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A COMPARISON OF TRIZ AND AXIOMATIC DESIGN

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ABSTRACT

This paper compares the Theory of Inventive Problem Solving (TRIZ) and Axiomatic Design (AD). Both AD and TRIZ are briefly reviewed and their possible similarities and relationships are analyzed and listed. A case study is given.

Keywords: axiomatic design, TRIZ, designs

1. INTRODUCTION

It is self-evident that decisions made during design stage of product and process development will profoundly affect the product quality and productivity. Traditionally, product and process have been designed based on know-how and trial-and-error; however the empiricism of a designer is limited and can lead to costly mistakes. Axiomatic Design and the Theory of Inventive Problem Solving have been developed to aid design decision making and related problem solving.

Axiomatic design is a general methodology that helps designers structure and understand design problems, thereby facilitating the synthesis and analysis of suitable design requirements, solutions, and processes. This approach also provides a consistent framework from which the metrics of design alternatives can be quantified.

TRIZ offers a wide-ranging series of tools to help designers and inventors avoid trial-and-error in design process and solve problem in a creative fashion. The most part of TRIZ tools were created by means of careful research of the world patent database (mainly in Russian), so they have been evolved independently and separately from many of the design strategies developed outside Russia.

This paper compares and contrasts TRIZ and Axiomatic Design problem solving methods, analyzes their compatibility and discusses the possibility of integration of them. The long-term goal of this work is to develop a generic framework and tools to help designers understand and make correct design decisions.

The remaining body of paper is divided into 4 parts. Section 2 gives a brief review of AD and TRIZ. Section 3 gives the comparisons of AD rules and TRIZ tools. Section 4 provides a case study and section 5 is the conclusions of this paper.

2. REVIEW OF AXIOMATIC DESIGN AND TRIZ

2.1. REVIEW OF AXIOMATIC DESIGN

The design process usually consists of several steps as follows.

Establish design objectives to satisfy a given set of customer attributes
Generate ideas to create plausible solutions
Analyze the solution alternatives and select the best one
Implement the selected design

Axiomatic Design theory has been developed to aid above decision making process. It is based on the following important concepts [1] [8]:

1) There exist four domains in the design world, customer domain, functional domain, physical domain and process domain.

2) Solution alternatives are created by mapping the requirements specified in one domain to a set of characteristic parameters in an adjacent domain. The mapping between the customer and functional domains is defined as concept design; the mapping between functional and physical domains is product design; the mapping between physical and process domains corresponds to process design.

3) The mapping process can be mathematically expressed in terms of the characteristic vectors that define the design goals and design solution.

4) The output of each domain evolves from abstract concepts to detailed information in a top-down or hierarchical manner. Hierarchical decomposition in one domain cannot be performed independently of the other domains, i.e.,

decomposition follows zigzagging mapping between adjacent domains.

5) Two design axioms provide a rational basis for evaluation of proposed solution alternatives and the subsequence selection of the best alternative. The two axioms can be stated as follows:

> Axiom 1 (independence axiom): *maintain the independence of the FRs.*
> Axiom 2 (information axiom): *minimize the information content of the design*.

The first axiom is the independent axiom, and it focus on the nature of the mapping between "what is required" (FRs) and "how to achieve it" (DPs). It states that a good design maintains the independence of the functional requirements. The second axiom is the information axiom and it establishes information content as a relative measure for evaluating alternative solutions that satisfy the independence axiom.

Many corollaries and theorems are derived from these two fundamental axioms.

2.2. REVIEW OF TRIZ

TRIZ is Russian acronym for The Theory of Inventive Problem Solving that originated from extensive studies of technical and patent information. Studies of patent collections by Altshuller, the founder of TRIZ, indicated that only one per cent of solutions were truly pioneering inventions, the rest represented the use of previously known ideas and concepts but in a novel way [2]. Thus, the conclusion was that an idea of a design solution to a new problem might be already known. However, where this idea could be found? TRIZ, based on the systematic view of technological world, provides techniques and tools to help designers create a new design idea and avoid numerous trials and errors during a problem solving process.

Any problem solving process involves two components: the problem itself and the system in which the problem exists. Successful innovative experience shows that both problem analysis and system transformations are equally important to problem solving. Accordingly, TRIZ methodology includes the analytical tools for problem analysis and the knowledge base tools for system changing. The theoretical foundations of these tools are the patterns of evolution of technological systems. Figure 1 illustrates the basic structure of TRIZ.

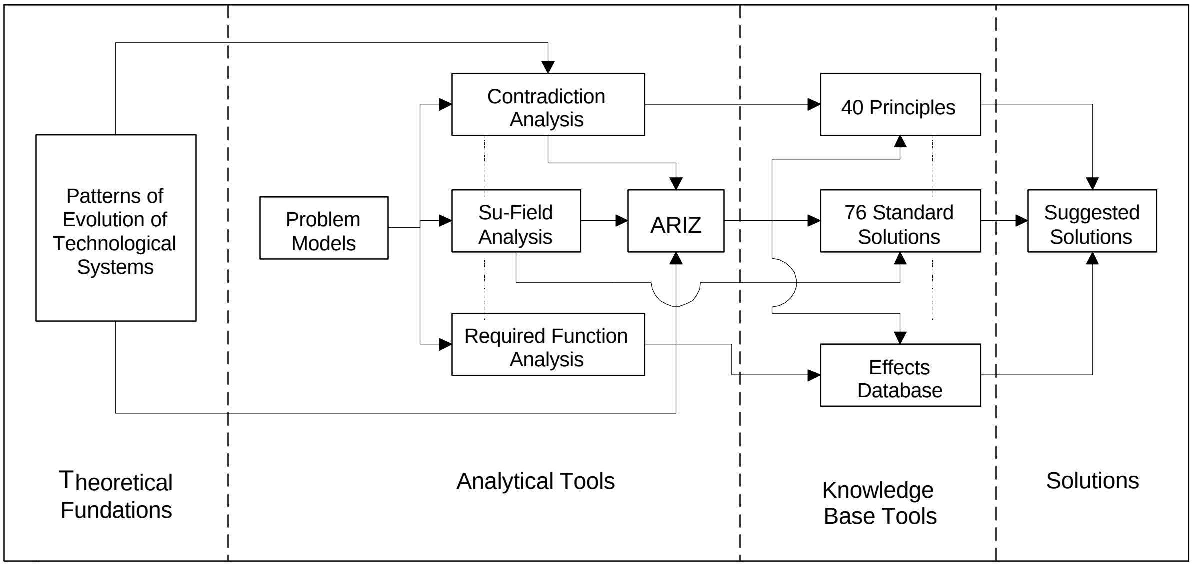

Figure 1. Structure of TRIZ Mothodology

THEORETICAL FOUNDATIONS

The Patterns of Evolution of Technological System are the theoretical foundations of TRIZ methodology. These patterns indicate that there exist basic laws for engineering system development, and understanding them enhances ones ability to the design problem solving. There are eight patterns and each pattern consists of several sub-patterns or lines [9].

(1) Stages of evolution of a technological system
(2) Evolution toward increase ideality
(3) Non-uniform development of system elements
(4) Evolution toward increase dynamism and controllability
(5) Increased complexity followed by simplification
(6) Matching and mismatching elements
(7) Evolution toward micro-level and increased use of fields
(8) Evolution toward decrease human involvement

Patterns and their lines serve as “soft equation” or “function” describing the system “life curve” in the evolution space. Based on them, the further configurations of a system can be reliably “calculated or forecasted” if the current system configuration is given [5].

TRIZ ANALYTICAL TOOLS

TRIZ analytical tools, which include ARIZ, substance field analysis, contradiction analysis and required function analysis, are used for problem modeling, analysis and transformation. These analytical tools do not use every piece of information about the product where the problem resides. The way they generalize a specific situation is to represent a problem as either a contradiction, or a substance-field model, or just as a required function realization. ARIZ is such a sophisticated analytical tool that it integrates above three tools and other techniques.

Substance field analysis is a TRIZ analytical tool for building functional model for problems related to existing or new technological systems. Each system is created to perform a certain function. Typically, a function represents some action toward a certain object, and this action is performed by another object. This situation can be modeled by a triangle whose corners represent objects and an action or interaction (called a field). A substance may be an article or tool and the field may be some form of energy. In general, any properly functioning system can be modeled with a complete triangle as shown in figure2. Any deviation from the complete Su-field triangle, for example missing elements or occurring inefficient and undesired functions, reflects the existence of a problem [2] [8] [9].

Contradiction Analysis is a powerful tool of looking problem with the new perspective. In TRIZ standpoint, a challenging problem can be expressed as either a technical contradiction or a physical contradiction. A technical contradiction might be solve using contradiction table that identifies 39 characteristics most frequently involved in design process. A physical contradiction might be solved by separation principles. A technical contradiction may be transformed to a physical contradiction in some circumstances. Contradiction analysis is the fundamental step to apply 40 inventive principles, one of the knowledge base tools [2] [5] [7] [10].

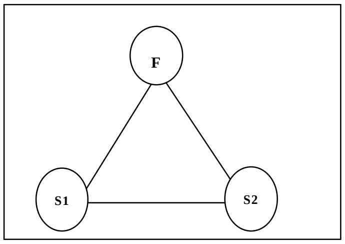

Figure 2. Substance Field Model

Required function analysis refers to select the objective of the system and match it with the function list in the TRIZ Effect Knowledge Base. Required function analysis is the first step to use this knowledge base to search for the recommendations for accomplishing the objective [10].

ARIZ refers to Algorithm for Inventive Problem Solving, a set of successive logical procedures directed at reinterpretation of a given problem. In TRIZ standpoint, a technical problem becomes an invention one when a contradiction is overcome. However, “real world” problems do not always appear as contradictions. Furthermore, Su-field analysis and required function analysis may not be applied directly in some situations. Thus, it is not obvious how to apply TRIZ knowledge base tools to aid the problem solving. ARIZ is a step-by-step method, whereby, given an unclear technical problem, the inherent contradictions are revealed, formulated and resolved [5].

KNOWLEDGE BASE TOOLS

TRIZ knowledge base tools include 40 Inventive Principles, 76 Standard Solutions and Effects of Knowledge Base. These tools are developed based on the accumulated human innovation experience and the vast patent collection. The knowledge base tools are different from analytical tools in that they suggest ways for transforming the system, while analytical tools help changing the problem statement in favor of problem solving [7].

Forty Inventive Principles are used to guide the TRIZ practitioner in developing useful “concepts of solution” for inventive situations. Each of solutions is a recommendation to make a specific change to a system for eliminating technical contradictions. Contradiction table recommends which principles should be considered in solving approximately 1250 contradictions.

Seventy-six Standard Solutions were developed for solving standard problems based on the Patterns of Evolution of Technological Systems. These Standard Solutions are grouped into five classes according to their objectives; the order of solutions within the classes reflects certain directions in the evolution of technological systems. To use these tools, one identifies (based on the model obtained in Su-field analysis) the class of a particular problem and then chooses a set of Standard Solutions accordingly. The standard solution is a recommendation as to what kind of system transformation should be made to eliminate the problem.

Effects of Knowledge Base is probably the most easy to use tool in TRIZ. Very early in his research, Altshuller recognized that given a difficult problem, the ideality and ease of implementation of a particular solution could be substantially increased by utilizing various physical, chemical and geometric effects. Up to now, a large database has been developed. In applying Effects of Knowledge Base tool, one has to select an appropriate function the system performs (based on the required function analysis), then the knowledge base provides many alternatives for delivering the function.

3. COMPARISONS OF AD RULES AND TRIZ PROBLEM SOLVING TOOLS

The following table summarizes the possible relations between Axiomatic Design rules and TRIZ problem solving tools. Seven corollaries and three theorems in AD are selected to compare with TRIZ tools. Seven corollaries, which serve as the design rules, are derived from two axioms directly, so comparing these “lower level design rules” with TRIZ tools is useful to understand these two methodologies. Only three theorems are selected because we do not think other theorems in AD can be linked with TRIZ. Mann gives the general comparisons of AD and TRIZ at the level of domain, mapping, hierarchies and axioms [6].

AXIOMATIC DESIGN	TRIZ
Corollary 1 (Decoupling of Coupled Design) Decouple or separate parts or aspects of a solution if FRs are coupled or become interdependent in the proposed design. This corollary states that functional independence must be ensured by decoupling if a proposed design couples the functional requirements. Functional decoupling may be achieved without physical separation. However, in many cases, such physical decomposition may be the best way of solving the coupling problem [1] [3].	**Contradiction** concept in TRIZ is similar to the functional coupling in AD. Overcoming contradiction in TRIZ means the removal of functional coupling in AD. There are two types of contradictions: technological contradiction and physical contradiction. A technological contradiction is derived from a physical contradiction. So, certain changes of the physical structure of a technological system guided by Contradiction Table and 40 Inventive Principles or Separation Principles are often required to remove contradiction.
Corollary 2 (Minimization of FRs) Minimize the number of functional requirements and constraints. Corollary 2 states that as the number of functional requirements and constraints increases, the system become more complex and thus the information content is increased. This corollary recommends the designer strive for maximum simplicity in overall design or the utmost simplicity in physical and functional characteristics.	**Ideal Final Result (IFR)** philosophy corresponds to Corollary 2 in AD. IFR states that a system is a “fee” for realization of the required function and IFR will be realized if the system does not exist, but the required function is performed. IFR helps an engineer to focus on concepts that minimize requirements in substance, energy and complexity of engineering product and process.

Corollary 3 (Integration of Physical Parts) Integration design features into a single physical process, device or system when FRs can be independently satisfied in the proposed solution. Corollary 3 states that the number of physical components should be reduced through integration of parts without coupling functional requirements. However, mere physical integration is not desirable if it results in an increase of information content or in a coupling of functional requirements.	**Evolution Pattern 5,** Increased Complexity followed by Simplification. This pattern states that technological systems tend to develop first toward increased complexity (i.e., increased quantity and quality of system functions) and then toward simplification (where the same or better performance is provided by a less complex system). Line Mo-Bi-Poly reflects that Mono-function products evolve into bi-function or poly-function products through integration of physical embodiments.
Corollary 4 (Use of Standardization) Use standardization or interchangeable parts if the use of these parts is consistent with FRs and constraints. The corollary states a well-known design rule: use standard parts, methods, operations and routine, manufacture, and assembly. Special parts should be minimized to decrease cost. Interchangeable parts allow for the reduction of inventory, as well as the simplification of manufacturing and service operations, i.e., they reduce the information content.	No patterns, principles or tools correspond to this corollary. TRIZ focus its studies on inventive problem solving, so it pays less attention to the standardization and interchangeability of physical components.
Corollary 5 (Use of Symmetry) Use symmetrical shapes and/or arrangements if they are consistent with the FRs and constraints. It is self-evident that symmetrical parts are easier to manufacture and easier to orient in assembly. Not only should the shape be symmetrical wherever possible, but hole location and other features should be placed symmetrically to minimize the information required during manufacture and use. Symmetrical parts promote symmetry in the manufacturing process.	**Principle 4, Asymmetry** (one of 40 Inventive Principles) in TRIZ is in opposition to Corollary 5 in AD. The reason why TRIZ and AD propose opposite principles is that AD theory states the general rules of engineering design, but TRIZ methodology concentrates its studies on the inventive problem solving techniques. These techniques are derived from the patent database, which relates to novel methods and unique ideas.
Corollary 6 (Largest Tolerance) Specify the largest allowable tolerance in stating functional requirements	No corresponding tools are found in TRIZ. Corollary 6 is a general rule of design and it is nothing to do with invention.
Corollary 7 (Uncoupled Design with less Information) Seek an uncoupled design that requires less information than coupled designs in satisfying a set of FRs. This corollary states if a designer proposes an uncoupled design which has more information content than a coupled design, then the designer should return to the “drawing board” to develop another uncoupled or decoupled design having less information content than the coupled design.	**40 Inventive Principles** 40 Inventive Principles provide the techniques to overcome contradictions.

Theorem 1 (Coupling Due to Insufficient Number of DPs) When the number of DPs is less than the number of FRs, either a coupled design result or the FRs cannot be satisfied.	**Substance Field Analysis** states any properly functioning system can be modeled with a complete Su-field triangle and any deviation from a "complete" triangle, for example missing one element, reflects the existence of a problem.
Theorem 2 (Decoupling of Coupled Design) When a design is a coupled due to the greater number of FRs than DPs ($m>n$), it may be decoupled by the addition of the design new DPs so as to make the number of FRs and DPs equal to each other, if a set of the design matrix containing $n´n$ elements constitutes a triangular matrix.	**Building Su-field Models**, class 1 of 76 Standard Solutions, shares the same idea with Theorem 2 in AD. This Standard Solution states: if a given object is unreceptive (or barely receptive) to required changes and the problem description does not include any restriction for introducing substances or fields, the problem can be solved by completing the Su-field model to introduce the missing element.
Theorem 5 (Need for New Design) When a given set of FRs is changed by the addition of a new FR, or substitution of one of the FRs by a new one, or by selection of a completely different set of FRs, the design solution given by original DPs cannot satisfy the new set of FRs. Consequently, a new design solution must be sought.	**Enhancing Su-field Model**, Class 2 of 76 Standard Solutions, corresponds to Theorem 5. The addition of a new FR, or substitution of one of the FRs by a new one means the previous system is an inefficient Su-field model. In this case, enhancing Su-field model is required to improve the system functions.

4. A CASE STUDY: USING INDEPENDENCE AXIOM IN AD AND SEPARATION PRINCIPLES IN TRIZ

Independence Axiom in AD implies that the design matrix be of a special form. The consequences of applying Axiom 1 to the design matrix are as follows:

(1) It is desirable to have a square matrix, i.e., $n=m$
(2) The matrix should be either diagonal or triangular.

In real design situation, we need to search for DPs that yield a diagonal or triangular design matrix. The degree of independence can be treated as the definition of tolerance.

There are a hierarchy in both the functional domain and the physical domain, and a zigzagging process between two domains in design process. The domain process is most straightforward when the solution consists of uncoupled design at each level. When the design is uncoupled, we can deal with the individual FRs of a hierarchical level without considering other FRs of the same level and proceeding hierarchical levels. When the design is coupled, we must consider the effect of a decision on other FRs and DPs. Therefore, the designer should try to find solutions by attempting to uncouple or decoupled design in every level of design hierarchy.

The problem is how to decouple a coupled design. It is obvious to modify design matrix to be either diagonal or triangular. In practice, many coupled designs undergo changes and become a decoupled design through a trial and error process that is in opposition to TRIZ methodology.

In TRIZ methodology, a coupled design is defined as the existence of a contradiction. Removal of dependency of coupling means to overcome a technical or physical contradiction by applying inventive principles or separation principles. Thus, these principles can serve, with AD corollaries and theorems, as the guidelines of de-coupling a coupled design.

The design process of the Paper Handling Mechanism [11] illustrates how separation principles in TRIZ aid to satisfy Axiom 1 in AD.

Paper Handling Mechanism Case Study

The function of the paper handling mechanism used in an automatic teller machine is "isolate one bill from pilled bills", which is the first FR of the system. Several physical structures can be used to realize this functional requirement, such as friction, vacuum, leafing etc. Friction method is selected and its mechanism is showed in figure 3.

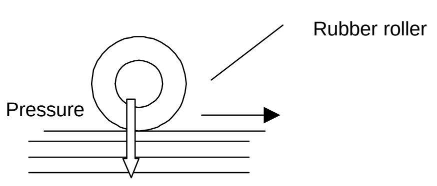

Figure 3. Basic concept of friction mechanism

However, this DP does not always work correctly because the friction is changeable under some circumstances. If the friction force working on the tope of bill becomes too large by some accident, two or more bills will be sent forwards, and if it becomes too small, the top bill may not be isolated. Therefore, we have to decompose the first level functional requirement into two functional requirements: “give a forward force to the first bill” and “give a backward force to the second bill”. To satisfy these two requirements, the new DP of this design is a pair of rollers rotating in the same direction shown in figure 4. Furthermore, the friction coefficient of the upper roller is larger than that of the lower roller.

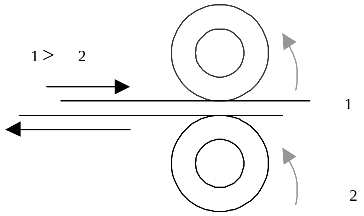

Figure 4. Basic concept of paper isolation mechanism

The design equation is:

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} A11 & A12 \\ A21 & A22 \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

FR1: give the a forward force to the first bill
FR2: give a backward force to the second bill
DP1: upper roller
DP2: lower roller

A11 represents the friction between upper roller and the first bill; A22 is the friction between lower roller and the second bill. A12 and A21 represent the friction between two bills, so A12 is equal to A21. Compared to A11 and A22, A12 and A21 can be ignored, thus two requirements can be satisfied independently.

The remaining questions are:

> What happens if there are three or more bills are inserted between the two rollers at the same time?
> What happens after the first bill is sent forward if the roller keeps rotating?
> What happens when the quality of the bill changes?

To solve these problems, the following four FRs are defined.
FR3: slant the cross section of the piled bills to make isolation easy.
FR4: pull out the isolate bill
FR5: adjust the friction force.
FR6: decrease the forward force after one bill is gone

In AD theory, these six FRs are the minimum set of independent requirements that completely characterize the design objectives for the specific needs of the paper handling mechanism. Six DPs in the physical domain are selected as follows and the mechanism is illustrated in figure 5.

DP1: upper rollers
DP2: lower roller
DP3: wedge-shaped floor guide
DP4: carriage pinch rollers
DP5: press plate
DP6: cam

The function of cam (DP6) is to reduce the forward force after one bill is gone. However, when the cam turns, it also affects FR1, FR2, FR3 and FR5 because it changes the pressure and slope of the floor guide.

The design equation is as follows. Clearly, this is the coupled design.

$$\begin{Bmatrix} FR\,1 \\ FR\,2 \\ FR\,3 \\ FR\,4 \\ FR\,5 \\ FR\,6 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & x \\ 0 & X & 0 & 0 & 0 & x \\ 0 & 0 & X & 0 & 0 & x \\ 0 & 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & 0 & X & x \\ 0 & 0 & 0 & 0 & x & X \end{bmatrix} \begin{Bmatrix} DP\,1 \\ DP\,2 \\ DP\,3 \\ DP\,4 \\ DP\,5 \\ DP\,6 \end{Bmatrix}$$

However, from TRIZ standpoint, FR1 and FR6 can be viewed as a technical contradiction because FR1 requires a large forward force and FR6 requires a small forward force. The technical contradiction can be overcome by applying contradiction table and 40 inventive principles. However, if the technical contradiction can be transformed to a physical contradiction, the separation principles can be utilized to solve the problem.

In this case, FR1 and FR6 require the friction between upper roller and the first bill should be large and small. Physically, two factors control the friction force between the upper roller and the first bill: pressure and friction coefficient. This means that the pressure, or the friction coefficient or both of them should be large and small. Since FR1 and FR6 are not required at the same time, the pressure and friction coefficient should not be same all the time. Therefore, the separation of opposite properties in time, one of TRIZ separation principles, can be utilized to overcome the contradiction.

One design solution, making the pressure large and small, is given in figure 5. Another design alternative is illustrated in figure 6. A partial rubber roller is used to satisfy the FR1 and FR6 because its friction coefficient is large at one time and small in another time when it turns. Thus, the technical contradiction is transformed to the physical one and the contradiction is overcome using TRIZ separation principles. In figure 6, two DPs are integrated into one part and five components are used to satisfy six functional requirements independently.

The design equation is:

$$\begin{matrix} FR\,1 \\ FR\,2 \\ FR\,3 \\ FR\,4 \\ FR\,5 \\ FR\,6 \end{matrix} = \begin{matrix} X & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 \\ 0 & 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & 0 & X \end{matrix} \begin{matrix} DP\,1 \\ DP\,2 \\ DP\,3 \\ DP\,4 \\ DP\,5 \\ DP\,6 \end{matrix}$$

This is the uncoupled design. It is clearly that the design solution in figure 6 is better because it is the uncoupled design and has the simpler structure too. Simple structure means less information and easy to produce.

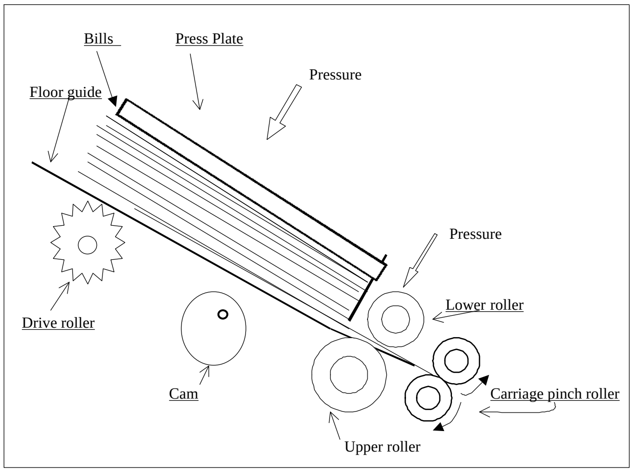

Figure 5 Design of paper isolation mechanism (Solution 1)

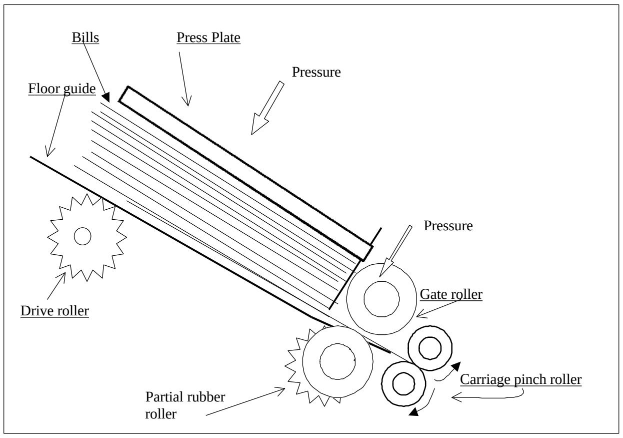

Figure 6 Design of paper isolation mechanism (Solution 2)

5. CONCLUSIONS

1. The basic premise of the axiomatic approach to design is that there are basic principles that govern decision making in design. Two basic principles, Independence Axiom and Information Axiom, are derived from the generation of good design practices. The corollaries and theorems, which are direct consequences or are derived from the axioms, tend to have the flavor of design rules.

2. The main axiom of TRIZ is that the evolution of technological systems is governed by objective patterns. These patterns can be employed for conscious development of technological system and inventive problem solving, replacing the inefficiencies of blindly searching. These patterns and other TRIZ tools are revealed by analysis of hundreds and thousands of inventions available in the world patent database.

3. Axiomatic design pays much attention to the functional, physical and process hierarchies in the design of a system. At each layer of the hierarchy, two axioms are used to assess design solutions. However, TRIZ abstracts the design problem as either the contradiction, or the Su-field model, or the required function realization. Then corresponding knowledge base tools are applied once the problem is analyzed and modeled. Though approaches to the solutions are of some differences, many design rules in AD and problem-solving tools in TRIZ are related and share ideas in essence. However, Axiomatic design lacks the vast knowledge base to support the application of its theory, so the creative process of conceptualizing and devising a solution is not very clear.

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