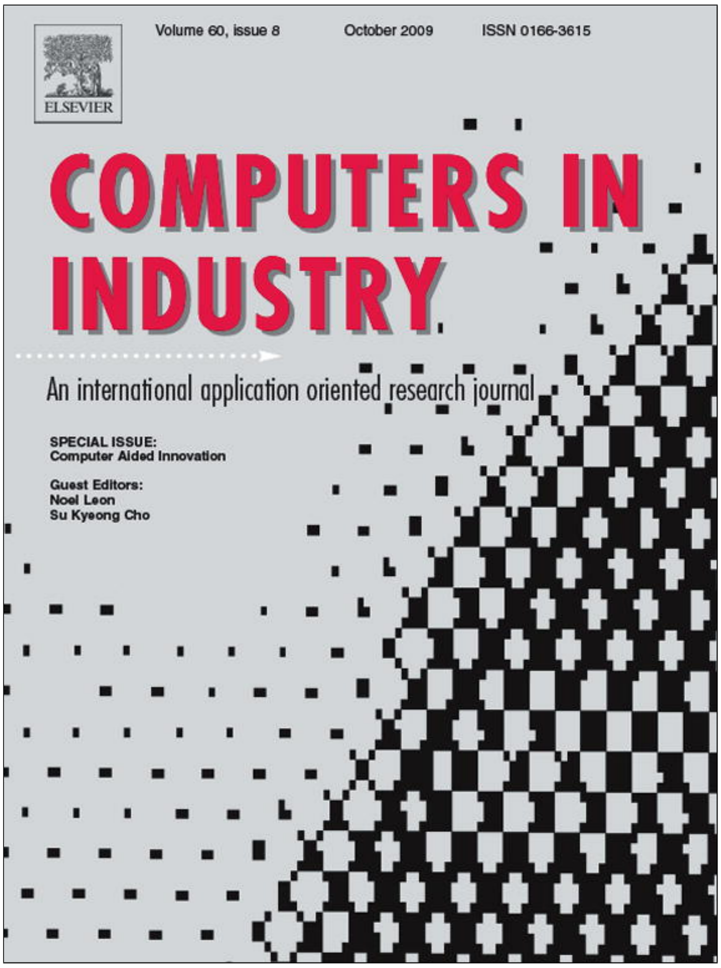
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UXDs-driven conceptual design process model for contradiction solving using CAIs

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ABSTRACT

Design is situational, which means the explicit consideration of the state of the environment, the knowledge and experience of the designer, and the interaction between the designer and the environment during designing interact. When computer-aided innovation systems (CAIs) are applied to the design, the environment and the situation are different from the traditional design process and environment. The basic principles of some CAIs available in the world market are directly related to theory of inventive problem solving (TRIZ). Special TRIZ solutions, which have a few inventive principles and the related cases for contradiction problem solving, are medium-solutions to domain problems. The second stage analogy process is used to generate domain solutions and in this process, the TRIZ solutions are used as source designs of analogy-based process. Unexpected discoveries (UXDs) are the key factors to trigger designers to generate new ideas for domain solutions. The type of UXDs for the specific TRIZ solutions is studied and a UXDs-driven contradiction solving for conceptual design is formed. A case study shows the application of the process step by step.

1. Introduction

It is generally agreed that the conceptual design is the most critical phase in the design processes [1]. The inputs for this phase are product or design specifications, and the outputs are principle solutions or concepts [2]. There are many research results in this field, which may be divided into three types: studies on process models; methods for generating ideas or concepts; and computer applications. The process models [2–5] for conceptual design are descriptions at some level for real conceptual design processes in industrial firms. Pahl and Beitz's model [2], as a case in point, includes seven steps. Many methods to generate ideas or concepts [6] have been developed, such as brainstorming, mind mapping, lateral thinking, etc. These methods are basically brainstorming-driven. Different types of methods [7,8] to assist designers to generate concepts are continuously studied. Computer systems [9–11] have been applied in conceptual design processes. In these systems the lack of formal product representations of function, behaviour and structure [12], which are the knowledge base for conceptual designs, have been identified as a kind of shortcoming.

Contrary to the brainstorming-driven methods, theory of inventive problem solving (TRIZ) [13] is a systematic method to guide designers on a high plane to generate ideas for inventive problems [14]. Today, several computer-aided innovation systems (CAIs) [15], such as Goldfire Innovator, IWB, and InventionTool, have been developed and commercialized to support designers in conceptual design. The basic theory for developing these systems is TRIZ. Several knowledge bases are included in the CAIs, which are abstracted from patent analysis or different scientific branches. By these knowledge bases, designers have a chance to apply the cases of other designers and the effects from the scientific world. Nevertheless, how to integrate the TRIZ and CAIs into a conceptual design process is also a problem.

Design situation is a particular state of interaction between designers and the environment at a particular point in time [16]. CAIs are new systems for most designers and will change the design situations when they are applied. In this new situation, the interactions mainly happen among designers and a serial of interfaces of CAIs. The reason that the interfaces will support designers to generate ideas is needed to be studied.

Contradictions are a kind of inventive problems in conceptual design. Contradiction matrix in TRIZ is a tool for solving that kind of problems. The matrix was developed many years ago [13], but it is still applied today [17,18]. The matrix does help designers to solve some contradictions faced during the design. This study will be restricted to find solutions for contradiction solving. The target is to form a new conceptual process model under the environment of CAIs.

2. Contradictions in conceptual design and solving them using CAIs

Pahl and Beitz [2] divided a design process into four phases. The conceptual design is a phase or process to develop the principle

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solution. Several sub-processes are divided, which are an abstract of the essential problems, establishment of the function structure, search for suitable working principles, and combinations of these principles, to form a working structure. Some difficult problems, which exist during conceptual design, may be as follows:

(1) Adoption for a suitable principle solution of a function in a function structure that will result in the existence of a new harmful function, or intensifying an existing harmful function.
(2) Elimination or reduction of a harmful function in a function structure will deteriorate a useful function.
(3) Intensification of a useful function or reduction of a harmful function will cause the unacceptable complication of the design.

All of the above problems are technical contradictions from the point of view of TRIZ [13]. As a result, designers in conceptual design face some difficulties to solve these contradictions. The tool in TRIZ for solving technical contradictions includes 39 generic engineering parameters to represent contradictions; 40 inventive principles to solve the contradictions; and a matrix to find a few suitable inventive principles. Under each inventive principle there are several design cases abstracted from patent bases of the world. Every case shows a result to solve a contradiction by former designers. Fig. 1 shows the structure of the tool.

Every case under an inventive principle in Fig. 1 is the result of analyzing patent bases from outside world. The knowledge, which is tacit in different domains of a patent base, is difficult to have them applied by designers because it is a problem to find a useful one from different domain. If a patent abstracted from any domain is stored in the case base of TRIZ it becomes explicit knowledge or codified knowledge, which can be found following the TRIZ problem solving routine and applied for idea generation.

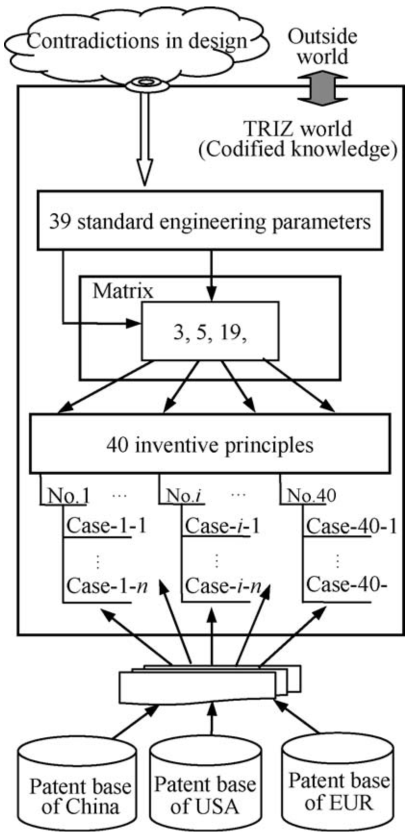

Fig. 1. Contradiction solving model in TRIZ.

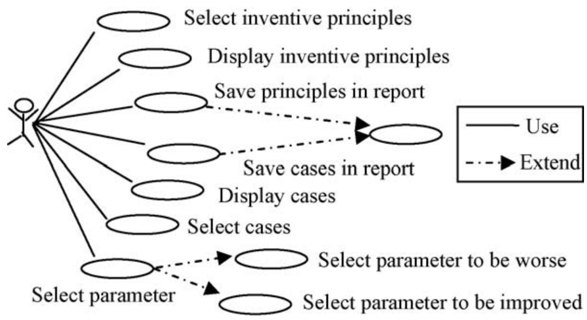

Fig. 2. Use cases for contradiction solving in InventionTool.

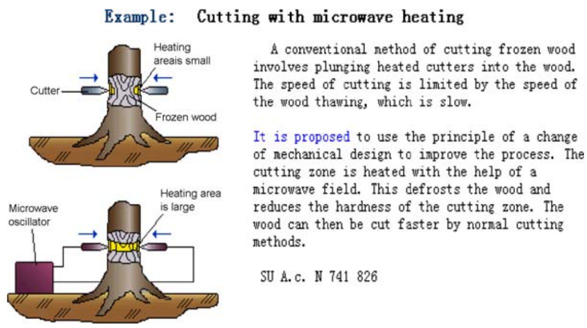

Fig. 3. A cases in knowledge base of CAIs.

The TRIZ world in Fig. 1 has been programmed as a kind of arithmetic and a module of CAIs, such as in the Goldfire Innovator and InventionTool, which are cases of CAIs. Interaction between TRIZ world and outside world is realized by the interfaces of the CAIs. Fig. 2 shows a used cases model to describe an interface of a module for contradiction solving in InventionTool. The application of different CAIs based on TRIZ has made the TRIZ more powerful and applicable. There are a few knowledge bases in CAIs. The knowledge is arranged by the framework of TRIZ. By applying the knowledge base, the design cases from different industrial fields are accessed by designers.

In the knowledge base of CAIs, a case for a technical contradiction solving is described using a sketch with text to explain the working principle of that sketch. Fig. 3 shows an example of a case in which the sketch shows the working principle for cutting with microwave heating and the text is the explanation. When one principle as a TRIZ special solution is selected, all the cases relevant to that principle can be browsed one by one. New ideas for the domain solutions may be formed from designers' mind during the browsing process.

3. An analogy-based concept generation for contradiction solving

The process of solving inventive problems using TRIZ is shown in Fig. 4. The TRIZ process is supported by CAIs, in which the TRIZ's special solutions, inventive principles and the cases related to the principles, are produced automatically after TRIZ mapping. The designer can browse them one by one as shown in use case model in Fig. 2.

From the TRIZ special solutions to domain solutions is an analogy-based process. Analogies are partial similarities between different situations that support further inference. Analogy-based conceptual design (ABCD) means the application of an analogy to generate a new concept in the process of the conceptual design. In this process, the existing designs and the designs to be carried out are source designs and goal designs, respectively. One of the

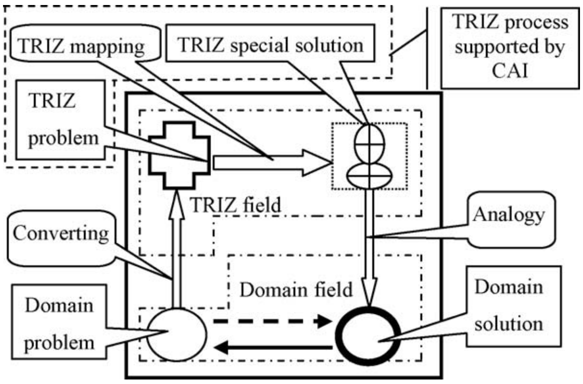

Fig. 4. The process of solving problem using TRIZ.

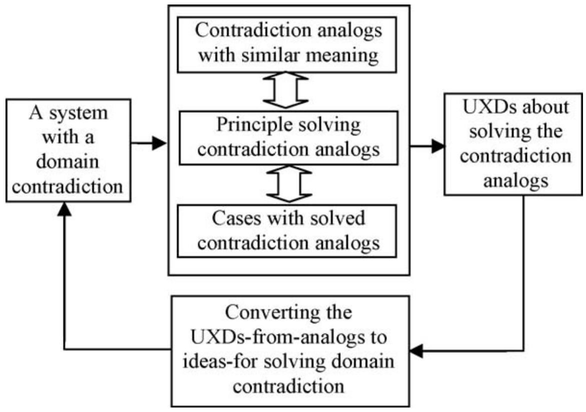

Fig. 5. The macro-process of ABCD for contradiction solving using TRIZ.

conditions to carry out ABCD is the existence of source or base designs in different domains in large number. In the situation of the conceptual design supported by CAIs, there are many source designs because every case included in a TRIZ special solution, which is stored in the case bases of CAIs, is a source design.

Fig. 4 shows two mappings from a domain problem to domain solutions, which are from domain problem to TRIZ special solution and from TRIZ special solution to domain solution. Both mappings are analogy processes [19], which are the first stage and the second stage analogy process, respectively [19]. The first stage analogy process is completed by the application of CAIs and the outputs are TRIZ special solutions. The second stage analogy process is a process of analogy-based conceptual design, which is a human-based process.

Suwa et al. [20] have developed a concept "situated-invention (S-invention)", which means a designer generates the issue or requirement for the first time in the current design task in a way situated in the design setting. Gero et al. [16,21–23] have studied the generation of S-invention, and summarized a design process. Firstly, the designer apperceives the domain problem and determines source design and goal design. Then the designer finds unexpected discoveries (UXDs) through the matching of source design and goal design; UXDs are transferred to goal design by mapping, and a new goal is generated, and then the modified goal design is produced. There may be multi-source designs, and the last modified goal design is the concept of solving domain problems through modifying goal designs continually.

Gero and his group have majored in architectural design, so the source designs are drawings of different kinds of architectures. If the source designs are substituted by TRIZ special solutions the design process for generation of S-invention can be applied to generate the domain solutions in TRIZ-based design processes. Designers find several UXDs and modify goal design depending on their design experience, their comprehension of domain problems, and the situation. At times some modified goal designs are domain solutions. The macro-process of ABCD for contradiction solving using CAIs and TRIZ is shown in Fig. 5.

The contradiction analogs are the technical contradictions selected from the 39 engineering parameters, which have similar meanings to the domain contradictions. The UXDs solving contradiction analogs are found from the principles solving contradiction analogs and cases.

The main processes of implementation of the process in Fig. 5, is how to find UXDs in solving the contradiction analogs, and converting these UXDs into ideas for solving the domain contradictions. UXDs enlighten designers on invention and make new ideas appear, so discovering and transferring UXDs is the key to success. According to the concept of constructive memory [21], the memory is not a direct reappearance of a former experience but a function of a former experience, which changes after producing these experience and situation of memory requirement. An UXD is a "new" perceptual action that has a dependency on "old" physical action(s) [20]. This means that if a designer traces or pays attention to the existence of source designs, the perceptual action is an instance of UXD. Experiences and UXDs drive designers to generate new ideas. The new ideas are mapped to the goal design to produce a new goal design. The last few goal designs are the solutions for a conceptual design.

Perceptual actions [20] are operated for architectural drawings. They must be extended to TRIZ special solutions for TRIZ-based design. Ideas from the constructive memory driven by UXDs are developed to form concepts. Concepts are described using working principles, combinations of these principles to form a working structure or system working principles, or sketches.

4. UXDs from TRIZ special solutions

Suwa et al. [20] have divided UXDs into three types, depending on the types of visuo-spatial feature, which are the discovery of a visual feature; a spatial or organizational relation among more than one previously drawn element; and a space that exists in previously drawn elements. The types are suitable for the design of an architecture, in which the basic elements are dots, lines, rectangles, circles, arrows and so on. For complex system design, such as complex mechanical system design, the basic elements are more complex. The types divided are not suitable for them. New types are needed.

Currently, there are several well-known design theories and methodologies, such as Systematic Design Methodology [2], Axiomatic Design Theory [24], and General Design Theory [25]. The common feature for all these theories and methodologies is the function-based design. The first step for the design is to transform the design specifications or the product needs to a function model, such as a function structure. Then, the structure model of the design, such as a working principle or a sketch, is developed from function model by mapping.

There are two kinds of mapping: function–structure mapping and function–behaviour–structure mapping, as shown in Fig. 6. The former is suitable for the mapping of extrinsic functions and the latter is suitable for intrinsic functions. There are different kinds of functions, behaviours and structures [26–28]. Functions are divided into atomic, source, destination and transfer functions. Behaviours are divided into three kinds, continuous-time-behaviour, discrete-time-behaviour, and state-transition-behaviour. According to the specific design context, a structure may refer to a sub-system, a sub-assembly, a component, a feature, or a geometric entity, and a physical relationship.

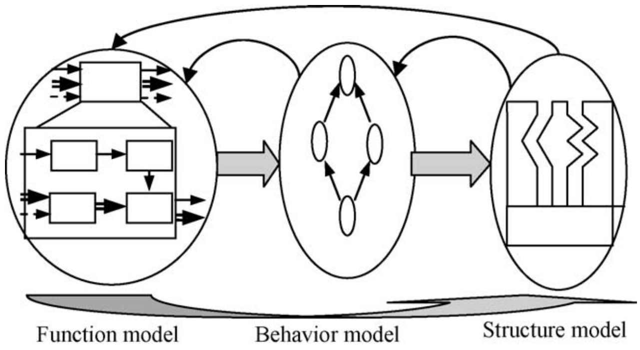

Fig. 6. Function–behaviour–structure and function–structure mapping.

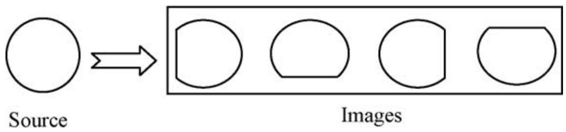

Fig. 7. Some images from a source using an inventive principle.

A structure of a design implicates all the information about the behaviour and the functions for that design. If a TRIZ special solution with some cases is applied as source designs for analogy, the designers will find the explicit behaviours and functions, except for structures. As a result, some functions, behaviours, or structures stimulate the designers and the new concepts are appeared in their minds. Therefore, the implicit functions, behaviours and structures in TRIZ special solutions in different levels are UXDs for designers when TRIZ and CAIs are applied. The UXDs here are different from types of the definitions applied in Gero's group.

For technical contradiction problem solving, forty the inventive principles in TRIZ will be applied. One principle selected from the forty has implicit meaning, which will be a kind stimulus for designers. For example, if a circle is applied for a product design, in order to make some modifications by the inventive principle 6 'asymmetry', designers may image different forms to substitute the circle, as shown in Fig. 7. As a result an inventive principle for technical contradiction solving is also a UXD, when it is selected.

There are four types of UXDs when TRIZ special solutions are applied as resource designs under the situation applying CAIs. The first type is to find an inventive principle and the others are to find a function, a behaviour, or a structure in different levels. Table 1 shows the types, definition of each type, and the instances of each type and how to find an UXD.

For the designers using CAIs, the physical actions to find a UXD are only looking, which means designers viewing the computer screen: the principles of contradiction solving and the cases shown by pictures and contexts. By viewing actions, designers discover the UXDs implied.

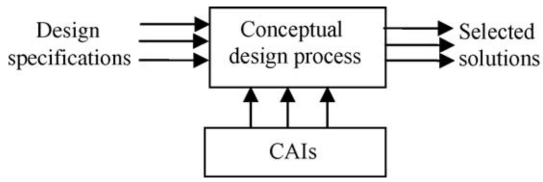

Fig. 8. Conceptual design supported by CAIs.

5. An UXDs-driven process model for conceptual design

A top-model for conceptual design is shown in Fig. 8. The inputs are design specifications and outputs are selected solutions. However, the process is supported by CAIs. This implicates that the new ideas for the solutions are developed by the stimulation of TRIZ special solutions.

There are several models for conceptual design process from literatures. Refs. [2,3], and [6] are examples of these. In this study, Pahl and Beitz's model [2], as a traditional and human-oriented process model, is selected as a base to extend from. Fig. 9 shows a new model of conceptual design process which is driven by UXDs and supported by CAIs.

According to Fig. 9, the process is divided into eight steps, which are as follows:

Step 1: Establish or modify function structures. For original design [2], the function structure of the design is established from the design specification directly. For adoptive design [2], the existing function structure is modified to adopt the changed specifications.
Step 2: Search for working principles for sub-functions. The working principles for every sub-function in the existing function structure are found by searching.
Step 3: Analyze the working principles of sub-functions and find whether there are technical contradictions or not. If there are no contradictions turn to step 7. Otherwise continue the process.
Step 4: Identify contradictions. Analyze all the working principles again and identify all the contradictions clearly. There may be multi-contradictions and they need to be identified one by one.
Step 5: Find TRIZ special solutions. For each contradiction, the TRIZ special solutions are found under support of CAIs.
Step 6: Find UXDs for every contradiction. Designers analyze the selected inventive principles, browse the cases one by one and find UXDs implied.
Step 7: Form solutions. There are two sub-processes in this step. One is following step 3 and the other is continuing from step 6.

(1) Combine every working principle of sub-functions into a few system working principles, named working structures.
(2) Find new working principles for sub-functions which relate to the contradictions and eliminate all the contradictions. Then, combine every principle into a few system working principles.

Step 8: Evaluate solutions. Identify one or two working structures as the outputs of conceptual design processes.

Table 1
Types of UXDs.

Types	Definition	Instances	How to find
UXD-1	An inventive principle which is suitable for solving the contradiction faced	One to four inventive principles	Check the matrix using two engineering parameters
UXD-2	A function that one case implicated	Atomic, source, destination and transfer functions	Physical actions
UXD-3	A behaviour that one case implicated	Continuous-time-behaviour, discrete-time-behaviour, state-transition-behaviour	Physical actions
UXD-4	A structure that one case implicated	A sub-assembly, a component, a feature, or a geometric entity, and a physical relationship	Physical actions

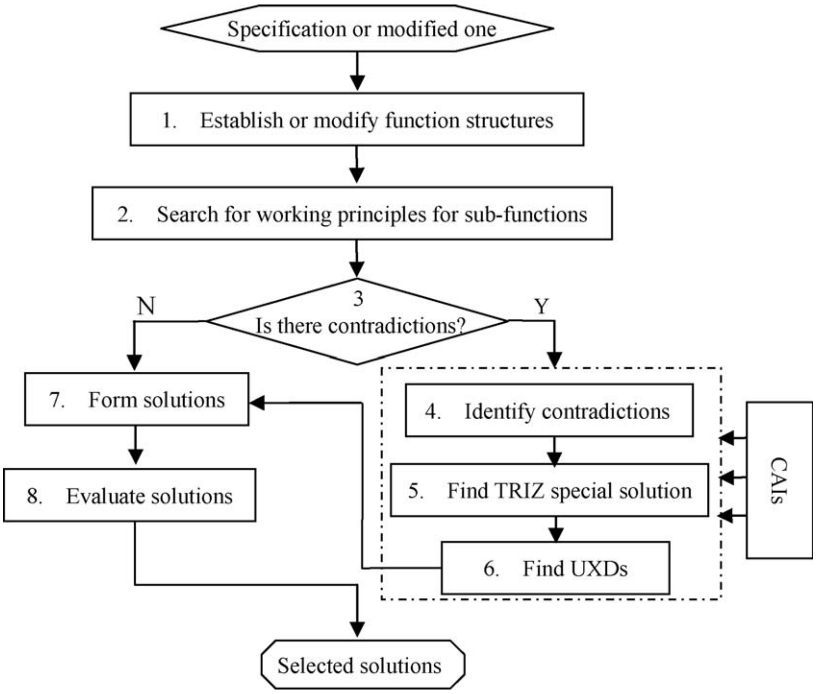

Fig. 9. An UXD driven process model for conceptual design.

Step 5 belongs to the first stage analogy process and step 6 to 7(2) belongs to the second stage analogy process. The second stage analogy process is a UXDs-driven process. The evaluation is included in step 8, and many methods have been developed for this application.

6. Case study

Dropping pills, produced by dropping pill machines, are a kind of Chinese traditional medicine. After dropping and drying, the pills should be put into little bottles for selling in the market. The machine to put the pills into bottles is a kind of packaging machine. There are no standard machines of this kind. The machines have been developed by one or two firms in China. New operating principles for the machines are needed to be produced by other firms of medicine production.

The sub-functions of the machine are distributing pills, discharging pills, bottling and lidding. The working principle of existing pills packaging machines is shown in Fig. 10. Certain amount of pills are carried by pills board fixed on a tumbling cylinder. When running the tumbling cylinder, the pills are transferred, discharged, and then put into bottles. The pills board which is not full of pills will be detected by a counting sensor array. The bottles, which are filled with unqualified amount of pills, will be removed after lidding.

There are two problems in the existing design of pills packaging machines:

(1) The sub-function of distributing certain amount of pills is implemented by a pills board. This results a difficulty in changing the amount of packaging. The flexibility of the machine is poor.
(2) The amount of pills is detected twice in the original design, which leads to a large number of photoelectric counters.

The model in Fig. 9 is applied to form a new working principle for this kind of machines.

Step 1: Establish or modify function structures.

To solve the above problems, the original function structure for the existing product is modified as shown in Fig. 11. In order to express the modified structure clearly, some sub-functions of converting energy is omitted. In Fig. 11 the sub-function of distributing pills is substituted for the sub-function of distributing certain amount of pills, the pills are detected once, and the sub-function of counting pills is added.

Step 2: Search for working principles for sub-functions.

To implement the modified functions, i.e. distributing pills, a pills board is added, and a tumbling cylinder in Fig. 12 is adopted to distribute pills. To adapt to this change, counter array correspondence with pills board is replaced by a single counter. But the counter in the tumbling cylinder cannot implement the sub-function of counting pills. New position of the counter is set on top of filler as shown in Fig. 13.

Step 3: Find contradictions.

Contradiction 1: distribute pills and discharge pills.

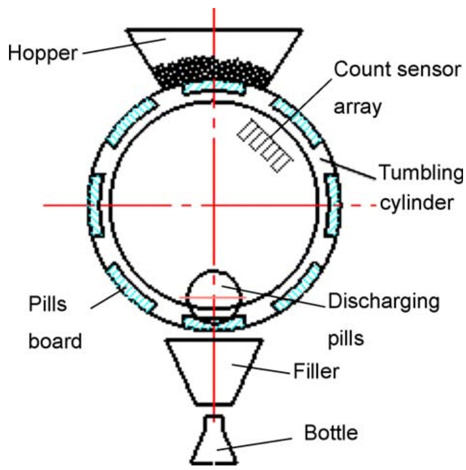

Fig. 10. The working principle of existing pills package machine.

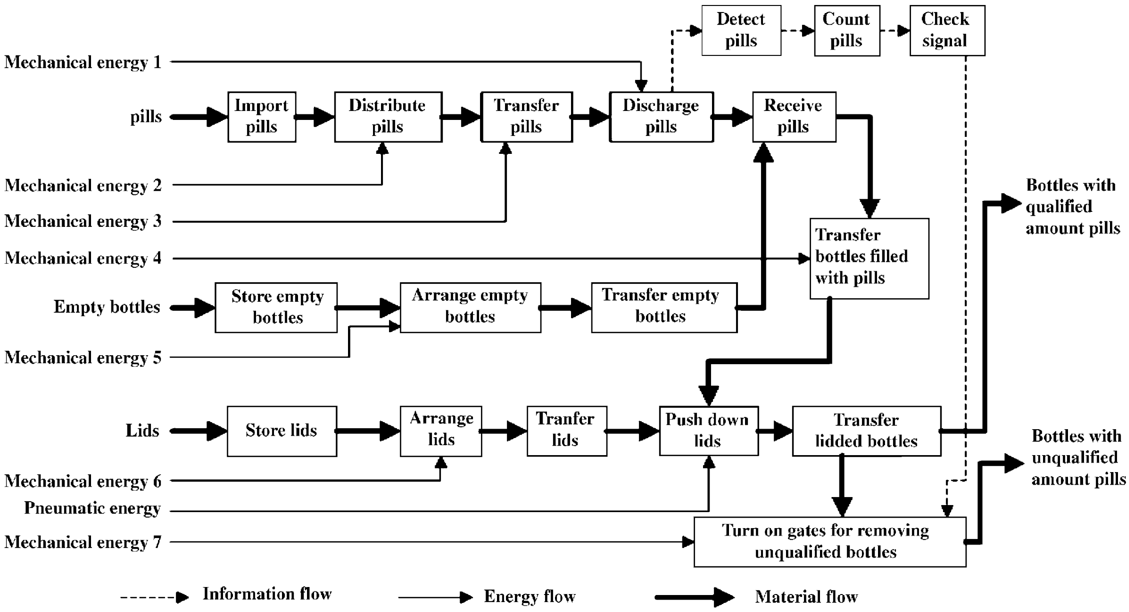

Fig. 11. Modified function structure.

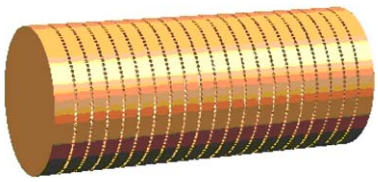

Fig. 12. Tumbling cylinder.

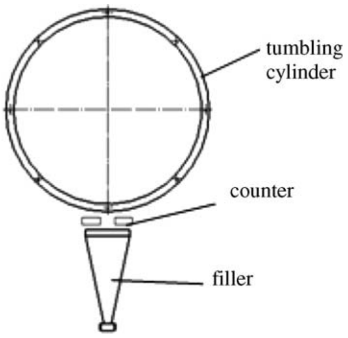

Fig. 13. New position of the counter.

The pills are distributed in the several circles. The implementation of discharging pills is based on the principle of distributing bills. Fig. 14 shows a principle for discharging pills that is used at present. When the roller is redesigned and used inside the cylinder, a transmission mechanism is also needed, which leads to the complexity of the device.

Contradiction 2: distribute pills and transfer bottles filled with pills.

Transferring bottles requires a pause in distributing and discharging pills. Tumbling cylinder must be stopped accurately and frequently. This is difficult and harmful.

Step 4: Identify contradictions.

Contradiction 1 defined as a technical contradiction between adaptability (No. 35) and complexity of a device (No. 36).

Contradiction 2 defined as a technical contradiction between adaptability (No. 35) and complexity of control (No. 37).

Step 5: Find TRIZ special solutions.

InventionTool 3.0, which is CAIs, is applied in this step. The module 'contradiction solving' in InventionTool 3.0 is used to find TRIZ special solutions. Select the improved parameter 'adaptability' and worse parameter 'complexity of a device', then, the interfaces shows the TRIZ special solutions of contradiction 1, which are No. 29 (Pneumatic or hydraulic construction), No. 15 (Dynamicity), No. 28 (Replacement of mechanical system), No. 37 (Thermal expansion). The four principles and the relevant cases in the case base are the TRIZ special solutions.

By the same process, special solutions of contradiction 2 can be found, which is No. 1 (Segmentation) and No. 15 (Dynamicity).

Step 6: Find UXDs for every contradiction.

For the solutions of contradictions the designers may find several UXDs and generate several ideas under the stimulations of UXDs by browsing the cases in InventionTool 3.0. Fig. 15 is a case, which shows the principle of a component used in a kitchen machine. The ball moves up under the pressure of air flow to releases the

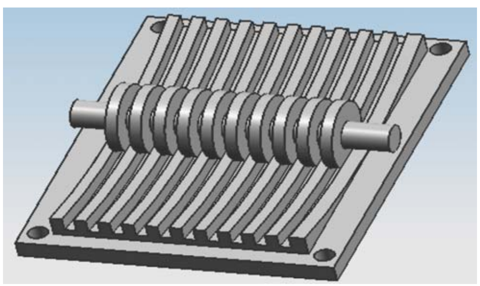

Fig. 14. A principle for discharging pills.

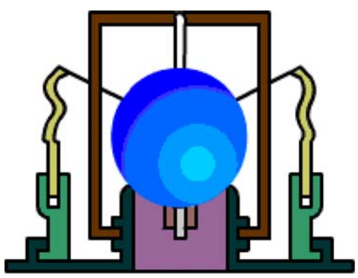

Fig. 15. A case in no. 15.

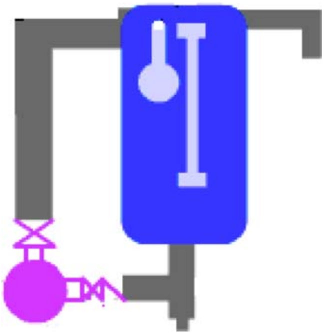

Fig. 16. Another case in no. 15.

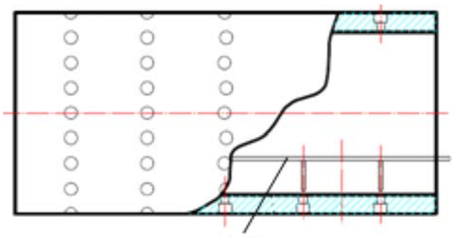

Fig. 17. Structure for discharging pills.

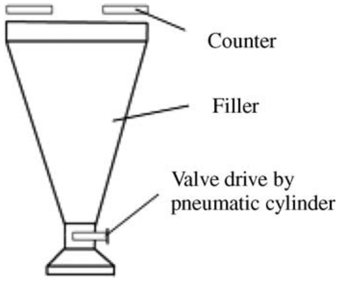

Fig. 18. Structure for controlling falling of pills.

exhausted gas produced during frying. The principle implies an UXD, which is the ball moving under the pressure of the exhausted gas. The UXD is a kind of behaviour, which is an UXD-3 in Table 1.

Fig. 16 is a case in InventionTool 3.0 that shows adjusting the pipe's hydraulic pressure by using valves dynamically. This case implies an UXD for the solutions of contradiction 2.

Step 7: Form solutions.

Solutions of contradiction 1: transfer UXDs in Fig. 15 to goal designs. Convert the UXD into the new ideas and generate a principle for discharging pills. The pill moves under the pressure of airflow. A possible structure for this principle is shown in Fig. 17.

Solutions of contradiction 2: to solve contradiction between distributing pills and transferring bottles, a valve is used to control the falling of pills, which is similar to the valve in Fig. 16. When the required amount of pills fall into the bottle, the valve turns off to ensure that no pills fall during the shifting of bottles. A possible structure for this principle is shown in Fig. 18.

7. Conclusions

CAIs show all inventive principles and cases, which are the source designs of ABD. The databases of CAIs are a fruit of TRIZ researchers for many years, which have broad applicability. The application of the database will improve the validity of ABD that has been extensively accepted by designers.

When TRIZ is applied to solve a contradiction in design the first and second stage analogy processes exist. The results of the first stage analogy process are source designs of the second stage analogy process. To find UXDs from the sources is the key step to generate successful ideas for innovation. Four types UXDs have been divided. The physical action for finding UXDs on the computer screen of CAIs is by viewing.

A human-oriented eight-process step model is formed for conceptual design, in which UXDs are the driving force for generating new ideas. Designers find UXDs from the TRIZ special solutions and react with experiences that designers have to construct memories suddenly. Then new ideas for domain solutions are formed.

The model put forward is only related to contradiction solving of TRIZ. It needs to be extended to technological evolution, effects, and standard solutions of TRIZ, in order to be effective in future application of CAIs.

The eight-step model is suitable for the experienced designers. For the inexperienced designer, a detailed or formal model is needed. This is a future work.

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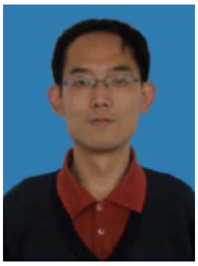

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