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Triz and axiomatic design: a review of case-studies and a proposed synergistic use

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Abstract With increasing competition in the market, expediting the problem solving process has become crucial in the industry. As such, a number of problem solving techniques have been devised to efficiently tackle problems of varying natures. Two such techniques, Theory of Inventive Problem Solving (TRIZ) and Axiomatic Design (AD), have been widely applied in a variety of industries and services, recently. This paper reviews practical applications of TRIZ and AD in solving industrial problems related to manufacturing and designing. In addition, compatibility issues of TRIZ and AD are discussed. Based on our review, we propose a new approach of applying these two techniques concurrently to solve a problem to attain efficiency and quality in the problem solving process. The approach has been demonstrated through a real life case-study of productivity enhancement in a manufacturing industry.

Keywords TRIZ · Axiomatic Design

Introduction

In the face of competition, the ever more rapid emergence of new products, changing consumer fashions and globalization, innovation plays an essential part in the growth and progress of every industry. Consequently, companies are forced to question the efficiency of their design methods to keep their competitive edge and ensure their survival (Cavallucci & Lutz, 2000). As global technology competition becomes fiercer, an ability to solve engineering and technology problems expeditiously becomes critical for the survival of individual businesses and entire industries (Jugulum & Sefik, 1998). As such, numerous problem solving techniques have been devised to solve a variety of industrial problems.

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A carpenter's toolbox contains a variety of tools like chisel, hammer, spanner etc. However, every tool does not suit every application. Even though a spanner can be used to drive a nail into wood, it is definitely not as effective and efficient as a hammer. Hence, it is essential that the right tool be selected for the right application. In many cases, a combination of tools seems to be more effective in attaining the objective. Similarly, while numerous problem solving tools have been proposed in literature, it is critical to select the appropriate tool or combination of tools in order to solve a problem. Büyüközkan, Dereli, and Baykasoglu (2004) have summarized a number of tools for new product development. Here we provide a reduced set of these tools which have been traditionally applied to the problem solving processes in industry. It is possible to classify these tools as those used primarily for problem analysis and those used for idea generation. Table 1 below discusses some of these commonly applied problem solving tools used to solve manufacturing and design related problems.

All tools have distinct advantages and drawbacks. Some tools are specific application oriented. In spite of all this, there exists a basic systematic approach to problem solving. First, it is necessary to define and structure the problem accurately taking into consideration all the parameters involved in the problem space. More often than not, an industrial problem is more complex in nature than it initially appears. This necessitates a thorough analysis of the problem to break it down into smaller basic level problems. Once this is done, innovative solutions can be developed for each of the basic level problems which ultimately resolve the main problem. As mentioned earlier, efficiency and systemacy of developing these solutions has become extremely critical and hence the need to apply suitable problem solving techniques. Out of all the techniques listed in Table 1, we assert that TRIZ and AD better fit the current needs of industrial problem solving. In support of this observation, we provide a comprehensive review of industrial applications of TRIZ and AD as found in literature.

TRIZ is a systematic approach for generating innovative solutions. It is based on patent analyses, which articulated numerous solution patterns from diverse disciplines. TRIZ has been recognized as a concept generation process that can develop clever solutions to problems by using the condensed knowledge of thousands of past inventors. The foundation of TRIZ is based upon the following observations:

1. Problems and solutions were repeated across industries and sciences.
2. Patterns of technical evolution were repeated across industries and sciences.
3. Innovations used scientific effects outside the field where they were developed.

TRIZ provides steps that allow the design teams to avoid "psychological inertia" that tends to draw them to common, comfortable solutions when better, non-traditional ones may exist. Figure 1 captures the essence of the TRIZ philosophy. It is based on classifying any problem in terms of technical or physical contradictions and using the suggested 40 inventive principles, separation principles or substance field analysis to develop a solution. Although these separation principles and the inventive principles were extracted from mechanical engineering solutions, both the solution systems and the principles have much broader significance (Stratton & Mann, 2000). Unlike many heuristic techniques, TRIZ provides a definite direction to the thinking process. Moreover, the concept of integrating other tools such as brainstorming with TRIZ is not new and has been effectively used in generating innovative solutions. TRIZ applications have been discussed in an array of fields including manufacturing, engineering design and material sciences.

Many AD applications in designing products, systems, organizations and software have appeared in the literature in the last 10 years (Kulak, Durmusoglu, & Tufekci, 2005). The AD approach is based on application of two axioms to systematically solve a given problem. The two axioms were identified by examining the common elements that are always present in good design—be it product, process, or systems design (Suh, 1995). The first axiom, independence axiom, states that the functional requirements (FRs) of the problem should be independent of each other. The second axiom, information axiom, states that the better solution is the one with minimum information content, i.e., lesser complexity.

It would indeed be a good idea to develop a methodology which integrates TRIZ and AD together. Mann (1999) talks about the compatibility issues between TRIZ and AD. Kim and Cochran (2000) discuss TRIZ from the perspective of AD. Enhancing the compatibility suggested by Mann (1999) and Kim and Cochran (2000), we propose a problem solving approach based on using TRIZ and AD in synergy.

The paper is structured as follows. Sections "Literature review on applications of TRIZ" and "Literature review on applications of axiomatic design" consist of literature reviews on TRIZ and AD applications in solving problems related to designing and manufacturing. Section "Compatibility of TRIZ and axiomatic design" discusses compatibility issues of TRIZ and AD, proposing the advantages of applying the two techniques in unison to solve a problem. The effectiveness of this approach is demonstrated through a case study in Section "Case-study."

Literature review on applications of TRIZ

For the review, journal articles and conference proceedings from publications such as "Journal of Intelligent Manufacturing," "Computer Integrated Manufacturing Systems Journal," "Proceedings of ASME Design Engineering Technical Conferences," "TRIZ Journal" and various other on-line sources have been gathered through Compendex— the Engineering Database. "TRIZ," "TRIZ applications," "Industrial Applications of TRIZ" and "TRIZ applications in Manufacturing" were the keywords used for literature search.

Product designing and manufacturing related TRIZ applications

With the advent of concurrent engineering, manufacturing has transformed into a cross-functional activity associated with much more responsibilities than just the final production of merchandise. Problems can occur at different levels of the manufacturing phase. Depending upon the nature of manufacturing related problems, they can be categorized into three domains: (1) design for manufacturing, (2) manufacturing processes, and (3) manufacturing systems.

TRIZ helps in concept generation for solving design problems related to manufacturing. More than 30 years ago, Skinner (1969) used the concept of mechanical design tradeoffs to help acknowledge and manage conflicting performance parameters associated with manufacturing (Stratton & Mann, 2003). A problem of designing a 500 passenger plane that could land on a carrier and also break the sound barrier was put forth. Stratton and Mann (2003) suggest the use of TRIZ to develop a solution for this problem. The design problem is codified in terms of technical contradictions, and principles suggested by the contradiction matrix

Table 1 A review of commonly used problem solving tools

	Technique	Description
Problem analysis tools	Axiomatic Design (AD)	Nam Suh introduced AD in 1978. AD provides a systematic approach to structure and analyze a problem giving due consideration to all the parameters involved in the problem. The primary focus is on mapping the problem into different domains to attain an optimum solution
	Failure Mode Effect Analysis (FMEA)	The concept of FMEA was introduced in 1949 by United States Military. FMEA analyzes a product in order to determine the various ways in which the product is likely to fail and the necessary modifications can be made
	Value Engineering (VE)	VE was developed during World War II by General Electric Corporation. It is the systematic analysis of a product, process or system aimed at improving its value (factors like reliability, performance and cost)
	Total Quality Management (TQM) Tools	TQM techniques resulted mainly from work of scientists like E. Deming, J. Juran, P. Crossby and A. Figenbum. These consist a set of a variety of tools that are widely used for solving problems in industry. Some of the tools in this set include: Scatter Diagrams, Fishbone Diagrams, Pareto Analysis and Force Field Analysis
Idea generation tools	Heuristics	Heuristic techniques are characterized by trial and error. They involve choice, hunch, knowledge, and a lot of creativity but lack a systematic approach. They possess inherent drawbacks. The trial and error approach brings inefficiency into the problem solving process. Although they increase probability of finding a solution, an optimum solution is not guaranteed (Harris, 2002)
	Brainstorming	In 1953, A. Osborn introduced the concept of brainstorming. Brainstorming utilizes teamwork in developing solutions to a problem. It is characterized by two stages—idea generation and judgment. It can be highly effective in utilizing individual capabilities in a team atmosphere to generate solutions but lacks the ability to systematically analyze and define a problem
	TRIZ	Generich Altshuller introduced TRIZ in 1946. TRIZ is a systematic problem solving technique based on an extensive patent study by Altshuller. TRIZ uses various tools like the contradiction matrix, separation principles and substance-field analysis for generating efficient solutions. The primary focus is more on generating innovative solutions than problem definition and analysis

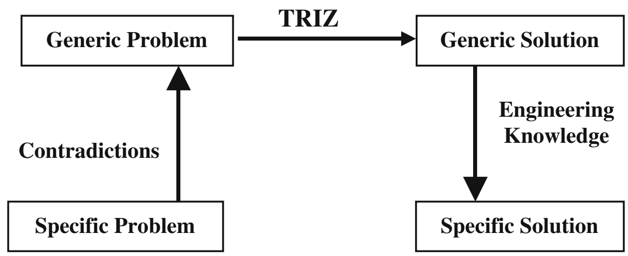

Fig. 1 TRIZ way of innovative problem solving

are used for resolving the tradeoffs to develop a primary solution concept. The suggested technical contradictions can be formulated into a contradiction statement as follows: as the speed (9) of take-off and landing increases (improving factor), the adaptability (35) of the plane (using carrier for take-off and landing) decreases (worsening factor). The contradiction matrix provides Dynamism (15), Preliminary action (10) and Copying (26) as recommended design principles. Principle 15, dynamism, is used to develop the concept of variable wing geometry as a possible solution. Further, the problem is classified in terms of physical contradictions in order to develop this solution: smaller wing area is essential for achieving higher speeds (reduction of weight), while take-off, landing and general maneuverability demand a larger wing area. Stratton and Mann (2003) suggest the use of "separation in time" principle. The wing spoilers can function differently at various points in time. Their operations can be separated as a function of time, i.e., they can perform the work of boosters during take-off and function as maneuvers while flying.

Tsai, Chang, and Tseng (2004) use TRIZ for concept generation while redesigning a seated ball valve mechanism. A major function of the seat, a part that is assembled in the valve body, is to make a seal surface with the closure member for which soft materials such as plastics, Teflon, and Nylon are usually used on account of their flexibility. However, when these materials are under high pressure, at a high temperature, or in a corrosive environment, the seat may be distorted out of shape or destroyed, and therefore will not form an effective seal (Tsai et al., 2004). Because of this problem, it was decided to redesign the valve seat using a metal instead of plastic. The problem was formulated in terms of a technical contradiction and a substance-field (Su-field) model and solved using principles of Asymmetry (4), Spheriodality (14) and Porosity (31) from the contradiction matrix and class II and class III solutions from the 76 standard solutions. Figure 2 shows the substance field model for the problem.

A TRIZ application in the automobile industry is illustrated by Cascini and Rissone (2004), where TRIZ was used for redesigning aluminum wheel of a motorscooter using plastic. Bariani, Berti, and Lucchetta (2004) have used TRIZ (technical and physical contradiction systems) in unison with Design

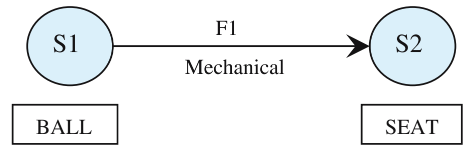

Fig. 2 Substance-field model for seated ball valve mechanism problem

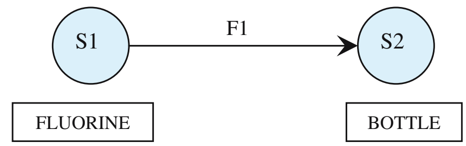

Fig. 3 Su-field analysis for the fluorination process

for Manufacture and Assembly (DFMA) to redesign a satellite antenna. This resulted in comparatively lower manufacturing costs for the new design and a 43% reduction in the assembly time.

TRIZ has also been successfully implemented for improvement of manufacturing processes. Monplaisir, Jugulum, and Mian (1998) present a case-study based on the use of TRIZ for improving the fluorination process of plastic bottles. Fluorination process is a gas modified plastic technology that reduces permeability and improves chemical resistance through surface treatment of the polymer. It enhances the usability of plastic container so that it can carry different solvents to help maintain product shelf life without solvent penetration (Monplaisir et al., 1998). The main aim of this case-study was cost reduction in the fluorination process. It was required to find such a resource that would take the fluorine gas to each of the plastic bottle without increasing the cost and without making the system complicated. A physical contradiction was found to exist. Increasing the amount of fluorine gas enhanced the uniformity of fluorination in plastic bottles, but it increased the process cost substantially. On the other hand, reducing the amount of fluorine gas brought about a substantial reduction in manufacturing cost at the expense of non-uniformity of fluorination among plastic bottles. Figure 3 represents the Su-field diagram for the problem.

F1 is the force of gas coming out of the nozzle. S1 is the first substance, fluorine gas, which exerts field F1 on substance S2, the bottle. Application of Class II standard solutions from the 76 standard TRIZ solutions suggests that the problem can be solved by changing the field F1 acting on S2 or adding another field (F2) in addition to F1. Based on this concept, a new fluorination system making use of gravity was suggested. Gravity could take the fluorine gas up to each plastic-bottle without complicating the system. Fluorine gas being 1.5 times heavier than air would provide additional help. The authors suggest placing showerhead injection ports at the top of the process reactor to generate better gas dynamics and hence uniform distribution as opposed to the earlier design where the ports were at the side of the gas chamber.

Yang and Zhang (2000) demonstrate the potential of TRIZ in process improvement by modifying an ampoule sealing process. Cavallucci, Lutz, and Thiebaud (2002) applied TRIZ to improve a bottle-filling process. Literature also discusses TRIZ applications which pertain to solving problems related to manufacturing systems. For example, Stratton and Warburtonb (2003) discuss a case-study where TRIZ principles are used for development of responsive and efficient supply chains. Skinner (1969) and Hill (2000) promoted separation of different business requirements taking a note of the fact that various products perform differently in the market based on their functionality. Stratton and Warburtonb (2003) suggest that the concept of group technology (GT) and flexible manufacturing systems (FMS) evolved from the separation in space principle. They put forth a case where the decision to outsource fashion sportswear manufacture from the USA to Honduras reduced the cost of manufacture, but had a detrimental effect on critical market response. The conflict was eventually resolved by separating out the requirements in time and space. Honduras provided low cost early supply, while the order was completed once sales demand at the start of the sales season had been determined (Stratton & Mann, 2003).

Table 2 below summarizes all the design and manufacturing related TRIZ applications mentioned above.

Literature review on applications of axiomatic design

Applications of AD in solving manufacturing related industrial problems are reviewed in this section. "Axiomatic Design," "Concurrent Engineering," "Applications of Axiomatic Design," and "Applications of Axiomatic Design in Manufacturing" were keywords used for the literature search done in Compendex. "Proceedings of International Conference on Axiomatic Design," "Issues in Design Manufacturing/Integration," "Research in Engineering Design," "International Journal of Production Research," "Computers and Industrial Engineering," "Journal of Nuclear Science and Technology" and "CIRP annals—Manufacturing Technology" were among the referred publications.

Product designing and manufacturing related axiomatic design applications

Although AD originated in the engineering design domain, it has found significant applications in manufacturing. Similar to applications of TRIZ, AD applications can be classified into three domains, based on the focus of the application as: (1) design for manufacturing, (2) manufacturing processes, and (3) manufacturing systems. An observation based on the reviewed literature is that whereas a majority of manufacturing applications of TRIZ relate to design for manufacturing and manufacturing processes, AD applications primarily focus on manufacturing systems. AD may be an appropriate approach to encompass to the new challenges of manufacturing system design (Houshmand & Jamshidnezhad, 2003).

The AD approach involves splitting a design problem into distinct functional requirements (FR) in a functional domain and then mapping them into design parameters (DP) in the physical domain. Yang and Zhang (2000) explain how the design of a simple bottle/can opener is practically an AD application. Figure 4 shows the opener design.

The opener possesses two FRs—(i) to open a bottle, (ii) to open a can. These two FRs satisfy the first independence axiom of AD. The opener is used to open either a bottle or a can at a time, but never both simultaneously. Current design of the opener is a same physical device that satisfies both the FRs. Hence, the design is satisfactory in terms of the second one, information axiom, as well. Physical integration without functional coupling is advantageous, since the complexity of the product is reduced (Yang & Zhang, 2000). Thus, one design satisfies two functions, which implies better manufacturability.

Park, Kang, Song, and Park (2003) explain the use of AD in designing a spacer grid. The conceptual design stage was achieved using the first axiom—independence—while optimization techniques and finite element analysis were applied to achieve the detailed design. Bae, Lee, and Chu (2002) demonstrate an AD application in designing an automotive suspension system. They also explain how a coupled design can be decoupled using the independence axiom. Hirani and Suh (2005) make use of AD in designing a journal bearing. AD is used to primarily provide insight into the objective functions and design variables for designing and improving the operating characteristics of fluid-film steadily loaded journal bearings.

Kumar and Weller (1991) demonstrate an AD application in improving a manufacturing process. They apply AD to synthesize a process for production of parts from polycarbonate that have a microcellular structure. The problem in the existing process was an undesired coupling between cell structure and geometry of the polycarbonate. Developing the ideal microstructure and then deforming the material to its required shape would impair the cell structure. Molding into the desired geometry and following it up with a microstructure treatment resulted into two thermal cycles causing manufacturing inefficiencies. Thus, a process designed to improve one property would adversely affect the other. The aim was to develop a process such that independent control of the microstructure and the geometry could be realized using one thermal cycle (Kumar & Weller, 1991). Structuring the problem in terms of the first AD axiom of independence, DP in the physical domain were chosen to satisfy the FR in the

Table 2 Summarization of TRIZ case-studies

	Design problem	TRIZ system for problem definition	TRIZ system for problem solution	Suggested parameters	Potential solutions
Design for manufacturing	Design of a 500 passenger supersonic air plane (Stratton & Mann, 2003)			•(15) Dynamism	Variable Wing Geometry—perform as boosters during take-off and maneuvers while flying
		(1) Technical Contradictions (2) Physical Contradictions	(1) Contradiction Matrix (2) Separation Principles	(10) Preliminary Action (26) Copying •Separation in Time	
	Design of a metal seated ball valve mechanism (Tsai et al., 2004)			•(1) Segmentation	Use of magnets, electro-magnets or magnetic fluid for sealing for three designs illustrated in Tsai et al., (2004)
		(1) Technical Contradictions (2) Su-Field Analysis	(1) Contradiction Matrix (2) 76 Standard Solutions	(4) Asymmetry (14) Spheriodality (31) Porosity • Class II and III Condensed Standards	
	Design of motorscooter wheel using plastics (Cascini & Rissone, 2004)			• (1) Segmentation	(1) Two-piece assembly
				(32) Optical changes	(2) Three-dimensional web
		(1) Technical Contradictions	(1) Contradiction Matrix	(17) Dimensionality change	(3) Strengthening hollow rim with a high viscosity substance like foam for energy dissipation
		(2) Su- Field Analysis	(2) 76 Standard Solutions	(28) Replacing a mechanical system • Class I Condensed Standards	
	Design of a satellite antenna (Bariani et al., 2004)			• (3) Local Quality	(1) Making the antenna out of plastic and coating the reflector surface with a metal
				(11) Previously placed pillow	(2) Properly designed rib/web to reduce the material volume but maintain stiffness
		(1) Technical Contradictions (2) Physical Contradictions	(1) Contradiction Matrix (2) Separation Principles	(10) Preliminary action (32) Optical changes • Separation in space	
Manufacturing processes	Improvement of fluorination process (Monplaisir et al., 1998)	(1) Physical Contradiction	(1) 76 Standard Solutions	• Class II Condensed Standards	Making use of gravity to induce uniformity into the fluorination process by placing gas port on the top

Table 2 continued

	Design problem	TRIZ system for problem definition	TRIZ system for problem solution	Suggested parameters	Potential solutions
		(2) Su-Field Analysis			
	Improvement of the ampoule sealing process (Yang & Zhang, 2000)			• (11) Previously placed pillow	Keeping the part of ampoule containing drug, immersed in water while sealing its ends with a burner
		(1) Technical Contradiction	(1) Contradiction Matrix	(13) Other way round	
		(2) Physical Contradiction	(2) Separation Principle	(1) Segmentation	
				• Separation in space	
	Improvement in bottle-filling process (Cavallucci et al., 2002)	(1) Technical Contradiction	(1) Contradiction Matrix	• (1) Segmentation	(1) Splitting the main tank into two smaller tanks to reduce water pressure
				(28) Replace a mechanical system	(2) Use acoustics or optical level gauging system instead of physical contact
				(35) Physical or Chemical Properties	(3) Chemical sterilized Nozzle
				(23) Feedback	
Manufacturing systems	Modifying supply chain management for a fashion apparel manufacturer (Stratton & Warburton, 2003)	(1) Physical Contradiction	(1) Separation Principle	(1) Separation in Time	Supply chain focus shifted from efficiency of production to speed of response. Early runs will be production focused and later orders will be delivery speed focused
	Principle of FMS and GT	(1) Physical Contradiction	(1) Separation Principle	(1) Separation in Space	The machine setups can be designed according to the part family designs. Batches of different families can be manufactured in the same cell
				(2) Separation in Time	

functional domain and process variables (PV) in the process domain were chosen to satisfy the design parameters. Two possible strategies to uncouple the conflicting properties were developed and design equations for the process designs were formulated as:

$$\{DP\} = [A]\{PV\} \tag{1}$$

where design matrix [A] was experimentally determined for both strategies. Finally, applying the second AD axiom, the process with lesser information content was chosen. The chosen process being uncoupled was demonstrated by the diagonal nature of its design matrix.

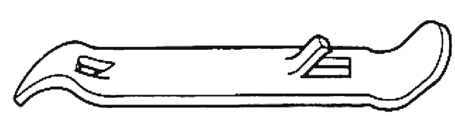

Fig. 4 Bottle/can opener—an AD application

Vallhagen (1994) uses process requirement (PR) domain proposed by Sohlenius (1992) in addition to the four domains of conventional AD to discuss design and development of complex manufacturing systems. Sohlenius (1992) and Vallhagen (1994) suggest a model that subdivides a design into three worlds: customer, designer, and manufacturing.

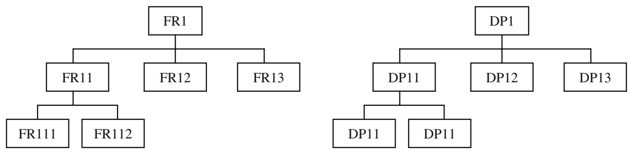

Fig. 5 Hierarchical structure of FRs and DPs

Sohlenius (1992) expresses the relationship between the different domains as

$$\{FR\} = [A]\{DP\} \tag{2}$$

and

$$\{PR\} = [B]\{PV\} \tag{3}$$

where functional domain and physical domain form a part of the designer world and process requirements and process domain form the manufacturing world. Vallhagen (1994) proposes dividing the manufacturing world into five spaces namely parts, assembly, material handling, control and integration, and human factor space based on Suh's work (1990). A case-study of airbag assembly is described to explain mapping from the designer world into the assembly space. The DPs have been categorized into dimensioning DPs, component DPs and sub-assembly DPs and the component DP hierarchy is mapped into the PR assembly space.

Suh, Cochran, and Lima (1998) emphasize the importance of accurate design of manufacturing systems. Two manufacturing systems can have two identical sets of machines and yet have significantly different production rates and cost, depending on how the system is designed and operated, which in turn will affect how people and information are used (Suh et al., 1998). The authors demonstrate the application of AD for designing a hypothetical manufacturing system producing a mix of products in high volume in a competitive environment. A hierarchical structure is created for the FRs and subsequently for the DPs. The FR at the topmost level of the hierarchy is based upon the point of view of the owners/shareholders which is maximizing the return on investment. The FR is mapped into the physical domain in terms of a DP. The wants of the internal customers (employees) and external customers are accounted for at lower levels. The hierarchy has seven levels. At each level, a check for independence axiom is carried out by determining nature of the design matrix. Figure 5 demonstrates nature of the hierarchy.

The design of manufacturing systems is an important but neglected aspect of concurrent engineering which has focused on the relationships between product design and process design and has ignored system design (Black, 1991). Black (1991) demonstrates the use of AD in designing manufacturing systems using two case-studies. Through the first case study of an American supermarket, the author explains that many existing systems do not adhere to the AD axioms which can have damaging effects in the long run. The example of a supermarket is analogs to an AD application for a manufacturing plant. The second case-study of Honda manufacturing plant demonstrates a real life application of AD in designing a manufacturing system. Further, (Black, 1991) proposes six corollaries based on the two axioms which can assist while solving a real life problem.

Durmuşoglu, Kulak, and Tufekci (2002) and Kulak et al. (2005) propose a framework based on AD principles to convert a traditional manufacturing setup into a cellular manufacturing system (CMS). A case study of converting a conventional metal ramp/stairwell manufacturer from process-oriented layout to cellular manufacturing based on the proposed framework is explained. Albano and Suh (1994) demonstrate the use of AD as a platform for building concurrent engineering systems. Jung and Billatos (1993) discuss application of new radical production principles to increase productivity in industries that face a growing competition in the marketplace. They develop a knowledge based expert system for assembly (KBESA) for assisting engineers in designing better products and features, using Design for Assembly (DFA) and AD principles. Gu, Rao, and Tseng (2001) present a method for designing manufacturing systems based on AD and systematic design approach using the case-study of a furniture manufacturing system. The designing process is divided into multiple stages—definition of design requirements, conceptual, configuration and detailed design—based on systematic design and AD is used to evaluate design solutions at each stage. Houshmand and Jamshidnezhad (2003) present a practical application of AD in redesigning a car body assembly line. Suh et al. (1988) provide an AD-based model for an ideal production system in line with lean principles (Kulak et al., 2005).

Compatibility of TRIZ and axiomatic design

The reviews show the effectiveness of TRIZ and AD in solving industrial problems. However, both techniques have their own forte. While TRIZ has the capability of generating innovative solutions, AD has the capability to systematically define and breakdown the main problem and to analyze effectiveness of the solution in terms of satisfying the two axioms. In Suh's (1990) terms, problem definition is an iterative process centered on the definition and optimization of the Functional Requirements of a design (in Mann, 1999). AD guidelines concentrate more on problem definition rather than solution generation. Although creating and optimizing solutions is a step in the AD methodology, it does not propose any specific techniques for generating accurate and efficient solutions. On the other hand, TRIZ focuses primarily on generating innovative solutions. TRIZ proposes defining any problem in terms of a physical or technical contradiction, which may not always be feasible in case of complex multi-layered problems. Though TRIZ can be used as a problem definition tool, its greatest strength lies in resolving contradictions and solving problems defined by other techniques (Hipple, 2003). Axiomatic Design is recognized to provide designers with a tool to structure their thought processes in the early design stages, and TRIZ gains its fame as a tool to guide designers to solutions for conflicts in an existing system (or design) (Kim & Cochran, 2000).

Whereas AD technique used alone lacks the ability to develop innovative solutions, TRIZ can fall short in solving complex problems involving a combination of multiple variables. This statement is substantiated by the fact that while a majority of TRIZ applications have been found in solving problems specific to a manufacturing process or a product design, majority of AD applications have dealt with solving problems related to manufacturing systems. Hence, the need to use AD and TRIZ together.

Mann (1999) suggested the idea of applying TRIZ and AD concurrently to solve a problem by citing examples from the book “Principles of Design” by Suh (1990). From an AD perspective, TRIZ fits very elegantly into the “Ideate and Create” element of Suh’s map of the design process. From a TRIZ perspective, AD offers the potential for improving the problem definition and problem solving processes through axioms offering means of assessing the effectiveness of a design concept, and new perspectives on the specification of functional requirements and the handling of multi-layered problems (Mann, 1999). Kim and Cochran (2000) enunciated how the TRIZ concepts of ideality, contradictions and su-field modeling fitted in the AD framework.

We propose a framework for applying the two techniques in concert. This is done by assigning specific functions to TRIZ and AD. We call this framework, the synergistic problem solving approach. By applying TRIZ within an AD framework, we try to capitalize on the strengths of both tools. The synergistic approach primarily uses AD in order to analyze the problem and decompose the main problem into a hierarchy of basic level problems. TRIZ is applied to separate functional requirements (if they are coupled) and to generate innovative solutions to the basic problems in the AD hierarchy. Thus, the framework attempts to synergistically use detailed analysis capability of AD with the innovative idea generation prowess of TRIZ.

Ruihong, Runhua, and Guozhong (2004) have proposed an approach combining AD and TRIZ and explained it using the case study of a paper machine. However, we suggest a more robust and enhanced approach. While the Ruihong et al. (2004) approach employs TRIZ only in cases where the design matrix of AD is coupled, the synergistic approach proposed here utilizes TRIZ more effectively. TRIZ is used not only for decoupling in case of a coupled design matrix but is also used for the mapping and zigzagging processes between the functional domain and physical domain of the AD hierarchy. This will bring more efficiency into the problem solving process. Figure 6 shows the flowchart for the synergistic problem solving approach proposed in this paper.

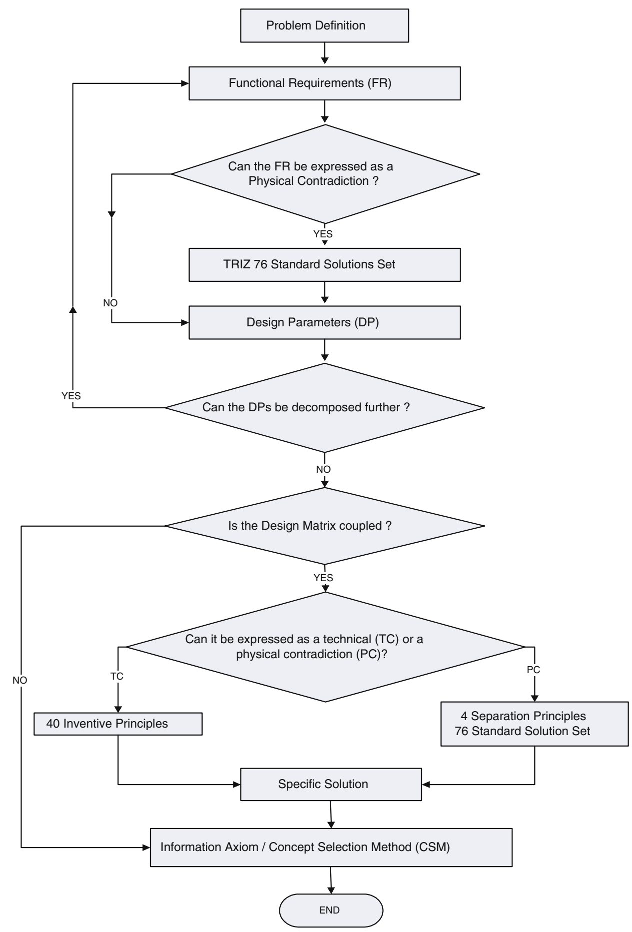

Fig. 6 Flowchart for the synergistic problem solving approach using TRIZ and AD

A stepwise procedure for the systematic application of synergistic approach is explained below.

Step 1: *Define the basic problem using AD terminology*. The main FR is defined at the highest hierarchy level.

Step 2: *Map the FR into physical domain using TRIZ*. The FR can be expressed in terms of TRIZ a technical or physical contradiction. Contradiction matrix or the standard solution sets can be used to resolve the contradictions. Alternatively, the problem can be modeled as a substance-field model. Various idea generation techniques (i.e., brainstorming, c-sketch, idea-trigger) can be applied to develop potential concepts for each suggested TRIZ principle.

Step 3: *Zigzag the DP back into the functional domain*. The DP developed in the step above should be mapped back into the functional domain. The main FR should be split up into FRs at the second level of hierarchy.

Step 4: *Create a hierarchy of FRs and DPs using steps 2 and 3 until no further decomposition seems feasible.*

Step 5: *Formulate equations (i.e., Eq. 2) at each level of the hierarchy for each FR and corresponding DP*. The equations should be classified as being coupled, decoupled or uncoupled.

Step 6: *Determine the nature of the matrices*. Accept the design if all the design matrices are uncoupled or decoupled. However, if any design matrix is coupled, the FR needs to be decomposed further until the matrix becomes uncoupled or decoupled. It is possible to use TRIZ separation principles to achieve this.

Step 7: *Apply the second AD axiom—Information*. If more than one potential concept is generated using TRIZ and both lead to an uncoupled or decoupled design matrix, the information axiom should be applied. The optimum design should be selected as the one with the least complexity.

The effectiveness of this approach is demonstrated by the case study below.

Case-study

In this section, a case-study involving a real life manufacturing related problem is discussed in light of the synergistic problem solving approach. This case-study deals with a problem that occurred in a manufacturing company in India (Shirwaiker, 2005).

The problem

The company manufactures and assembles different ratings of electrical Air Circuit Breakers (ACB), where each ACB consists of at least 500 individual components and sub-assemblies. One of the functionally important sub-assemblies of the ACB is the trip latch roller pin sub-assembly (TLRPSA). Although the individual assembly of TLRPSA does not take place on the main ACB assembly flow-line, it has to be assembled on to the ACB on the flow-line. TLRPSA assembly takes place on separate workstations as batch production and the production rates required are high. In order to permanently eliminate some of the frequently occurring defects so as to make the assembly foolproof, the TLRPSA was redesigned as part of an internship project. Figure 7 (adapted from Shirwaiker, 2005) shows a CAD representation of the sub-assembly. Figure 7a represents the original design and (b) represents the modified design.

Functionally, the TLRPSA can be split up into two parts—the trip latch assembly and the roller pin sub-assembly. The assembly process of the entire TLRPSA based on the original design consisted of five operations. The modified design reduced the number of assembly operations to four by combining the last two riveting operations into one. The first three operations were manual, which could be performed on individual workstations while the last one needed to be performed on a pneumatic riveting press. Since the design was changed, the existing riveting procedure could not be applied for the modified design.

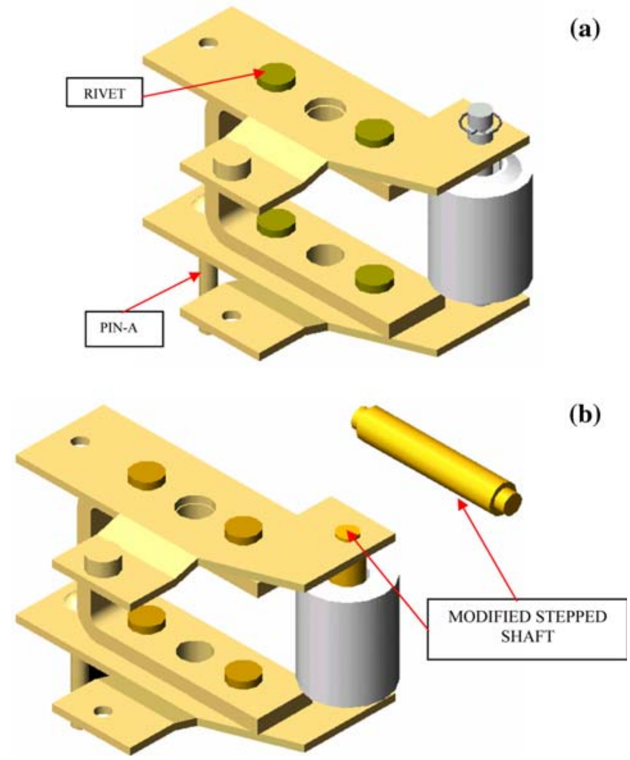

Fig. 7 Design of TLRPSA (**a**) before modification (**b**) after modification

The riveting operation needed to be fast and accurate. As riveting was the last value adding operation on the TLRPSA, inaccurate riveting would result in very high quality costs. Another important consideration in the problem was that the riveting press was used for a variety of different sub-assemblies and not exclusively meant for TLRPSA.

Solution based on axiomatic design and TRIZ

Step 1: Defining the basic problem using AD terminology:

The problem under consideration is to develop a medium for faster and economical riveting operation. In AD terms, the basic functional requirement (FR) at top of the hierarchy can be expressed as: FR 1: Developing a medium for productivity improvement.

Step 2: Mapping FR into the physical domain using TRIZ:

In terms of TRIZ, the problem can be simply expressed as a physical contradiction: "For improving manufacturability of the TLRPSA, the design has to be changed. But redesigning the sub-assembly is not suitable for its manufacturing process (riveting)." The component (TLRPSA) and the machine (riveting press) constitute the system under consideration in this problem definition. TRIZ Condensed Standards I, solution 1.1 (Ogot & Kremer, 2004), suggests the addition of a temporary or permanent internal or external additive. Thus, the AD design parameter (DP1) in the physical domain based on the TRIZ standard solutions recommendation would be: DP 1: Use of a Riveting Fixture.

Step 3: Zigzagging the DP back into the functional domain:

Based on DP1, further decomposition of FR1 results into the following FRs:

FR 1.1: The medium (fixture) should be easy to manufacture. (Ease of construction)

FR 1.2: The medium (fixture) should be easy to operate. (Ease of operation)

FR 1.3: The medium (fixture) should be interchangeable. (Interchangeability)

FR 1.4: The medium (fixture) should allow good part quality. (Quality Issues)

Step 4: Creation of a hierarchy of FRs and DPs using steps 2 and 3:

To satisfy FR 1.1, the corresponding DP should allow better manufacturability. When design of the fixture was started, the designer had envisioned making the fixture out of one block of material. However, considering physical geometry of the TLRPSA, a lot of material would have to be machined out of the raw material block. The use of single block of raw material reduced complexity of the design. However, it made the manufacturing inefficient and costly. Thus, there was a technical contradiction in terms of TRIZ: "As complexity of the fixture (36) decreased (improving factor), its manufacturability (32) decreased (worsening factor)." The contradiction matrix provides the following principles: Cheap disposable (27), Copying (26), Segmentation (1), other way round (13). Following the principle of Segmentation (1), the fixture can be made out of multiple components and assembled together. This will result in time and cost efficiency. Thus, the corresponding DP will be: DP 1.1: Use of a multi-piece assembled fixture.

According to FR 1.2, the operator should find it easy to operate the tool. This implies that it should be easy to load and unload the job. Considering the geometry of the TLRPSA, the most ergonomic way for an operator to load and unload the workpiece will be from the front side. Thus, DP 1.2: Design for front loading.

Since the riveting press is used for components other than TLRPSA, FR 1.3 states that the tool should be interchangeable from point of view of the machine. Geometry of the TLRPSA causes a problem in this case. Refer to the Pin-A in Fig. 7a. The pin extends from base of the sub-assembly in the downward direction as the riveting operation occurs on the top side, resulting in interference between the pin and the machine table. The pin can be accommodated by either changing the direction of the riveting operation or machining a slot in the machine table. Changing the direction of riveting is impractical. Machining a slot in the machine table is undesirable for two reasons. First, this may cause problems while assembling tool for another operation on the same machine table, thus deteriorating the interchangeability. Second, the machine table being hardened will pose practical difficulties while machining the slot. Even though machining a slot in the machine table makes it easy to accommodate the pin and use the tool, it results in additional problems. This can be expressed as a TRIZ technical contradiction. "As convenience of use (33) of the fixture increases (improving factor), the harmful side effects (31) increase (worsening factor)." The contradiction matrix suggests all design principles. A solution can be developed based on beforehand cushioning (11) and cheap disposable (27) principles. A spacer block can be provided as a buffer between the main fixture and the machine table. The slot for clearing Pin-A can now be machined in the spacer block instead of the machine table and the spacer block can be assembled onto the machine table. Thus, DP 1.3: Introducing the spacer block as a buffer.

FR 1.4 deals with quality aspects of the finished part. This can be achieved by fool-proofing the design so that a component cannot be loaded in a wrong way. The component being asymmetrical along the riveting axis cannot be loaded into the fixture with a wrong orientation. DP 1.4: Introduce Foolproofing.

Figure 8a and b represent the AD hierarchy of FRs and DPs as explained above.

Step 5: Formulating equations (i.e., Eq. 2) at each level of the hierarchy for each FR and corresponding DP.

The second level of hierarchy can be checked for satisfying the independence axiom based on the equation:

$$\{FR\} = [A]\{DP\} \tag{4}$$

$$\begin{bmatrix} FR1.1 \\ FR1.2 \\ FR1.3 \\ FR1.4 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP1.1 \\ DP1.2 \\ DP1.3 \\ DP1.4 \end{bmatrix} \tag{5}$$

$$\text{where, design matrix } [A] = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix}$$

DP 1.1 suggests using a multi-piece fixture. Thus, different parts of the fixture will have to perform different functions. Following "Zigzagging" of DPs into the functional domain, FR 1.1 can be further decomposed into the following:
FR 1.1.1: Component Location
FR 1.1.2: Component Resting
FR 1.1.3: Component Clamping

Using engineering design knowledge, the DPs were selected as follows:

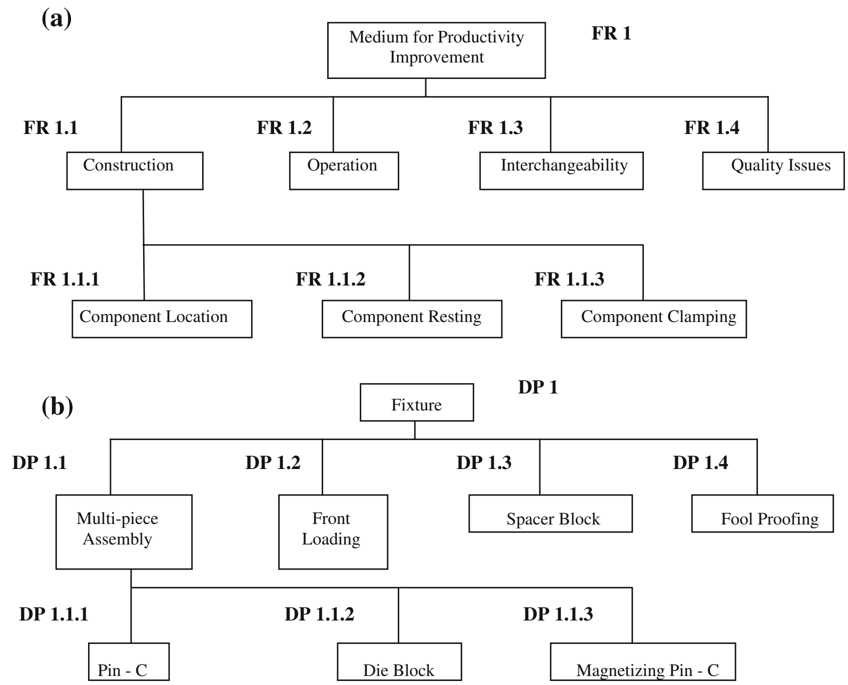

Fig. 8 TLRPSA AD hierarchy of (**a**) FRs (**b**) DPSs

DP 1.1.1: Pin-C
DP 1.1.2: Die Block
DP 1.1.3: Magnetizing Pin-C

Checking for independence axiom using the equation:

$$\{FR\} = [B]\{DP\} \tag{6}$$

$$\begin{bmatrix} FR1.1.1 \\ FR1.1.2 \\ FR1.1.3 \end{bmatrix} = \begin{bmatrix} X & X & 0 \\ 0 & X & 0 \\ X & 0 & X \end{bmatrix} \begin{bmatrix} DP1.1.1 \\ DP1.1.2 \\ DP1.1.3 \end{bmatrix} \tag{7}$$

Where design matrix B $= \begin{bmatrix} X & X & 0 \\ 0 & X & 0 \\ X & 0 & X \end{bmatrix}$

Step 6: Determining nature of the design matrices:

Design matrix A is uncoupled because the DPs do not affect any FR other than their own. Thus, the independence axiom is satisfied at the second level of the hierarchy. However, design matrix B is coupled. Hence, the independence axiom is not satisfied at the third level. This is because while the die block provides resting for the trip latch part of the sub-assembly, it also provides nesting (location) for the roller. Hence, it is necessary to decompose FR 1.1 further.

Location of the roller and resting of the trip latch should be defined as separate functional requirements. According to the proposed framework, TRIZ separation principles should be applied to achieve this. “Separation in structure” principle can be applied in this case. Ogot and Kremer (2005) state the following design principles as being related to “separation in structure” principle: segmentation (1), local quality (3), joining (5) and opposite solution (13). Based on the segmentation principle, the die block can be separated into die block 1 for resting the trip latch sub assembly and a nesting block for nesting the roller. Now, while the die block 1 provides a resting surface for the trip latch part of the assembly, the nesting block nests (locates) the roller. It is worth noting that machining the nest for the roller in the earlier die block design also posed manufacturing difficulties. This problem could be framed as a technical contradiction where complexity of the part (36) improved because of one piece construction but decreased the manufacturability. Once again, segmentation (1) is a suggested design principle for this contradiction which is used to solve this problem. Figure 9a shows the coupled design of the die block while Fig. 9b and c show the modified design. Another note is that as the roller is held onto the pin and stands in a vertical position, separate resting is not required by the roller. As such resting of the roller is an inherent function of the pin, a part of the TLRPSA itself.

The modified set of FRs and DPs are as follows:

FR 1.1.1: Trip Latch	LocationDP 1.1.1: Pin-C
FR 1.1.2: Roller Location	DP 1.1.2: Nesting Block
FR 1.1.3: Trip Latch Resting	DP 1.1.3: Die Block 1
FR 1.1.4: Component Clamping	DP 1.1.4: Magnetizing Pin-C

Figure 10a and b depict the modified hierarchies of the FRs and DPs, respectively.

Now, the modified design equation at the third level can be written as

$$\{FR\} = [C]\{DP\} \tag{8}$$

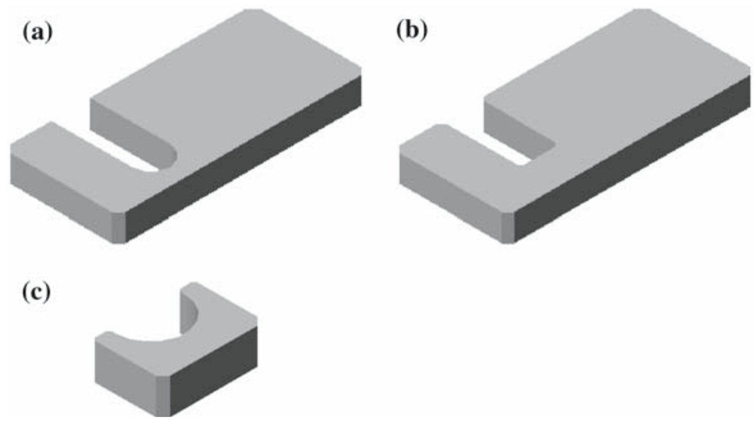

Fig. 9 (**a**) Coupled design of the die block (**b**) dieblock 1 (**c**) nesting lock

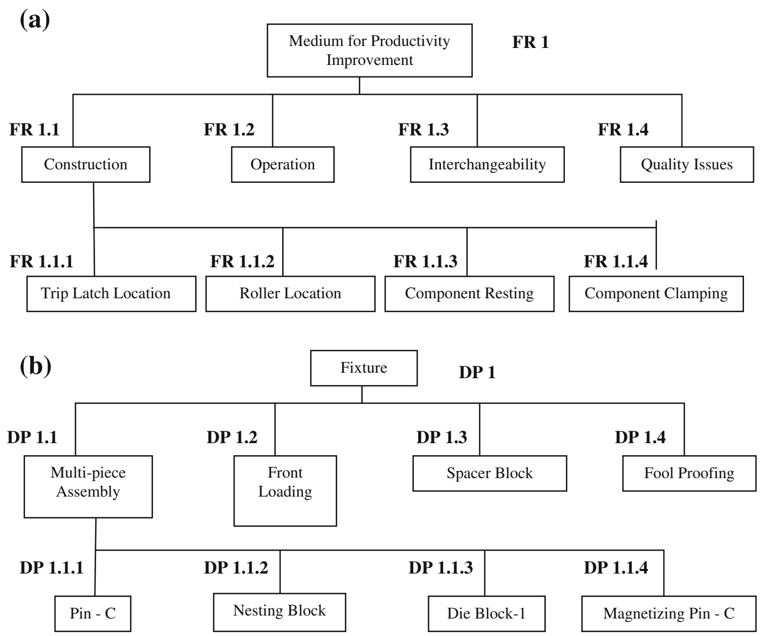

Fig. 10 Modified hierarchical structure of (**a**) FRs (**b**) DPs

$$\begin{bmatrix} \mathrm{FR1.1.1} \\ \mathrm{FR1.1.2} \\ \mathrm{FR1.1.3} \\ \mathrm{FR1.1.4} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ X & 0 & 0 & X \end{bmatrix} \begin{bmatrix} \mathrm{DP1.1.1} \\ \mathrm{DP1.1.2} \\ \mathrm{DP1.1.3} \\ \mathrm{DP1.1.4} \end{bmatrix} \tag{9}$$

where, $$C = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ X & 0 & 0 & X \end{bmatrix}$$

Design Matrix C is now decoupled. Therefore, the independence axiom is also satisfied at the third hierarchical level. Consequently, the design is acceptable as independence axiom is satisfied at all levels of the hierarchy. Step 7 of the framework is not applicable for this case-study as no alternate concept was designed.

Figure 11 depicts the final design of fixture that was designed and implemented (adapted from Shirwaiker, 2005).

Conclusion

It is essential that the right problem solving tool is used in order to tackle problems that occur in an industry. A review of industrial applications of TRIZ and AD in solving manufacturing and design related problems shows that TRIZ applications have primarily focused on problems related to product design and manufacturing processes whereas AD has been primarily applied to solve multi-layered systems related problems. While AD was found to be most effective in defining and analyzing a problem, TRIZ was found to be one of the best systematic techniques for generating innovative solutions.

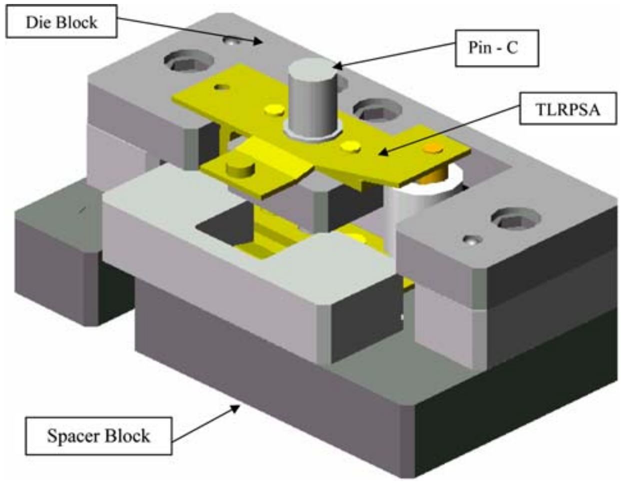

Fig. 11 Final design of the riveting fixture

Hence, a new problem solving approach based on the use of TRIZ and AD is proposed. AD is used for systematically defining a problem and breaking up the functional requirements into individual hierarchical elements. TRIZ is used for developing DPs to satisfy the corresponding FRs. In case the design matrix is coupled, TRIZ separation principles can be applied to separate the non-independent FRs. Additionally, any suitable concept selection method (CSM) from literature can be used for selecting the optimum solution in case more than one solution were generated using TRIZ. The case study of designing a tool to improve productivity is discussed to demonstrate the proposed problem solving approach. TRIZ and AD are compatible, as seen through the case study. This approach of using TRIZ and AD is expected to increase the efficiency and quality of problem solving.

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