one has been added to the Altshuller list.
Innovation Situation Questionnaire (ISQ)	The ISQ helps the problem solver in understanding the system surrounding before starting to solve the problem. It provides a structure for gathering the information needed for reformulating a problem and then breaking it down into a set of smaller problems [14]. It is composed by several questions concerning information about the system to be improved, its environment, the available resources, etc. It is recommended the use of generic rather than technical terminology in order to lower the negative effects of psychological inertia.

Continue

Table A1 Continued

Tool	Short description
LESE	The Laws of Engineering Systems Evolution (LESE) are eight and they are divided into three groups: laws of statics (1-3), laws of kinematics (4-6), laws of dynamics (7, 8) [24]. The Laws of statics are characteristic for the initial stage of the technical system. The laws of kinematics concern the development stage of the technical system. The laws of dynamics concern the closing stage of the system development and the transition to a subsystem. In practical activity, they have a twofold employment, i.e. for idea generation and for checking activites.
NoP	According to OTSM-TRIZ guidelines, the problem solving process starts from building the Network of Problems (NoP), where the overall problem is decomposed in a set of more elementary sub-problems (Pb) that, once solved brings to one or more a partial solution (PS). These partial solutions could come from an inventive session or, for example from a knowledge base investigation like a patent analysis or a literature search. Any gathered PS, very often generates one or more new elementary problems, thus the analysis and decomposition of the overall problem creates a network constituted by elementary problems and partial solutions [77].
Physical contradictions	Two parameters form a Technical Contradiction, and the improvement of one of them causes the worsening of the other. It means that there is at least one physical parameter which puts them in relation. Such a parameter is demanded to assume two mutually opposed values, and it represent the Physical Contradictions (PC) [7]. It can be expressed as following: supposing to have the parameter P, it is desired at the value (V) for satisfying the parameter A, but at the same time the opposite value (anti-V) is desired for fulfilling the parameter B, where A and B compose the Technical Contradiction.
Pointers to effects	The Pointers to Effects or Function Database are a list of all the physical, chemical and geometrical effects, which Altshuller found in his patent analysis [74]. They are classified by what they do, i.e. in terms of the function they provide. To use the Pointers, the function to achieve must be defined, allowing to simply match the related effects from list, simply by selecting from the listed functions definitions.
Problem formulation process	The outcome of the Problem Formulation Process is a cause-effect diagram showing the linkage between the primary harmful function of the system and its Main Useful Function (MUF) [14]. In such a context, “function” has a more general definition, comprising for example also events, activities, actions, processes, operations or conditions. The graph provides a representation of the interrelated problems between the harmful function and the MUF. To solve the main problem, any cause-effect relationships must be formulated, and the most impacting problem has to be solved at first.
Resources checklist	One of the basis of the TRIZ inventive problem solving is the creative utilization of the resources available in a system, in order to increase the system’s ideality. The Resources checklist is a structured organization of the typical resources (both readily available and derived) in six main families: substance resources, field (energy) resources, functional resources, space resources, time resources and informational resources [98].
S-Curve	The S-Curve describes the maturity level of a system. The evolution of a product or technology is and that of biological systems (the biological s-curve) are assumed as characterized by the same evolutionary steps: pregnancy, birth, childhood, growth, maturity, and decline [99]. For a specific technology, the location on the s-curve can be obtained by interpolating data concerning performances, the number of inventions, their inventive levels, and the profitability obtained. The derived position on the curve can be considered as a useful information for performing innovation.
Separation principles	The Separation Principles are intended to be used on Physical Contradictions. They help answering questions such as: under what circumstances (including where and when) do we need these contradictory requirements? [74]. The Separation Principles are four, i.e. the contradictory needs can be separated in “space”, in “time”, on “condition” and between “parts and the whole”.
SLP	Smart Little People (SLP) is a tool capable to help in overcoming mental inertia. The designer imagine the problem situation and its solution by means of one or more multitudes of Smart Little People. They are smart because they have the ability to create/solve problems and be anywhere, doing anything as they are provided of a magic wand. They are little because they are as tiny as necessary, also at a molecular level if required [74].
Standard solutions	A standard solution is a model of solution of a typical problem modelled by means of Su-Field interactions [24]. The Standard Solutions (sometimes briefly named Standards) are a list of 76 models of synthesis and transformations of technical systems, in agreement with the Laws of Evolution of Engineering Systems (LESE). Each standard solution is structured as a transformation of an initial “problematic” Su-Field model into a modified Su-Field model, where the undesired characteristics of the interactions between the subsystems disappear.
STC Operator	Altshuller introduced Size-Time-Cost (STC) operator for overcoming the psychological barriers. It is in the form of a simple morphological box where the three parameters (size, time and cost) can assume two opposite values: zero and infinite [80]. The designer must solve the problem answering to questions like “what will happen if the size of the system is decreased until about zero or increased until about infinite?”. Similar questions can be formulated considering the parameter time or cost.

Continue

Table A1 Continued

Tool	Short description
Subversion analysis	The term "subversion analysis" refers to the basic technique of using TRIZ in a reverse way. TRIZ is used to find ways to cause the design to fail, or to subvert the basic purpose of the system [100]. With the knowledge of how to subvert the design, the developer knows how to make the design better, so that the failures cannot occur. It can be considered a systematic procedure for identifying the root causes of a failure or other undesired phenomenon in a system, and for making corrections promptly. Instead of asking "Why did the failure happen?" designers should ask instead: "How can I make it happen?"
Su-Field Model	Substance-Field (Su-field) Analysis is a TRIZ analytical tool for modelling problems related to existing technological systems [81]. Every system is created to perform some functions. The system function is the output made by an object or substance (S2), toward another object (S1) with the help of some fields (types of energy, F). The general term, substance has been used in the classical TRIZ literature to refer to some object of any level of complexity. Any substance could be a material, tool, part, person or environment. S1 is the recipient of the systems action. S2 is the means by which some source of energy or field F is applied to S1.
System Operator	The System Operator (SO), or Nine Boxes, or Multiscreen, is a 3 by 3 matrix where the initial problem can be translated into 8 different tasks. The rows represent a hierarchical decomposition of the system, i.e. the considered element constitutes the System, that is constituted by parts (Subsystems) and is inserted in an environment (Super system) [24]. The columns consider the time dimension, i.e. the considered time interval constitutes the Present, but it must be considered as a specific phase of a sequence of events, therefore with a Past and a Future. The SO can be used for finding alternative problems whose solution allows obtaining the same overall goal, and can be helpful in looking for resources by focusing the attention on every relevant aspect of the system and its environment, at any time stage at any detail level.
Technical contradictions	A Technical Contradiction arises when the improvement of a certain system parameter (or property or performance etc.) causes the worsening of another one, and vice versa. According to Classical TRIZ nomenclature, both sides of the Technical Contradiction, TC1 and TC2, have to be expressed. Supposing to have two technical conflicting parameters A and B, TC1 is represented by the satisfaction of A and the discontent of B (briefly A and anti-B), and conversely TC2 is defined by the fulfilment of B and the dissatisfaction of A (anti-A and B) [82].
TOP-TRIZ	TOP-TRIZ is one of the different methods derived from Classical TRIZ [23] that integrates TRIZ methods into a system of analytical thinking. Tool-Object-Product (TOP) Analysis can be considered the next generation of Substance-Field Analysis, and besides the different way of building a functional model, TOP-TRIZ also provides additional tools. The "Ideal Ways", is a method for improving a function considering the ideal directions. The "Standard Ways", is a further improvement of Standard Solutions of Altshuller. Finally, a further development of ARIZ has been integrated with the initial function analysis of a system, in order to improve the conflict definition.
Trimming	One of the forward steps of the Functional Analysis is the Trimming. Trimming Rules helps in finding simple solutions by removing parts and simplifying the system by starting from the functional map showing its problems (harms and insufficiencies) [74]. Trimming increases Ideality (same or better benefits, less costs, less harms) and helps to eliminate troublesome components by reducing complexity and part count. It is useful also for patent circumvention and patent strengthening, and to generally improve a system by removing harms, expense and complexity.

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- TRIZ-FDM combinations are proposed but insufficiently explained in design textbooks
- Ten different literature proposals exists about possible TRIZ-FDM combinations
- No literature review on the argument has been performed before
- The reviewed contributions have been grouped in two different categories
- Two main research directions have been inferred for future developments

Enhancing Functional Decomposition and Morphology with TRIZ: Literature Review

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