Design Science

The process for individuating TRIZ Inventive Principles: deterministic, stochastic or domain-oriented?

Yuri Borgianni[1], Lorenzo Fiorineschi[2], Francesco Saverio Frillici[2] and Federico Rotini[2]

[1] *Free University of Bozen-Bolzano, Faculty of Science and Technology, Piazza Università, Bolzano, Italy*
[2] *Department of Industrial Engineering, Universitá degli Studi di Firenze, Florence, Italy*

Abstract

Although TRIZ is widely acknowledged as a powerful aid to improve efficacy and efficiency of the creative design process, practitioners diffusedly experience difficulties in the selection of the most suitable tool. Such an issue represents a severe limitation in consideration of the large number of tools TRIZ offers. Here, Inventive Principles (IPs) are acknowledged as the most popular TRIZ technique, and their conjointly use with the Contradiction Matrix makes the selection of the appropriate IP a sufficiently supported task. However, the reliability of the Contradiction Matrix is often questioned and an agreement on a solid and reliable procedure for the selection of IPs is far from being reached. In such a context, the paper investigates the recurrence of IPs to solve contradictions, with reference to a classification framework that takes into consideration the nature of the problem to be solved and the technical-scientific domain it belongs to. The outcomes of the analysis reveal that leveraged IPs are considerably related with the technical-scientific domain and the nature of the problem to be solved. The found relationships are worth delving into and translating into selection guidelines.

Key words: TRIZ, Inventive Principles, creativity, design process, problem-solving

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Corresponding author
Y. Borgianni
yuri.borgianni@unibz.it

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1. Introduction

Creativity strongly affects the design process and the innovativeness of the related outcomes. The literature shows the usefulness of stimulation means to enhance creativity since the early design phases, as their adoption results beneficial for the whole product development process. Among the tools available in the literature, the ones belonging to the TRIZ body of knowledge are widely acknowledged as powerful aids to the scope. Indeed, several experimental investigations demonstrate the effectiveness of TRIZ in supporting the systematic ideation process (Vargas-Hernandez, Schmidt, & Okudan 2013).

Notwithstanding the empowerment of the design process enabled by TRIZ, practitioners are not properly supported in the choice of the most suitable tool to face a specific problem; this is even more troublesome for unskilled users. Such an issue represents a relevant limitation, which is exacerbated by the large number of tools and techniques TRIZ offers. In particular, Ilevbare, Probert, and Phaal (2013)

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highlight the lack of rules and procedures to select proper tools. Consistently, Yan *et al.* (2014) stress the need to steer practitioners in the use of the TRIZ body of knowledge, which is mainly constituted by abstract and domain-independent tools that are not easy to contextualise to the application field of the problem to be solved. In other terms, the abundance of creative, abstract and domain-independent instruments might make the design process inefficient if users cannot identify the most appropriate ones in a quick and reliable way. This indeterminateness in the individuation of suitable TRIZ tools might be caused by the fact that TRIZ has not been developed following the standard procedures of scientific validation (Tomiyama *et al.* 2009; Chechurin & Borgianni 2016).

As a result, the actual usefulness of such a large set of tools is argued in the scholarly debate. Different proposals to sort TRIZ body of knowledge have emerged in the literature. Although the attempts to provide reference rules are still ongoing, for example the proposal of the standard VDI 4521 (Hiltmann *et al.* 2015), the initiatives and studies are still insufficient to standardise the employment of TRIZ. Moehrle (2005) contributed to the goal by surveying 40 cases of TRIZ implementation in companies. The results showed that the whole set of TRIZ tools was not exploited and only few combinations of techniques were frequently observed. In the last few years, the need has emerged to provide a better understanding of the right locus and function of TRIZ within the whole design process too (Chechurin & Borgianni 2016). For instance, Samuel and Ohler (2014) suggest a classification framework of TRIZ techniques based on their potential role with respect to various engineering design activities. In Frillici, Fiorineschi, and Cascini (2015) and Fiorineschi, Frillici, and Rotini (2018a), TRIZ tools are discussed with reference to their relationship with the main conceptual design phases and the functional decomposition tasks. In other works from the same authors (Fiorineschi, Frillici, & Rotini 2018b; Fiorineschi *et al.* 2018c), a specific set of TRIZ tools is integrated in a systematic conceptual design process based on problems and solutions co-evolution. From a slightly different perspective, Spreafico and Russo (2016) characterise Inventive Principles (IPs) according to the system's ontological domains (Function, Behaviour and Structure) for which their application makes the most sense. The focus on IPs is not surprising, since they represent the most popular TRIZ technique according to recent studies (Ilevbare, Probert, & Phaal 2013; Spreafico & Russo 2016). Actually, selecting the most appropriate IP is one of the most supported processes in classical TRIZ, thanks to the existence of the Contradiction Matrix. However, its reliability is often questioned (Mann 2002a), which has given rise to refinements and adaptations of the original matrix (Mann & Dewulf 2003; Lim *et al.* 2018), the redefinition of the IPs according to different distinction criteria (Mann 2002b) and alternative guidelines to overcome technical contradictions, for instance by analysing past successful solutions semantically (Verbitsky 2004). However, an agreement on a repeatable and reliable procedure is far from being reached, as the above references demonstrate how the paid efforts follow very different trajectories. Moreover, attempts to improve or adapt the matrix are considered of poor contribution to the general development of TRIZ (Livotov 2008). On the other hand, the reliability, innovatiness and effectiveness of IPs is also debated in the TRIZ community. Basically, it is claimed that the determination of technical parameters in a contradiction, which is conducive to the use of IPs, does not allow a full problem abstraction and identification of an ideal solution according to popular TRIZ models (Cascini 2012). In this sense, the possibility to identify action (or control) parameters giving rise to a physical contradiction would represent a step forward in the abstraction process, and, supposedly in the achievement of more ideal and effective solutions, which justifies experts' recommendation of these tools (Belski 2019). Nevertheless, IPs' usefulness for beginners and practitioners is overwhelmingly more addressed in the literature than their limitations are (Jafari *et al.* 2013; Labuda 2015; Abdala *et al.* 2017; Liu, Feng, & Wang 2020; Tan *et al.* 2021).

In this context, the authors believe that further efforts, based on the observation of how problems are actually solved, could result useful to ease the selection and the application of IPs according to the nature and the context of problems to be solved. Accordingly, the paper presents an empirical approach to investigate the recurrence of IPs to solve contradictions with reference to a classification framework based on a multidimensional approach, and the achieved results. The outcomes of the investigation provide further insights to develop rules for the selection of the most suitable solution strategy based on IPs, which could be useful to enhance efficacy and efficiency of design tools in a computer-aided perspective as well.

The content of the paper is organised as follows. Section 2 reports the analysis of the scientific contributions that try to investigate potential relationships between problems and TRIZ-based strategies and tools for their solution. Accordingly, it introduces the specific objective of the work. The research approach followed to pursue this specific objective is described in Section 3, while the achieved results are presented in Section 4. Section 5 discusses the achieved outcomes with reference to the issues presented in Section 2, and highlights findings and limitations of the investigation. Eventually, Section 6 draws conclusions.

2. Related work

TRIZ originates from the analysis of a plethora of inventive solutions and regularities, such as common principles or patterns. It follows that scholars tend to identify the TRIZ body of knowledge as a number of tools supporting designers in the understanding of evolutionary and deterministic mechanisms (Zeng 2015; Duran-Novoa *et al.* 2019). This is exacerbated by supposed existence of logic and repeatable processes in the problem-solution path in the Contradiction Matrix or in the inescapable developments foreseen by the Laws of Evolution in TRIZ (Lapidot & Conley 2015). However, on the one hand, these mechanistic paths in technological development have not been proven. On the other hand, this vision and its utility are challenged by a number of scholars claiming that people's creativity, along with its unpredictable outcomes, are the main drivers for technical evolution and improvements (Kaplan & Obojski 2017). In this perspective, TRIZ and its tools, which should not be interpreted in an excessively restrictive way, are viewed as valuable sources for stimulation and effective solution search, for example Burz and Marian (2011). Overall, the deterministic dimension in the identification of inventive solutions to problems has not been assessed. Understanding to which extent chosen IPs might be considered as dictated by the characteristics of existing problems and how designers individuate valuable ones contributes to assess the presence of deterministic and mechanistic phenomena.

As a starting point to address these issues, the authors here briefly review the literature contributions, which are considered relevant for the scopes of this study, that strive to improve the applicability and to guide the selection of IPs.

Yan *et al.* (2014) acknowledge the usefulness of the 40 IPs as a source of inspiration to overcome technical contradictions. However, the scholars claim that the different levels of abstraction featured by the IPs makes their application to domain-dependent problems difficult. To ease the use of such a source of creative stimuli, the authors propose an ontology-based approach to support the contextualisation of the abstract suggestion represented by an IP according to the specific problem's domain. In the study presented in Moehrle and Paetz (2014), IPs are used to represent similarities and differences in the thinking process of Japanese and European engineers when dealing with problems in the field of solar cell modules. The methodological approach presented in the paper is based on a statistical patent analysis and the outcomes are the frequency of IPs tracked within a large set of patents. The results of the investigation show that, not only it is possible to identify specific subsets of frequently used IPs, but also that these subsets depend on the geographic region the inventors belong to. In other words, the study confirms that a relationship exists between the problem domain, the most relevant IPs, and the different background/knowledge of inventors. In addition, the followed methodological approach can be considered as a further contribution of the paper, since it suggests how to use and manage large sets of patents as a source to collect the most used IPs in a specific domain field. In Gazem and Rahman (2014), a specific clustering of IPs is proposed for service design in order to diminish time and efforts spent in finding suitable IPs to solve a service problem. More in particular, the study is based on previous classifications of the 40 IPs, under different service redesign tasks: self-service, direct service and preservice. Pohkrel *et al.* (2015) acknowledge the need to facilitate the application of TRIZ in chemical process industries and recognise that IPs are too abstract to be used by chemical engineers. Therefore, the scholars attempt to customise the Contradiction Matrix of TRIZ to the most diffused problems encountered in the field of industrial chemical processes. As for the outcomes of the study, the paper presents new insights into the IPs emerging from the analysis of papers dealing with chemical process industries. Cherifi *et al.* (2015) present a methodology to support innovative eco-design tasks by TRIZ. More specifically, one of the key tools of the proposed approach is based on IPs, and is formulated according to a set of IPs the scholars identified as most applicable in eco-design. The relevant IPs are identified according to eco-efficiency engineering parameters and the scholars build a bespoke matrix for their selection. In Abdala *et al.* (2017), a comparison between TRIZ IPs and a specific set of bio-inspired TRIZ IPs is presented, which targets the stimulation of creativity in problem solving. The development/identification of bio-inspired TRIZ IPs is performed by using the 39 TRIZ engineering parameters, which are applied to describe the contradiction parameters in biological systems. Moreover, a new matrix is developed for the selection of the most suitable bio-inspired IPs. The 39 engineering parameters of TRIZ and the IPs are also used in (Tian-Syung, Kai-Chi, & Yee-Ming 2018); here, the objective is to design an optimisation strategy in the field of numerical-controlled machining. The design principles are achieved by matching seven eco-efficiency factors proposed by the World Business Council for Sustainable Development and the parameters of the TRIZ contradiction matrix. Still in the field of eco-design, Livotov *et al.* (2019) identify 20 universal TRIZ IPs and subprinciples that have a higher value for environmental innovation. These outcomes originate from a research approach based on the analysis of 100 eco-patents, 58 process intensification technologies, and the literature.

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In brief, the reviewed contributions highlight what follows.

(i) Scholars acknowledge the powerful capability of TRIZ tools to support problem-solving tasks.
(ii) Scholars often argue the applicability of TRIZ tools, and markedly IPs, due to their abstraction level. Abstraction is an aspect that, on the one hand, makes TRIZ tools of general applicability, but, on the other hand, causes usability challenges. Indeed, very often, it is not easy to identify the most suitable tool in relation to the specific problem domain. This issue strongly affects the efficiency and efficacy of the problem-solving process.
(iii) To overcome this drawback, a consolidated trend is to specialise the formulation and application of IPs through a 'reverse engineering' logic, hence making them domain-oriented, which somehow conflicts with a deterministic and universal vision of TRIZ in the evolution of systems and problem-solving.

Markedly, the trend of specialisation has led to the proliferation of several versions of the same tool, which constitutes another problem that affects TRIZ, as already highlighted in the previous section, that is the lack of standardisation. This applies especially to unskilled users, who could not be aware of the specific definitions that led to the domain-oriented formulation of IPs and the corresponding circumstances for their application. Therefore, the specific objective of the present study is to investigate the use of the IPs in real problems, so to acquire some more evidence about their applicability with the overall goal of speeding up their choice. The investigation targets the frequency of IPs' use in different domains while taking into consideration their original formulation as domain-independent stimuli and evaluating the presence of regularities in problem–solution patterns.

3. Materials and methods

The procedure to address the research objectives included the following steps, which are graphically summarised in Figure 1:

(i) Selection of problems and solutions from the TRIZ literature (Section 3.1)
(ii) Classification of problems, solutions and contradictions based on the chosen constructs (Section 3.2)
(iii) Analysis of the distribution of IPs (Section 4), preceded by methodological aims of the statistical study (Section 3.3).

3.1. Individuation of a sample of problems solved with TRIZ

The first step was intended to collect materials useful for the analysis, that is a number of problems solved with TRIZ. It is worth noting that the authors consider here original solutions developed by means of TRIZ and willingly neglect examples aimed to justify the use and the logic of TRIZ a posteriori. As reference sources, the authors decided to examine all the papers published in the recent editions of the TRIZ Future Conference (2015–2019), which follows a peer-review process and can be considered as an authoritative outlet for scientific and technical publications about TRIZ. Those papers reporting and describing in sufficient details problems and corresponding solutions compatible with TRIZ were processed further. More in particular, a problem was considered sufficiently described when two conflicting

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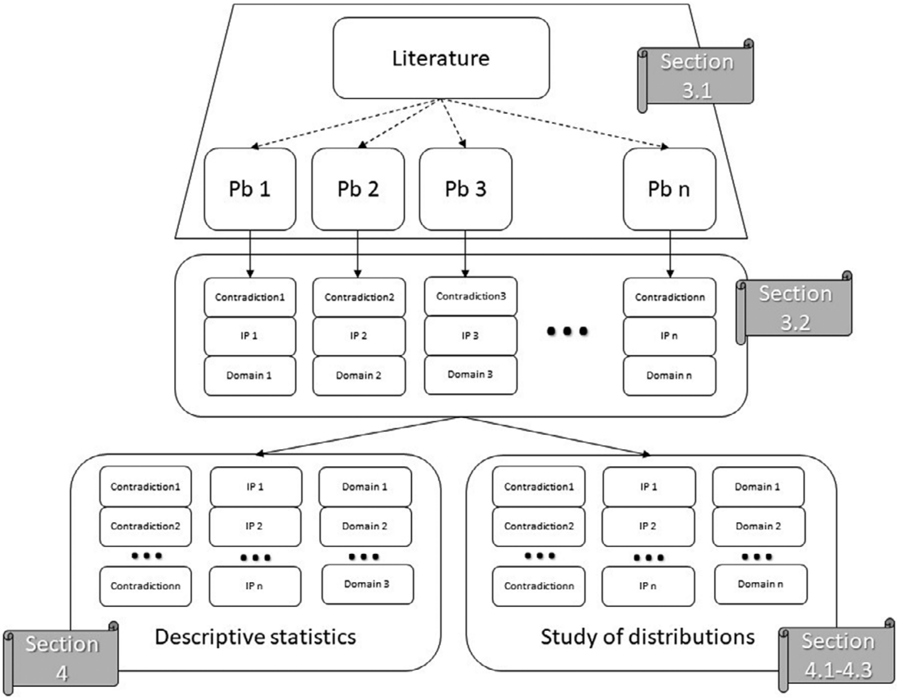

Figure 1. Roadmap followed from the collection of problems (Pb in the illustration) and their classification to the study of distributions across different characteristics. The strolls indicate the paper's sections in which the corresponding activities are described. The arrows represent the sequence of actions in terms of identification of new entities (dashed lines) and analysis thereof (continuous lines).

parameters and the corresponding solutions were inferable. If a paper presented multiple problems, all of them were taken into account. The selection of problems willingly neglected the specific TRIZ tool implemented, if declared. Also in those cases where the contradiction matrix and the IPs were used, the authors considered the sources' indications when they analysed the problems and solutions, but they confirmed the original indications just if in agreement. Otherwise, different classifications were made. This measure was intended to provide a consistent, uniform and homogeneous interpretation of problems and solutions.

The process led to select 161 solutions, which are fully documented in the Supplementary Material. This set is to be considered as the sample of convenience for the present study. The solutions and the corresponding problems are extracted from 53 distinct papers, summarised in Table 1.

3.2. Classification of problems

The classification described in the present subsection took place through a consensual process involving the four authors, who all have more than 10 years of experience in TRIZ research.

The classification of the selected problems aimed to identify multiple options to map relations between problems and solutions. In particular, while the latter is focussed on IPs, the former have been characterised as

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Table 1. Set of employed sources describing problems and solutions achieved by means of TRIZ tools

TRIZ Future Conference edition	Used sources
2015	Becattini, Borgianni, and Frillici (2016), Eisuke, Satoshi, and Hiroshi (2016), Gronauer and Schobert (2016), Hyun and Park (2016), Hyunju, Jeongmook, and Sunwook (2016), Kai and Tobias (2016), Kyeongwon (2016), Ohler, Shahani, and Borde (2016), Pfeuffer and Scherb (2016), Roderburg and Rey (2016), Samuel *et al.* (2016) and Sooyong, Sungdae, and Sangbum (2016)
2016	Busov (2016), Bzymek (2016), Hanifi *et al.* (2016), Brad (2017), Chechurin, Lohtander, and Borgianni (2017), Cooke (2017), Hess (2017), Hohnjec, Gošnik, and Koblar (2017), Lee (2017), Sawaguchi, and Utsugi (2017), Zeihsel (2017), Zhang, Zanni-Merk, and Cavallucci (2017), Brad (2018) and Chechurin *et al.* (2019)
2017	Bach, de Guio, and Gartiser (2017), Nishiyama, Leleito, and Sakai (2017), Koziołek *et al.* (2017), Shnai (2017), Sun *et al.* (2017), Borgianni, Frillici, and Rotini (2018), Dubois *et al.* (2018), Mysior, Koziołek, and Rusiński (2018), Houssin *et al.* (2017), Sun *et al.* (2018) and Zhang *et al.* (2018)
2018	BenMoussa *et al.* (2018), Bertoncelli, Mari, and Mayer (2018), Cherifi and Gardoni (2018), Cooke (2018), Frerard *et al.* (2018), Hentschel, Thurnes, and Zeihsel (2018), Lee (2018), Liu *et al.* (2018), Sheu and Yeh (2018) and Zhang *et al.* (2018)
2019	Ben Moussa *et al.* (2019), Bertoncelli, Gronauer, and Nähler (2019), Hanifi *et al.* (2019), Liu, Cavallucci, and Li (2019), Ouezgan *et al.* (2019) and Russo, Peri, and Spreafico (2019)

(i) combinations of conflicting parameters of a different nature, to assess the extent to which the nature of problem-solution patterns can be considered deterministic and
(ii) disciplinary domains to test the extent to which the suitability of IPs depends on different domains.

As a result, the classification overall involved (1) contradictions, (2) solutions and (3) problems, as illustrated in Figure 2, in which the text in grey highlights the terms used to classify the corresponding element. In particular, the following elements, which will be clarified below, were agreed on.

(i) The parameters that conflict and give rise to a technical contradiction, along with their characterisation.
(ii) The most appropriate IP that describes the presented solution.
(iii) The domain of the problem.

Details of all the classifications can be found in the Supplementary Material.

3.2.1. *Classification of the conflicting parameters*

The classification of the conflicting parameters was necessary to verify whether any relation is found between inputs (categories of parameters) and outputs (categories of solutions, here expressed as IPs). Traditionally, parameters are diffusedly classified in terms of the 39 (n) engineering parameters. The use of this

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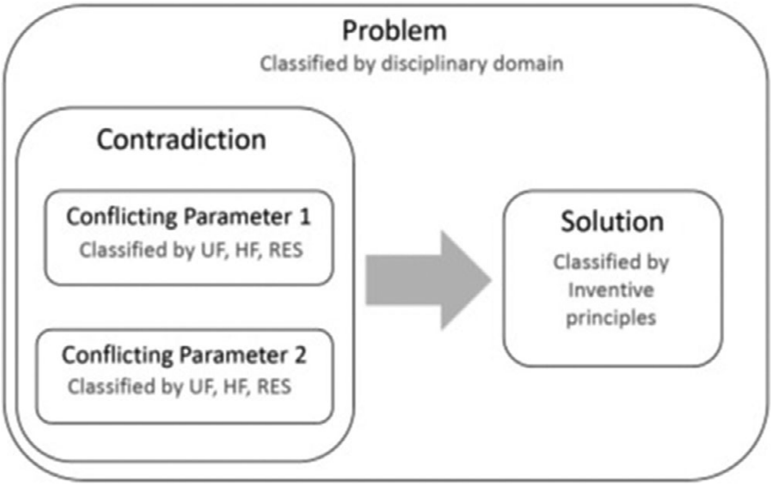

Figure 2. Classifications performed for the scope of addressing the research questions of the paper.

classification would have led to 741, that is $n \times (n-1)/2$, possible combinations to describe the contradictions. Such a number of combinations comes out if the role of parameters as improving and worsening factors is ignored, which is also in line with the authors' choice, as the two are diffusedly hard to distinguish. It is evident that said number is plainly incompatible with the quantity of available case studies to have the chance of achieving results of statistical significance. Moreover, the mapping of pairs of engineering parameters versus IPs would just result in providing more information on the reliability of the Contradiction Matrix, which is not in the paper's objectives.

Therefore, the authors willingly selected other TRIZ-related constructs to classify parameters and opted to use the performance terms of Ideality, namely Useful Functions (UF), Harmful Functions (HF) and Resources (RES), which is compliant with some examples in the literature (Zhang, Mao, & AbouRizk 2009; Becattini, Cascini, & Rotini 2011; Borgianni et al., 2011). This made it possible to classify the contradictions into six different combinations (UF–UF, UF–HF, UF–RES, HF–HF, HF–RES and RES–RES), indicated hereinafter as kinds of contradictions. For the sake of clarity, the process followed by the authors foresaw the steps below.

(i) The individuation and the definition of the two conflicting parameters involved in each contradiction.
(ii) The classification of the two parameters according to their adherence to one of the following: (a) an issue related to a desired outcome (UF); (b) the presence of an undesired effect (HF) and (c) an issue concerning channeled resources to make the system work (RES).

3.2.2. *Identification of IPs*

The determination of IPs involved in the solution was carried out based on the widely available definitions of IPs along with subprinciples. However, as a common practice, the subprinciples were not used as a term for further classifications of the solutions. To perform this task, the authors took into account the creative element of the solutions and matched it with IPs, where the latter classically represent an abstract description of the specific implemented solution.

3.2.3. Problem domain

Eventually, in line with the need to investigate the role of the disciplinary domain in the selection of IPs, all the problems were attributed to a specific scientific field. Here, a shared, repeatable and applicable classification of domains is not available to the best of the author's knowledge. The authors designated the problems into the disciplinary domains in the bullet list below.

(i) Human-related problems, meant as those belonging to disciplines that deal with people and their organisation. They include management, administrative, sociological, medical or educational problems.
(ii) Technical and engineering problems, i.e. those that involve applied sciences and the industry. They are mostly unrelated with the previous ones, but share problems in the field of medicine. They include fields such as mechanical, civil and electric engineering, optics, fluid mechanics, material science and chemistry.
(iii) Mechanical problems, meant as those ascribable to mechanical engineering, which is thought as the reference domain of application for TRIZ (Stratton & Mann 2003). These problems are a subset of the above technical and engineering problems.

3.3. Data analysis

As for the analysis of data, the followed procedure was intended to verify the randomness of the distribution of IPs across the classes of contradictions and domains of problems through χ^2 tests. The software Stata 13 was used to perform the statistical tests. The outcome of the test is the probability that the difference between the actual distribution and the expected one, that is all the IPs are equally distributed across the classes, is due to chance.

Based on the scopes of the study, the following distributions were investigated.

(i) The distribution of IPs with respect to kinds of contradictions for all the problems.
(ii) The distribution of IPs with respect to kinds of contradictions for all the problem domains.
(iii) The diffusion of IPs in specific problem domains in comparison with their distribution for all the problems.

4. Results

The attribution of each problem to one of the 6 kinds of contradictions resulted in 23 UF–UF, 79 UF–HF, 39 UF–RES, 5 HF–HF, 6 HF–RES and 9 RES-RES conflicts. Forty-four problems within the sample of convenience belong to the class of human-related problems. one hundred and twenty-seven problems were treated as technical and engineering problems; among them, 88 case studies referred to mechanical problems. Thirty-five out of the 40 Altshuller's IPs were used to classify the solutions at least once, which supports the claim that the sample of convenience well represents the outreach of TRIZ application. Figure 3 shows the frequency of

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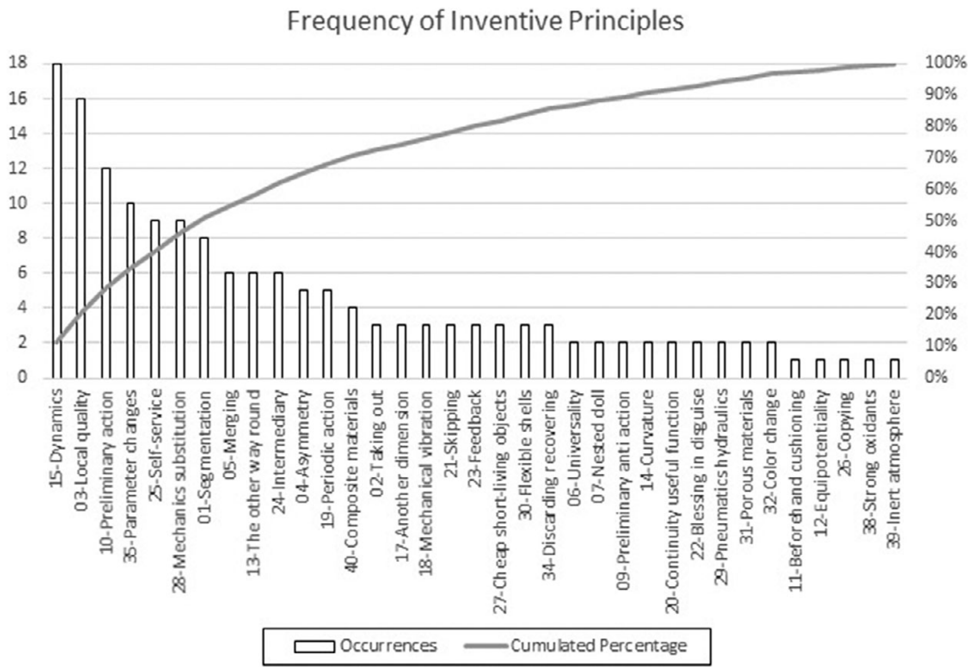

Figure 3. Occurrences of Inventive Principles, arranged in descending order, and their cumulated frequency. The principles are indicated with their names and the cardinal number they are conventionally attributed to.

IPs within the sample of convenience, which corroborates the anecdotal evidence of an overall uneven diffusion of TRIZ IPs.

The following subsections, which illustrate the outcomes of statistical tests, are articulated in line with the numbered list at the end of Section 3.3.

4.1. Distribution of IPs across classes of contradictions for all the problems

Following the use of χ^2 tests, low probability values are a proxy of the relevance of the kind of contradictions on the choice of the IP to overcome those contradictions. Large values indicate that the distribution of IPs is conversely random and a sort of nondeterministic process linking contradictions and solutions can be envisaged.

Table 2 presents the outcome of the χ^2 test, which leads to state that the probability of a random distribution of IPs across the classes of contradictions is 5.3%. As the threshold for statistical significance in tests is set to 0.05 as a rule of thumb, the present result rejects the hypothesis of a deterministic distribution of IPs across kinds of contradictions. However, this aspect is worth investigating further, as the outcome is very close to the established threshold.

4.2. Distribution of IPs across classes of contradictions for specific problem domains

The same test, as presented in Section 4.1, has been repeated by limiting problems in the three identified problem domains. The results are illustrated in Table 2 too. It

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Table 2. Probabilities of correctly stating that the distribution of IPs across kinds of contradictions is due to chance in the investigated disciplinary domains

Problem domain	Probability of a random distribution of IPs
All	5.3%
Human-related	1.1%
Technical and engineering	1.9%
Mechanics	81.6%

Abbreviation: IPs, Inventive Principles.

Table 3. Probabilities of correctly stating that the distribution of IPs in the investigated disciplinary domains differs from other expected distributions

		Probability of having the same distribution of IPs with respect to	
Problem domain	Number of IPs	All (35)	Nonhuman related (29)
Human-related	12	0.00%	0.07%
		All (35)	Nontechnical and engineering (12)
Technical and engineering	31	72.6%	0.00%
		All (35)	Nonmechanics (18)
Mechanics	23	0.26%	0.00%

Numbers in brackets indicate the number of IPs belonging to the expected distributions, which could be considered for the χ^2 test.
Abbreviation: IPs, Inventive Principles.

emerges that the use of specific IPs can be significantly considered affected by the kind of contradiction if we restrict our perspective to human-related, and technical and engineering problems. Conversely, the distribution of IPs across kinds of contradictions appears as considerably random if mechanical problems only are in focus.

4.3. Diffusion of IPs in specific problem domains

Table 3 presents the number of IPs involved in the specific problem domains to indicate how the focus on peculiar disciplinary areas might tend to reduce the quantity of IPs useful to find inventive solutions. The table includes also the results of the probabilities of a random distribution of IPs by clarifying, for each problem domain, the expected distribution that is considered.

Apart from the distribution of technical and engineering problems with respect to the whole sample, where a large overlap has been taken into account (127 out of 161 case studies), all the tests have proved the independent distribution of IPs within disciplinary domains.

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5. Discussion

5.1. Findings

The results and the presented analysis procedure show how IPs, in their original formulation, have proven to be suitable for solving problems belonging to different domains. This contributes to set forth the extension of TRIZ from traditional engineering fields to new disciplinary areas (Chechurin & Borgianni 2016; Teplov, Chechurin, & Podmetina 2017). The outcomes do not allow the authors to infer the overall deterministic nature of suitable IPs in light of the conflicting elements that feature contradicting parameters, here HF, UF and RES. At the same time, stating the complete randomness of IPs' choice would be likewise misleading. The presence of some logic behind the, although likely unaware, selection of IPs during the problem solving process is strengthened by the results illustrated in Section 4.2. Broadly, mechanisms leading to the selection of IPs in human-related and technical domains, if these are considered separately, are seemingly affected by the kinds of contradictions. Still based on the outcomes, this sort of deterministic behaviour is conversely invalidated if disciplinary domains become more specific, as in case of the analysis of mechanical problems out the whole set of technical and engineering case studies.

Yet, the chosen disciplinary domains result to play a fundamental role in the choice of IPs irrespective of the kinds of contradictions to be solved. It emerges that all these domains have some favourite IPs, which contribute to clearly independent distributions of IPs frequencies. For instance, by analysing the classifications insightfully, the great diffusion arises of the IPs 'Segmentation' and 'Parameter changes' for human-related problems as opposed to technical ones. Conversely, the IP 'Dynamics' is to be considered appropriate for solving technical problems and specifically mechanical ones. Still, other diffused IPs such as 'Local Quality' and 'Preliminary Action' are often found in the analysed sample whatever the kind of problem.

5.2. Implications

As the choice of IPs is one of the most challenging tasks in the use of TRIZ, the present paper attempts to provide some guidance. Although the results require a final validation (see Section 5.3) and guidelines cannot be formulated for the time being, the findings suggest the future possibility of fine-tuning different approaches and strategies to identify appropriate IPs. In particular, the outcomes of this research suggest considering the problem domain at a first instance when designers face an inventive problem. Such a consideration argues the usefulness of the recalled contributions aimed to interpret and adapt IPs for specific fields of science, which have never gained traction or become commonplace among practitioners. Indeed, in other terms, rather than specialising IPs for certain domains, it is here recommended to focus on some IPs, which, by their nature, might be already tailored for problems of those domains by taking into account the conventional TRIZ definitions of IPs. Still within the selection of IPs, a further chance lies in the characterisation of the contradictions in terms of the constructs used here to classify conflicting parameters. Not only problem domains have proven to be featured by peculiar distributions of IPs, but they also present significantly more deterministic contradiction-IP patterns than the overall set of problems.

In addition, the authors claim that the nonrandom phenomena underlying the link between categories of problems and solutions, in terms of both domain and kinds of contradictions, along with other insightful results, for example the general diffusion of IPs, might support the development of TRIZ-based information and communication technology or artificial intelligence (AI) supports. The birth of AI-based tools is besides seen as a fundamental development in the near future for TRIZ, as TRIZ ontologies are increasingly demonstrating their congruence with digital technologies, for example (Shim, Kim, & Shin 2019). This is also underlined by the fact that the latest editions of the TRIZ Future Conference (markedly the event concluded in 2020[1] and the one planned in 2021[2]) have included digitalisation and AI among the most relevant topics in their calls for papers.

In this respect, it is worth noting that some major developments of computer-aided innovation (CAI) systems swiveling on TRIZ have relinquished the prerogative of creating fully automated inventive machines, while they have opted for computer coaches, for example Becattini *et al.* (2013). Indeed, recent CAI systems entrust the user with the creative endeavor while providing TRIZ knowledge along with other prompts, for example Lopez Flores *et al.* (2015) and Feng (2016). In this context, the nontriviality of the task of guiding the user to adequate solution patterns within CAI systems is underlined by the fact that most established results have been achieved in the formalisation and analysis of problems (Zanni-Merk, Cavallucci, & Rousselot 2009; Becattini *et al.* 2013). Therefore, the capability of addressing towards promising IPs based on few and poorly populated classes (kind of domains, contradictions) might accelerate the computer-supported solution process especially when it comes to designers with little experience in TRIZ.

5.3. Limitations and future work

The results presented in the present paper are affected by some limitations. In particular, the authors have chosen a specific outlet for the individuation of case studies showing inventive TRIZ-oriented solutions. This outlet, that is the TRIZ Future Conference series, has been considered authoritative and suitable to support the rapid individuation of pertinent examples to build the sample of convenience for the present research. On the one hand, the gathered sample of convenience, although quite populated, might not be fully representative of inventive conceptual design and the use of TRIZ as a whole. On the other hand, the solutions presented in the consulted papers have been obtained with any TRIZ or problem-solving instrument and the use of IPs has been abstracted. No attention has been paid to the scholars who have presented problems and solutions; those scholars might be affected by their country, culture, and, markedly the way they have learnt TRIZ or their reference TRIZ school of thought (Chechurin & Borgianni 2016). All those factors might significantly affect the search for inventive solutions.

Moreover, all the classifications problems and solutions have undergone should be considered subjective despite the agreement reached by four people with a good experience in TRIZ. It is also worth noting that the authors have assumed that the

[1] https://tfc20.eu/call-for-papers/

[2] https://tfc21.events.unibz.it/?page_id=86

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standard 40 IPs represent different solution patterns or creativity triggers. Nevertheless, this aspect can be challenged by the fact that different sets of sub-principles are reported in TRIZ-related literature and some might assume that subprinciples are to be considered more appropriate to describe distinct solution strategies. Obviously, an analysis of sub-principles' occurrences and distribution would have required a larger sample of problems and corresponding solutions.

Due to these reasons, the authors claim the chance of finding new ways to speed up the individuation of appropriate IPs, but are very cautious in terms of how a novel approach to identify IPs should be structured. A final validation of the findings should undergo the testing of another set of problems along with their inventive solutions, possibly carried out by a different research group to avoid bias. Other tools belonging to the TRIZ body of knowledge could be worth being subjected to an akin investigation.

6. Conclusions

TRIZ is an important reference for problem solving tasks in design, observing an expansion from technical disciplines, still its reference domain, to humanity and non-engineering sciences, as the examples used in this paper demonstrate. However, the doubts about its development and scientific validation suggest acquiring more knowledge of its underlying processes and the correct use of the proposed tools. As the choice of IPs is one of the most challenging tasks in the use of TRIZ, the paper presents an empirical approach to investigate the recurrence of IPs to solve contradictions. Actually, the IPs are to be considered as one of the multiple tools TRIZ offers and some claim they are not the most effective. The paper's focus on IPs is justified by

(i) their recalled popularity;
(ii) the fact that they are not directly linked with the problem model, for example standard solutions apply logically to the substance-field analysis, and they are therefore worth investigating in this sense and
(iii) the majority of TRIZ tools and, markedly, ARIZ, suggest processes to follow, which cannot be reconstructed by the sole availability of described problems and solutions.

The study is conducted with reference to a classification framework that considers the nature of the problem solved, according to the TRIZ Ideality terms, and the technical-scientific domain the problem belongs to. The objective of the paper is to perform a preliminary investigation into potential correlations between solution paths and solved problems, as triggers for developing rules or standards to guide the designer in the selection of suitable IPs.

The investigation has included three main steps, namely

(i) the collection of a large set of problems and related solutions from the TRIZ literature;
(ii) the identification of the contradictions behind the problems and their classification and
(iii) the identification of the IPs used to solve the contradictions and the subsequent analysis of their occurrences according to both TRIZ Ideality and problem domain.

The outcomes of the analysis show that the IPs' choice follows a logic whose mechanism is not completely random; markedly, a role is played by both the kind of contradiction to be solved and the disciplinary domain the problem belongs to. However, the results also highlight that this sort of deterministic behaviour is no longer in place once the definition of the scientific domain goes from a broad level, encompassing several disciplines, to more focussed fields. Hence, the outcomes are somehow sensitive to the definition and the extension of the disciplinary domains. Anyway, it emerges in a sufficiently clear way that all the considered domains present some favorite IPs, which somehow constitute 'key solution paths' for those domains. Although the results require further validation, the findings suggest the future possibility of fine-tuning different approaches and strategies to identify appropriate IPs based on the terms the paper has investigated. These approaches to select the most useful IPs for a given problem would therefore involve

(i) first, the determination of the problem domain and
(ii) subsequently, the definition of a contradiction in terms of useful functions, harmul functions and required resources.

The relevance of the findings encourages further research aimed to develop TRIZ-based CAI tools to support the selection of the most suitable IPs. In such a way, the creative problem-solving process could become more efficient and effective when using TRIZ.

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Supplementary Materials

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