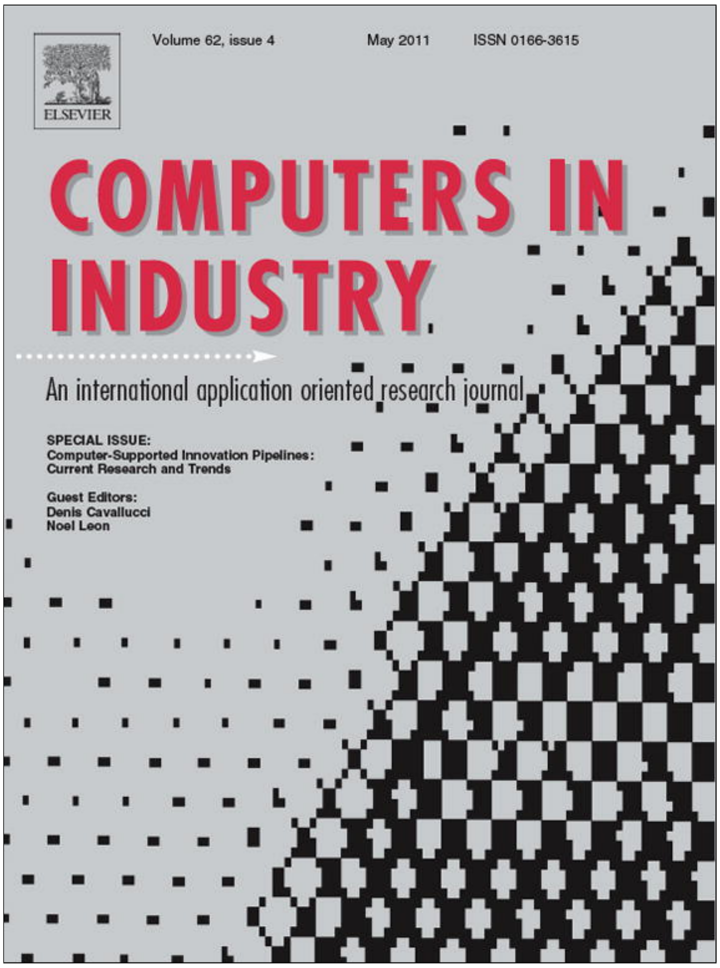
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Eliminating technical obstacles in innovation pipelines using CAIs

Tan Runhua

Institute of Design for Innovation, Hebei University of Technology, Tianjin 300130, China

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ABSTRACT

Ill-structured problems are difficult types to solve. When this type of problem is faced in an innovation pipeline, a technical obstacle emerges. Comparison between the definitions of ill-structured and inventive problems in theory of inventive problem solving (TRIZ) shows that the latter is a sub-set of the former in engineering. As a result, computer-aided innovation (CAI) systems (CAIs) based on TRIZ can be applied to solve some ill-structured problems that appear in an innovation pipeline. A model including two technical obstacles is developed for an innovation pipeline, and a case study is carried out to show how to eliminate the technical obstacles using the model.

1. Introduction

Innovation is a process of taking an original idea and converting it into a business value. Innovative companies have recognized the need to manage innovation as an explicit, repeatable, and measurable business process. Innovation is carried out in an innovation pipeline in a company, which includes inputs, processes and outputs.

There are different innovation pipelines for different situations and applications. The pipeline or funnel in IBM [1] includes market planning, concept, plan, develop, quality, and lifecycle. Jost et al. [2] build integrated and shelf-system innovation pipelines. Henderson [3] structures a two-part innovation pipeline, concept studio, development of crude value proposition and business case. Sahin [4] recommends a three stage pipeline, which are R&D, R&D&D, and R&D&D. Another pipeline is integrated by concept development, concept enhancement, and concept test and concept rollout [5]. Varma et al. [6] builds a nine step model for a typical pharmaceutical R&D pipeline.

The innovation pipelines assist companies to put new products into the market and make successful returns. However, innovation is a risky and expensive endeavor, which results in low success rates and many projects are terminated midway in the development cycle [7]. Research also indicates that a very high proportion of new product ideas fail commercially in the market place [8]. Liberatone and Stylianou [9] believe that only about 14% of ideas that enter the new product development process are commercially successful. In order to improve the situation, this is a meaningful research topic to undertake or to understand the obstacles and eliminate them in innovation pipelines.

In this paper we will study the types of the technical obstacles in an innovation pipeline for mechanical products. A model with two types of technical obstacles will be developed and how to eliminate them will be studied with the application of computer-aided innovation systems (CAIs) based on TRIZ.

2. Technical obstacles in an innovation pipeline

Innovation pipeline management is the process traditionally thought of as managing new product development. Through this process, companies drive ideas from the concept phase to full-scale deployment, and even to the end of the product lifecycle [1]. There are many problems to solve in the process. Some problems are easy to solve, but others are difficult, which forms the technical obstacles for the management of the pipelines or the innovations.

2.1. Two types of technical obstacles

A problem can be defined as the gap between the present and some desired state of affairs [10]. Simon [11] divides the problems into three types: well structured, semi-structured, and ill-structured. Rittle and Webber [12] finds two kinds of problems, wicked and tamed problems, in social policy planning. Issel et al. [13] characterize the problems as well- or ill-structured (or ill-defined). There are many studies in the literatures to deal with classifying problems [14–16]. The words ill-structured, ill-defined, and wicked problems, are often used synonymously in the literature. We adopt the first definition for our purpose here.

Well structured problems are the type with complete information, typically repetitive or routine with clear objectives and obvious alternative solutions. Ill-structured problems tend to be complex, non-routine, and difficult to define. Potential alternative solutions, objective(s) associated with solving ill-structured problems are often not obvious. The data required to

E-mail address: rhtan@hebut.edu.cn.

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Table 1
Cases and characteristics of ill-structured problems.

	Ill-structured problems
Cases	1. The problem of "War on Terrorism" 2. The problem of national immigration policy 3. The problem of dealing with crime and violence in schools 4. The problem of designing a future car
Characteristics	Ellspermann et al. [17] 1. The existence of several decision makers and stakeholders, each with their own viewpoint of the problem situation 2. Closely related to number one, the existence of multiple criteria, which are typically not known initially, which must be considered in the evaluation of proposed solutions 3. Large amounts of uncertainty associated with various aspects of the problem situation 4. The existence of an entire network of problems to which the original ill-structured problem is related 5. The fact that alternative solutions to the problem are not readily apparent Voss [18] 1. Ill-structured problems: (a) have vaguely stated goals (b) no unambiguously right or wrong answers (c) unstated or assumed problem constraints (d) requiring a large database of relevant information that is often difficult to access 2. Solutions to ill-structured problems: (a) are rarely correct or incorrect but fall on a range of acceptability (b) cannot be judged on their own but require some implementation and evaluation to test 3. Solvers of ill-structured problems: (a) divide their work into "problem representation" and "problem solving" phases (b) justify their solutions by means of argument

model the problems are usually not readily available [17]. Table 1 shows some cases and characteristics of ill-structured problems. If ill-structured problems exist in an innovation pipeline, we are faced with difficulties that have to be solved. We define these situations as technical obstacles to resolve for successful innovations.

There are different inputs into an innovation pipeline. McMahan et al. [5] suggests that innovation requires deep customer and marketing insights and effective market research as a critical input to successful innovation. The input in Varma's model [6] is a discovery. Hamel [19] suggests that the innovation is started by committing a big problem and adopting a new principle for solving the problem. The inputs of Brem and Voigt's innovation process [20] are market need, technology competence, and corporate interest. All the inputs should be transformed into problems to be solved first. Possible solutions of the problems, which are the ideas of future technologies or products, are evaluated or filtered. The inputs for the pipeline are complex situation, such as market need, technology possibility, corporate interest, and strategies of companies. Some problems that problem solvers or designers face, such as forecasting the future technologies, are ill-structured. This is the first type of the technical obstacles faced in an innovation pipeline.

For mechanical products, it is generally agreed that the conceptual design is the most critical phase [21]. The inputs for this phase are product or design specifications and the outputs are principle solutions or concepts [22]. There are several steps in the process models for conceptual design, such as Pahl and Beitz's model that includes seven steps [22]. The development of the function model, such as function structure, and the generation of product concepts from the function model are sometimes difficult and ill-structured problems. This is the second type of the technical obstacle in the innovation pipeline for mechanical products.

The manufacturing process is also a sub-process in an innovation pipeline for mechanical products. The manufacturing of complex elements with high precision is to solve ill-structured problems. But in a global environment, the elements or components to be manufactured are moved to different countries to lower cost. Or a company may buy some sub-systems with high precision from developed counties. The ill-structured problems faced in the manufacturing process may be transformed to a world-wide-manufacturing-net. In this study, we do not consider the ill-defined problems in the manufacturing process to be a technical obstacle.

As a result, we define that a technical obstacle is a situation in which an ill-structured problem is faced in an innovation pipeline. There are two types of technical obstacles. The first (I-obstacle) and the second (II-obstacle) appear separately in the input stage and in the conceptual design process, in which ill-structured problems always exist.

2.2. A model of the innovation pipeline with technical obstacles

The process in an innovation pipeline should be modified in order to consider the influences of the two technical obstacles. Fig. 1 is a possible model. Some of the problems coming from the market need, technological competence or corporate interest, are ill-structured and form the first type obstacle (I-obstacle). Some original ideas are generated after solving the problems. After the filter (I-filter), a few ideas are entered into the concept design stage, in which product concepts will be formed. During the conceptual design process some new problems are faced, in which ill-structured problems are also included. The contradictions between sub-functions [23] or unknown principle solutions for sub-functions in a function structure [24] are all examples of ill-structured problems. The ill-structured problems in this stage introduce the second obstacle (II-obstacle). After solving the II-obstacle some new product concepts are generated. The following is the other filter (II-filter). The final products and the returns are outputs of the pipeline.

The features of the model shown in Fig. 1 are that there are two types of technical obstacles in an innovation pipeline for mechanical products. The problems from the input produce the I-obstacle, and the difficulties in conceptual design produce II-obstacle. These obstacles should be eliminated in order to guarantee the idea flow in an innovation pipeline.

3. Methods to eliminate the obstacles

3.1. Inventive problems and ill-structured problems

So-called weak problem solving methods [25] are used to solve ill-structured problems. These methods are characterized by trial

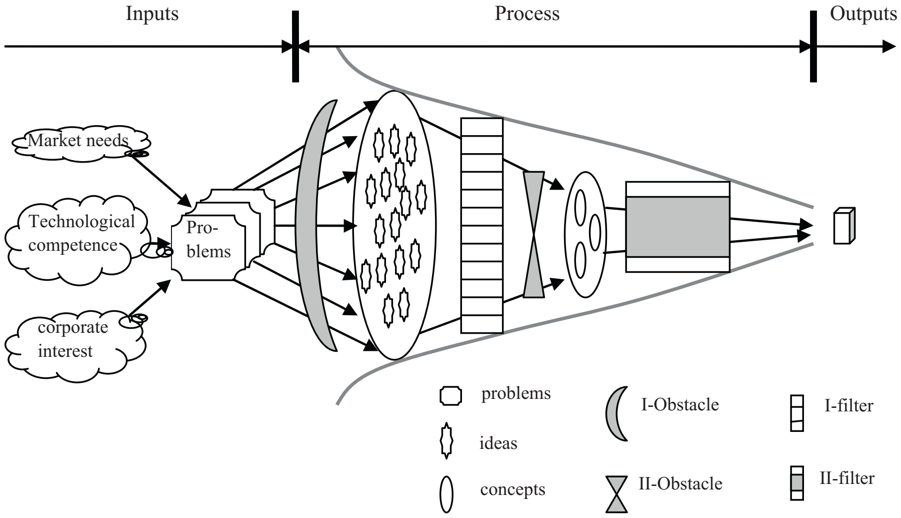

Fig. 1. The innovation pipeline with two kinds of technical obstacles.

Table 2
Cases and characteristics of inventive problems.

	Inventive problems
Cases	1. The problem of solving contradiction 2. The problem of trimming 3. The problem of making long distance analogy
Characteristics	Savransky [28] At least one step to a solution as well as the solution itself is unknown

and error learning [13]. Examples for weak problem solving methods are the generic search strategies, breadth-first-search and best-first-search [26]. The methods are computer-based and apply artificial intelligence. No literature shows that all ill-structured problems could be solved by these methods. The methods, which are human-based, are needed to solve ill-structured problems in innovation pipelines. The solution for this is appeared in the form of TRIZ, which is theory of inventive problem solving (TRIZ) developed in the former USSR. Some indication of its success can be derived from inquiries within the German industry classifying TRIZ as an effective approach to problem solving, and indicating a "rather high" to "very high" economic benefit obtained from using TRIZ for 57% of companies [27].

TRIZ is to solve inventive problems, which are defined as [28] "a problem which includes a contradiction and/or for which a path to a solution is unknown". Table 2 shows some cases and characteristics of the problems. Though the definitions of an inventive problem and an ill-structured problem are different they have some similarities. Table 3 shows the similarities and dissimilarities between them.

The research of ill-structured problems and inventive problems had been carried out in different counties. The former was in the Western world and later in the USSR. Though TRIZ has been known all over the world for some years, the literatures do not show that ill-structured problems and the inventive problems are the same. Because the three similarities we define as the inventive problems are at least a sub-set of ill-structured problems in engineering. This means that the principles in TRIZ can be used to solve some ill-defined problems in an innovation pipeline.

3.2. Applying CAIs and TRIZ to solve ill-structured problems

Creativity enhancing techniques (idea generation techniques) are used to solve problems [29]. There are many the techniques in literatures. Smith [30] carried out an extensive analysis of 172 techniques. Brainstorming, Method 635, and Synectics, are the kind of techniques, which are all human-based methods. The techniques do assist many problem solvers or inventors to solve problems, but they are not always successful because the creative capacities of problem solvers have reached their limits in finding novelties, especially when the artifacts are complex, since the value of engineering-like concepts and brainstorming-derived practices have been introduced [31]. If they are useful, problem solvers may not be able to generate ideas without the proper experience [32].

TRIZ, in contrast to these techniques, aims to create an algorithmic approach to the invention of new systems, and the refinement of old systems. TRIZ is a methodology, a tool set, a knowledge base, and a model-based technology for generating innovative ideas and solutions for solving inventive problems. TRIZ provides tools and methods for use in problem formulation, system analysis, failure analysis, and laws of system evolution.

A new category of tools known as CAIs (computer-aided innovation system) is an emerging domain in the array of computer-aided technologies [33]. CAIs have been growing as a response to greater industry in new product development. Some initial CAIs ideas and concepts focus on assisting product designers

Table 3
The similarities and dissimilarities between ill-structured and inventive problems.

Similarities	Dissimilarities
1. Both are difficult to find a path to a solution	1. Ill-structured problems may be in macro-level and but most inventive problems are in micro-level
2. Both are difficult to test the right or not of a solution	2. Ill-structured problems are from wide arrange domains but inventive ones are mainly from engineering
3. The solutions for the both are not only one	3. There are little effective techniques or methods to help people to solve an ill-structured problem but there are some methods and tools to help designers or inventors to solve an inventive problem

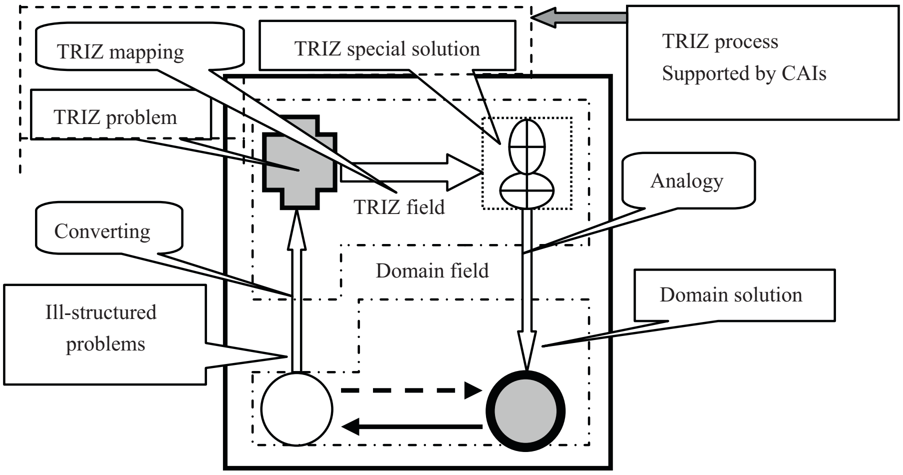

Fig. 2. The macro-process to solve ill-structured problems.

in the early stage of the design process, but now a more comprehensive vision conceives CAIs systems as beginning at the fuzzy front end of perceiving business opportunities and customer demands, then continuing during the creative stage in developing inventions and, further on, providing help up to the point of turning inventions into successful innovations in the marketplace [33].

Some CAIs emerged historically from software tools which supported the use of TRIZ [34]. From this perspective, CAIs has mainly been related to software tools like Innovation Work Bench (Ideation International Inc.) or Goldfire Innovator (Invention Machine). But Trizsolver, Creax, ProInovator, and InventionTool are all CAIs being applied in different countries now. Because of the development of these software products, a wave of software supported invention methodologies have started. For example, in the Institute of Design for Innovation at Hebei University of Technology, we have applied Goldfire Innovator, IWB, ProInovator, InventionTool at permission for years. Several research projects for postgraduate students have been carried out using these CAIs together with CAD/CAE tools, such as Pro-E, UG, and AnaSys.

In this study, the CAIs means only the software tools based on TRIZ. TRIZ is specific to solving inventive problems, a sub-set of ill-structured problems. In the input and conceptual stages of innovation pipeline, some ill-structured problems are always faced and the obstacles presented. CAIs are suitable software tools to assist the problem solver or designer to eliminate them, as shown in Fig. 2.

The ill-structured problems are the root causes of technical obstacles in an innovation pipeline. Problem solvers or designers apply CAIs and TRIZ to solve them. After that the obstacles in the pipeline are eliminated.

3.3. An example path to solve an ill-structured problem

How to make technology forecasting for future innovation is an ill-structured problem for market planning in an innovation pipeline. It is difficult to know the results of the forecasting in advance. But the forecasting is the key event for the following innovation process because the results of the forecasting are the input ideas in an innovation pipeline. By the laws and lines of technology evolution in TRIZ, development of a path to make technology forecasting is possible.

Technologies are in evolution along the directions of laws and lines. The laws in TRIZ are helpful for technology evolution forecasting since they identify the most effective directions for the technology, system development, or evolution. A law of evolution delineates a general direction for further system transformation but says nothing about the details of this transformation. The lines of technological evolution under each law describe more specifically the stages of the systems development and therefore provide even greater predicting power.

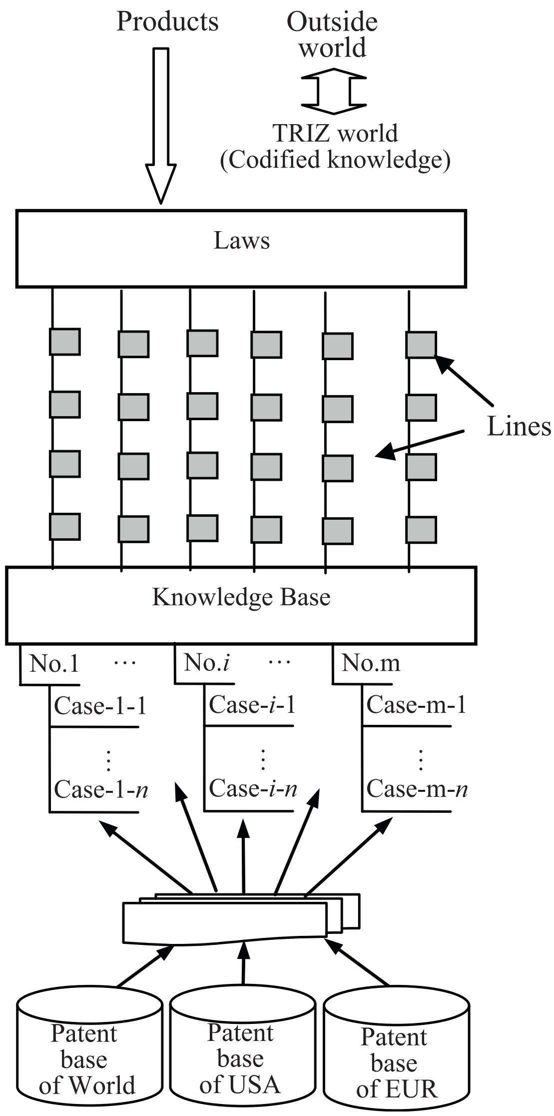

Fig. 3. Framework for technological evolution system in CAIs.

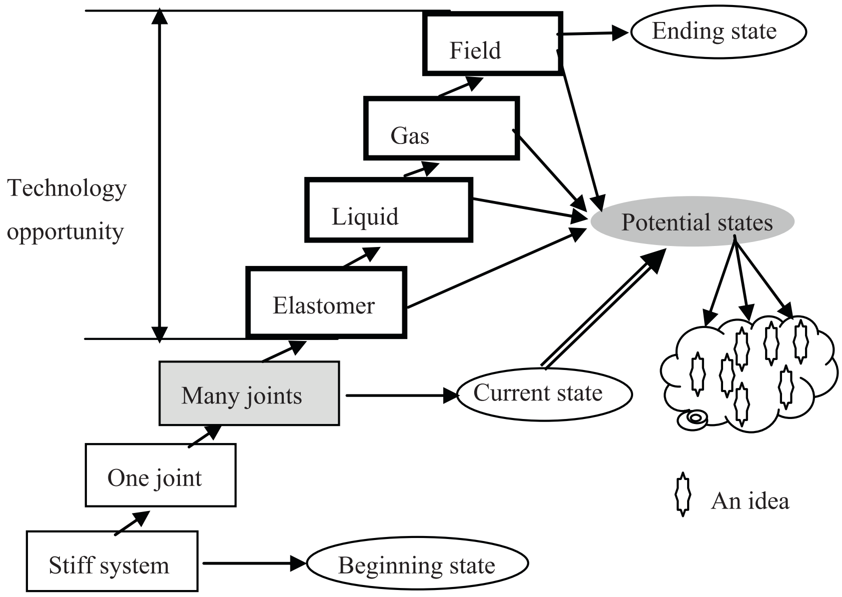

Fig. 4. A line of technological systems evolution.

There are several technological evolution laws and many technological evolution lines under each law, which form a system to support technological forecasting [35–38]. In some CAIs, such as Goldfire Innovator, the laws and the lines are integrated with some engineering cases as shown in Fig. 3. By using the CAIs, problem solvers find a suitable law and some lines. Following each line, there are a few cases abstracted from worldwide patent bases in which the knowledge of different fields is included. So technology forecasting using the knowledge from different fields can be carried out and some high quality ideas for future innovations can be generated.

Fig. 4 is a line under the law: evolution toward increased dynamism and controllability. There are seven states shown in this line, which are: (i) stiff system; (ii) one joint; (iii) many joints; (iv) elastomer; (v) liquid; (vi) gas and (vii) field. The beginning state for this line is stiff system and the ending state is field. If the current state of the technology selected is in many joints, the upper states are technology opportunities. The experience of application of lines shows that the several new ideas are implied in the states of the lines. The line shown in Fig. 4 is analyzed as an example. If the technology of the product under study is in the state of "many joints", the future states of technology evolution may be elastomer, liquid, gas, or field. Every future state may imply one or a few ideas for the future development of the technology. From the line a technology, opportunity can be found and several new ideas can also be generated.

A path to generate ideas is shown in Fig. 5, which is based on technology evolution forecasting. The path includes several operations to obtain ideas from the technology opportunities selected. The laws and lines are selected from CAIs, such as Goldfire Innovator or InnovationTool. Some potential states are selected from the lines and some ideas for future technologies are generated from the states selected.

Cavallucci [35] suggests a process to make the development laws operational. The laws themselves are applied in his process. The lines under the laws are the main objects to be used to generate ideas in Fig. 5 [39]. Both processes have a little difference but the main thinking is the same.

3.4. A model to eliminate the obstacles

Fig. 5 is only one path to solve a kind of ill-structured problems which existed during the technology forecasting for future innovation phase. There are other ill-structured problems in this phase and in the conceptual design phase. Table 4 is a summary of the ill-structured problems which are generally faced in these phases, from input to ideation and conceptual design. There are six types of ill-structured problems, which are all inventive problems in TRIZ. The technology forecasting and need forecasting are the first type of obstacles, which are I-obstacles. Solving technical contradiction, solving physical contradiction, finding a solution of a difficult function, and modifying a defect in a substance-field model, are the second type of obstacles, which form II-obstacles.

We have developed a two stage analogy model to solve inventive problems using TRIZ and CAIs [40]. The model can be simplified as shown in Fig. 6. The problems produced in the innovation pipeline are domain problems. The pre-step is to transform the domain problems into TRIZ problems. Then the first

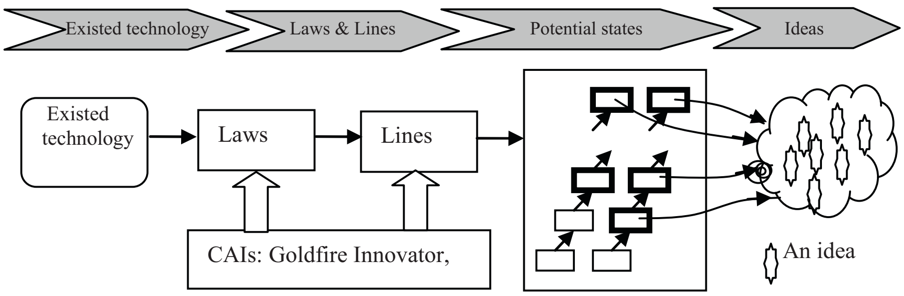

Fig. 5. A path to generate ideas using patterns and lines [39].

Table 4
Ill-structured problems in developing mechanical products.

Number	Phases	Problem name	Type of obstacles
1	Market planning	Technology forecasting	I
2		Need forecasting	I
3	Conceptual design	Solving technical contradiction	II
4		Solving physical contradiction	II
5		Finding a solution of a difficult function	II
6		Modifying a defect in a substance-field model	II

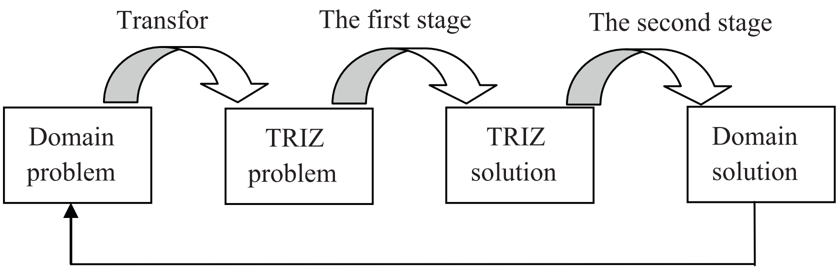

Fig. 6. Two stage analogy process model using TRIZ.

stage analogy process is applied to produce TRIZ solutions or TRIZ specific solutions. The domain solutions that are the solutions of the domain problems are obtained by applying the second stage analogy process.

Integrating Figs. 1, 2 and 6, a new model to eliminate obstacles using CAIs is formed as shown in Fig. 7. The obstacles in the innovation pipeline are firstly transformed into TRIZ problems. After the first-stage analogy (I-A) the TRIZ solutions or TRIZ special solutions are obtained. But the solutions are not the domain solutions which are needed. The second analogy stage (II-A) is then applied to generate the domain solutions. As a result, the obstacles faced in the innovation pipeline are eliminated. In the two analogy stage process, the CAIs supplies the principles and knowledge base of the TRIZ, which stimuli the designers or problem solvers to find ideas quickly and efficiently.

4. Case study

4.1. Situation

Fig. 8 demonstrates the working principle of a dropping pill machine for a kind of Chinese traditional medicine. The dropping nozzle is heated up by heating oil in advance. During the drop, the temperature of medicine is kept constant by using the heated oil. The pressure of liquid medicine is cushioned by compressed air during the fall. In this system, the dimensional uniformity of dropping pills can be kept. The machines of this kind satisfy small and medium sized companies to produce dropping pills. There is also a kind of machine suitable for the big company which can be bought in the market. There are some unsatisfied needs in the market, for examples, low cost dropping pill machines, machines

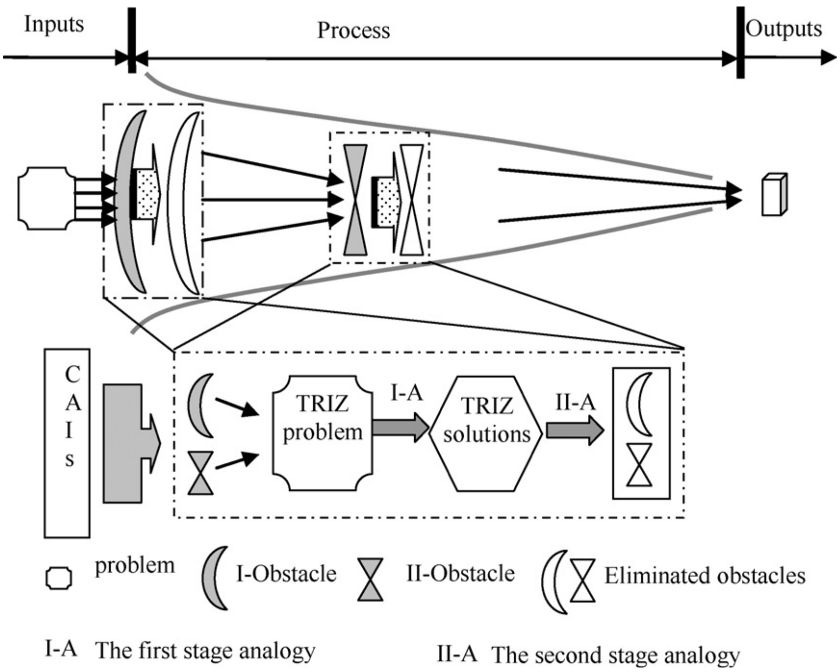

Fig. 7. A model to eliminate obstacles using CAIs.

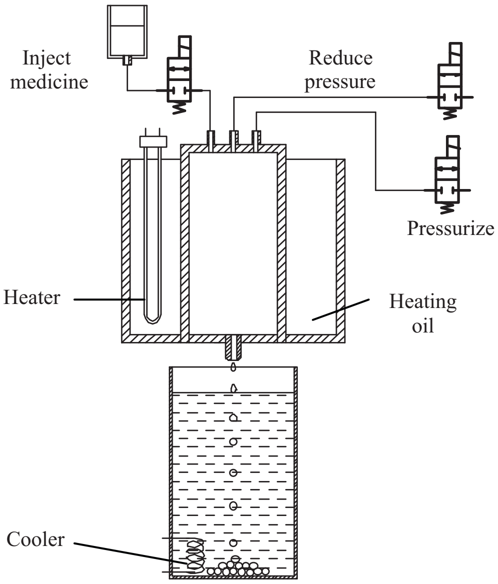

Fig. 8. The principle of a dropping pill machine.

used in experiments of new kind pills, etc. Development of a new machine to satisfy these needs is a challenge in this field.

The CAIs applied in this lab are Goldfire Innovator, IWB, ProInovator, and InventionTool.

4.1.1. Inputs of the innovation pipeline

- A new dropping pill machine, which is suitable for experiments and small companies, with low cost.
- The main technologies used in this new machine should not be the same as the technologies shown in Fig. 6. But the principles in the figure can be used as a benchmark.

4.1.2. Problems from the inputs

Make forecasting for the core technologies with new principles and low cost. But how to make technology forecasting is a problem, which is an I-obstacle.

4.1.3. Eliminate the I-obstacle

The path shown in Fig. 5 is applied first in order to select a few laws and lines using InvetionTool3.0 for eliminating the I-obstacle. From the laws and lines the next likely directions of the technology evolution may be found.

Fig. 9 shows two technological evolution lines under the law of "Transition from Macro- to Micro-level". The first line shows the flow, as a core technology, from a whole flow to two parts flow, then a few parts flow, and finally, as many small part flows. The original state in the second line is a block, then many small parts, grains, fluids and fields. The beginning or current states of the flow in the nozzle in Fig. 9 are in the first state of the line in Fig. 4. There are several states in that two lines to be used for finding new ideas, which are potential states. One idea is to divide the whole flow to two part flows. Another idea is to divide the whole flow into small sections.

The idea to divide the whole flow into small sections is selected as the kind of solution to eliminate the I-obstacle. It is with this idea that a project is carried out in the laboratory of the Institute of Design for Innovation, Hebei University of Technology.

4.1.4. Eliminate the II-obstacles

Fig. 10 shows the function structure of the dropping pill machine to be designed. The functions in the figure are realized using effects or effect chains. To find some effects for a function sometimes goes beyond the ability of problem solvers or designers. As a result ill-structured problems are faced by them. But by the knowledge base of CAIs the problems may be solved.

Taking the function of 'move liquid' as example, the effect is "volume displacement". The corresponding structures are impeller pump (momentum effect), piston pump (volume displacement

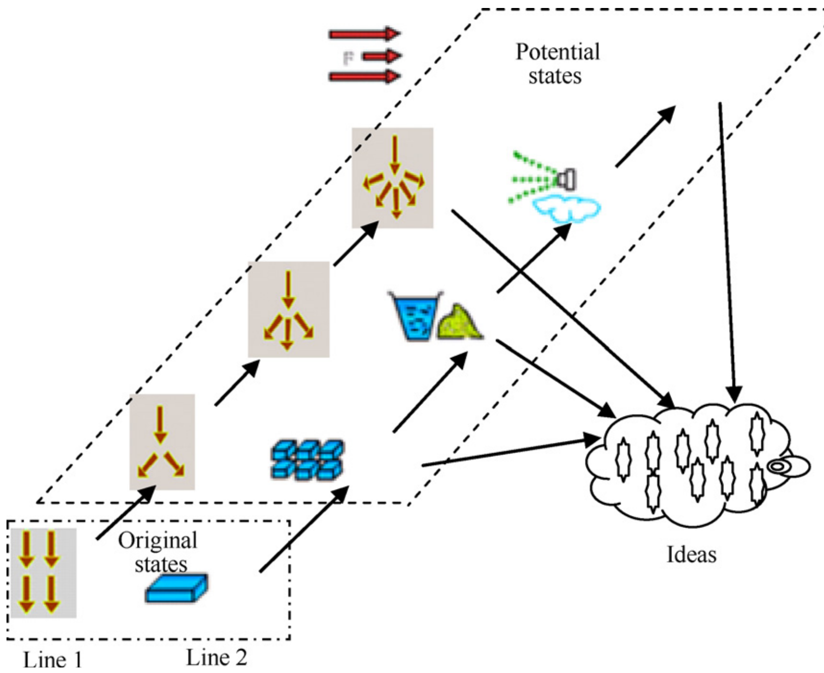

Fig. 9. Ideation for eliminating the I-obstacle.

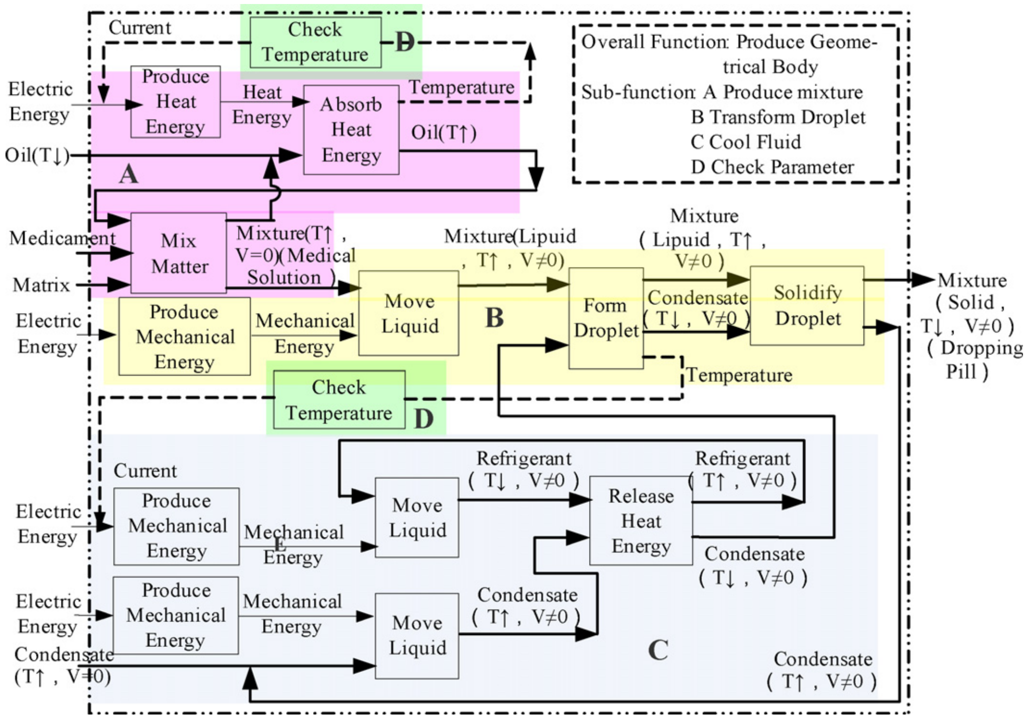

Fig. 10. Function structure of dropping pill machine [24].

effect), water injection pump (Bernoulli effect), gear pump (volume displacement effect), magnetic current pump (Coulomb effect), ultrasound pump (standing wave effect), helium pump (thermodynamic effect), electro osmotic pump (electro osmosis effect), air pump (volume displacement effect), peristaltic pump (volume displacement effect), etc.

4.1.5. The concept selected

If a pump is applied as a driving force of the dropping process a new concept machine is generated as shown in Fig. 11. An evaluation shows that the cost for realizing the concept is low. A simple experiment to test the possibility of the concept is carried out. In this experiment a specific pump used in the field of macromolecule, the peristaltic pump, is selected. The original but simple experiment shows that the pills are produced and the concept is possible.

4.1.6. The following development

An embodiment and a detailed design for the machine are also carried out following the concept shown in Fig. 11. After manufacturing, the experiment is made in the lab and the results show that the concept is right. The next step is to transform the design to a company and finish the whole process of an innovation.

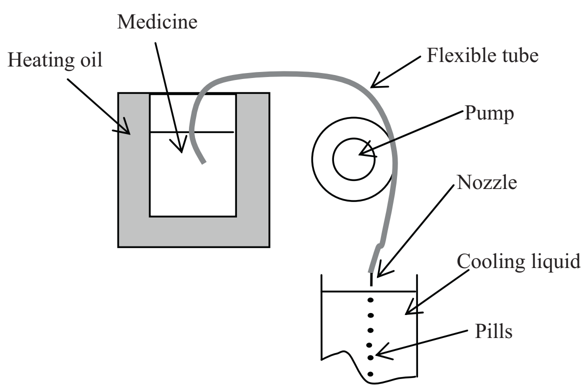

Fig. 11. A new concept of a dropping pill machine.

5. Discussion

The first contribution is that we defined that a technical obstacle in an innovation pipeline is a situation in which an ill-structured problem is faced. There are two types of technical obstacles. They appeared separately in the input stage and in the conceptual design process.

The second contribution is that we found that there are three similarities between ill-structured and inventive problems, and that the latter is a sub-set of the former in the engineering domain. It is more convenient to describe a problem at a high level using the concept of an ill-structured problem then the concept of an inventive problem. Literatures show that it is difficult to find a good method to solve an ill-structured problem. But you can find some methods to solve inventive problems in TRIZ effectively. As a result, some ill-structured problems in an innovation pipeline can be solved using TRIZ. This is a kind of fusion between the Western and the USSR models for problem solving.

The third contribution is that a new model to eliminate obstacles using CAIs is developed. There is a main process and two sub-processes in this model. The main process is the managing of all the activities in an innovation pipeline. And the sub-processes are designed to eliminate obstacles of two types using CAIs and TRIZ. It is the sub-process that the TRIZ process is integrated with as the main innovation process. This will make the TRIZ even more effective in assisting innovation processes.

The last contribution is that the case study is a real project carried out in our lab. We applied TRIZ in two sub-processes, the input design and conceptual design separately, in order to eliminate obstacles. In the first sub-process, we find an idea, and in the second, we make the concept that implements the idea in the downstream of the pipeline.

6. Conclusions

If an ill-structured problem emerges in an innovation pipeline, the problem solvers or designers face a technical obstacle because the problem is difficult to solve. The problems have always existed for the technology or need forecasting in the input stage, and concept generation in conceptual design stage. So there two types of technical obstacles, which emerge separately in the two stages.

Ill-structured problems have been studied in the Western world and inventive problems have been studied in the USSR for many years. The two studies are independent, but by the three similarities we define that the inventive problems are a sub-set of the ill-structured problems. So the methods and tools in TRIZ and CAIs, which are TRIZ based, could be used to solve ill-structured problems in an innovation pipeline.

A model to eliminate the two types of obstacles in an innovation pipeline is developed by the supporting CAIs, and a case study shows the process. This is just the beginning of studying the relationships between ill-structured problems and inventive problems. The research in this field will be carried out at this Institute in the future.

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Runhua Tan is currently a professor, the head of the Institute of Design for Innovation, and Vice-President of Hebei University of Technology. He received his MS and PhD, both in Mechanical Engineering from HUT in 1984 and from Zhejiang University in 1998, respectively. He worked as a Visiting Scholar at Brunel University (UK) from 1994 to 1995 and had a 3-month stay at Munich University of Applied Science (Germany) in 2001. He has authored 5 books, and authored or co-authored over 250 papers. He holds eight patents and seven software copyrights. His research interests include design theory and methodology and innovation management.

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Eliminating technical obstacles in innovation pipelines using CAIs

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Addresses:
1. Hebei Univ Technol, Inst Design Innovat, Tianjin 300130, Peoples R China

E-mail Address: rhtan@hebut.edu.cn

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Authors: Runhua, Tan[1]

Author affiliation: [1] Institute of Design for Innovation, Hebei University of Technology, Tianjin 300130, China

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