Systematic Decision Making Process for Identifying the Contradictions to be Tackled by TRIZ to Accomplish Product Innovation

Hajime Mizuyama, Kenichi Ishida

Abstract

This paper presents a systematic decision making process for accomplishing product innovation in accordance with the target quality, i.e. the target values and relative weights of the relevant quality characteristics of the product to be developed, with the help of TRIZ (the Russian abbreviation of the theory of inventive problem solving). Since TRIZ methodology deems innovation as resolving a contradiction, the proposed approach first reveals the contradictions that block the target quality from being reached, based on the engineering solutions that the current base product employs and the phenomena that take place while the base product is performing its function. Then, the approach structures the contradictions and distinguishes the causal conflicts from the resultant ones. It also calculates the criticality of each causal conflict according to the relationships with the quality characteristics. These steps make it possible to properly highlight the focus of innovation within the whole function and mechanism structure of the base product. The proposed method is described using a die-casting machine as an illustrative example, and the example confirms that some innovative conceptual design solutions can be successfully derived through the proposed decision making process.

Keywords**:** *conceptual design, conflict resolution, DEMATEL, product innovation, QFD, TRIZ*

1. Introduction

It is a critical issue for a manufacturing firm to develop an innovative product that not only meets customers' needs but also distinguishes itself clearly from existing competing products, especially in the recent mature market environment. Even when developing a new derivative product from an existing base product, it is desirable that the resultant product should be deemed innovative as well as responding to customers' needs. That is, now it is an important issue how to accomplish product innovation in a target-quality-oriented way. Upon this background, it has been pointed out that combining QFD (Quality Function Deployment) and TRIZ (the Russian abbreviation of what can be translated as the theory of inventive problem solving) will make a powerful approach for the conceptual design of such an innovative product. QFD will set an attractive target quality to the product, and TRIZ will help solve technical problems if any and thus enable to reach the given target quality.

In order to make such an approach actually work, the target quality to be achieved must be translated into technical problems in a form that can be handled by TRIZ. TRIZ methodology deems innovation as resolving a contradiction, and usually expresses the technical problem to tackle as a contradiction. Thus, this paper presents a systematic decision making process for capturing and structuring the contradictions that should be resolved to achieve the target quality, and thus enables product innovation to be accomplished in a target-quality-oriented way with the help of TRIZ.

The proposed approach calls it an engineering solution to perform each elemental function by the corresponding elemental mechanism, where elemental functions and elemental mechanisms are the smallest constituents of the function and mechanism structure of a product. Then, the approach reveals the contradictions based on the engineering solutions that the current base product employs and the phenomena that take place while the base product is performing its function. Any product realises its function by intentionally inducing some phenomena with its engineering solutions. Unfortunately, these beneficial phenomena often accompany some harmful phenomena as their side effects, and they cause the problems. This paper names the obtained contradictions the elemental conflicts. Then, the approach structures the complicated causal relationships among the elemental conflicts and distinguishes the causal conflicts from the resultant ones. It also calculates the criticality of each causal conflict according to the relationships with the quality characteristics. These steps make it possible to properly highlight the focus of innovation within the whole function and mechanism structure even when the quality characteristics to be enhanced are affected by many interrelated contradictions located in various parts of the base product. The proposed approach also provides a procedure for choosing an appropriate TRIZ tool and posing the technical problem to the chosen tool.

In the remainder of this paper, after a literature review section, the problem to be dealt with and the proposed decision making process for the problem are described using a die-casting machine as an illustrative example, and how the proposed approach works is demonstrated with the example. Finally, conclusions follow.

2. Related work

QFD is a well-known and widely-used methodology for prioritizing the customers' requirements on a product, and translating them into its design specifications [1][2]. Hence, it can be used to set appropriate target values for the key quality characteristics of the innovative product to be developed. Since this target quality should clearly differentiate the resultant product from competing ones, it is usually difficult to reach with the current function and mechanism structure of the base product. Thus, in order to attain the target quality, it must be determined what changes should be made to which parts of the base product. However, QFD itself does not provide any means to make the decision.

Whereas, when a technical problem is given in an appropriate form, TRIZ will provide several tools to support solving the problem [3][4][5][6][7]. It has been successfully applied to real-life design problems [8][9][10][11]. Thus, TRIZ can be utilised to identify what sort of innovation should be introduced into the function and mechanism structure of the base product so as to attain the specified target quality. Accordingly, it has been pointed out that combining QFD and TRIZ will make an effective approach for systematic product innovation [12][13].

To make such an approach actually work, the target quality set by QFD must be translated into technical problems in a suitable form for TRIZ, that is, a contradiction. However, this critical part of the innovation process still depends largely on the capabilities of human engineers, and only a few approaches have been proposed for supporting it. As a pioneer work in this field, Yamashina *et al.* [14] developed a systematic approach for bridging the gap between QFD and TRIZ. This approach first determines which part or sub-mechanism of the base product should be given changes according to the relationships between the sub-mechanism and the quality characteristics to be enhanced, and then defines contradictions to resolve for the chosen sub-mechanism based on its house of quality matrix. Hua *et al.* [15] adjusted this approach to a specific TRIZ software. Wang *et al.* [16] proposed a similar approach, which defines contradictions based only on the house of quality matrix of the whole product and hence can be deemed as a simplified version of Yamashina *et al.* [14].

What is common to these approaches is that they do not distinctly consider what technical problems prevent the quality characteristics from being improved as intended and only capture some resultant contradictions appeared on the house of quality matrix, for example, as trade-off relationships among quality characteristics. However, it is often the case, in practice, that any trade-off relationship may be caused by not just one but several different technical problems located in various parts of the base product, a same technical problem can affect many quality characteristics, and the technical problems are themselves interrelated. In such circumstances, it seems that the conventional approaches cannot always identify the root cause of the problems and may result in a tedious iteration process that reveals and resolves those problems one by one. This is obviously inefficient and may take a long time to converge. Therefore, more desirable will be a decision making process that can first exhaustively capture what technical problems exist in which parts of the base product and then properly narrow down the focus of innovation. However, such a decision making process has not yet been established, and hence will be newly developed in this paper.

3. Target-quality-oriented product innovation problem

3.1 Assumptions on target quality

This paper deals with the problem to establish a conceptual design of a new innovative product from an existing base product. It is assumed that the quality characteristics $\{y_1, y_2, ...\}$ which should be considered for fulfilling the customers' requirements on the product have been identified, and the target values $\{t_1, t_2, ...\}$ and the relative weights $\{u_1, u_2, ...\}$ for the quality characteristics have been set. The relative weights are assumed to have been normalised as below:

$$\sum_i u_i = 1 \tag{1}$$

where the higher the relative weight u_i, the more important to enhance the quality characteristic y_i to satisfy the customers' requirements. For example, QFD can be utilised to determine the target quality. However, the proposed approach does not assume, and is independent of, the use of QFD.

To make the below discussion easier to understand, we hereafter take up a die-casting machine, shown in Figure 1, for a certain aluminium product as an illustrative example. We assume that the below five variables have been identified in this example as the quality characteristics to be considered to satisfy customers' requirements:

y_1: fraction of defectives due to voids (%),
y_2: fraction of defectives in the other defect modes (%),
y_3: raw material yield (%),
y_4: cycle time (seconds),
y_5: die life (shots),

and that ambitious target values and appropriate relative weights have been already assigned to those characteristics so that the resultant product should be deemed innovative.

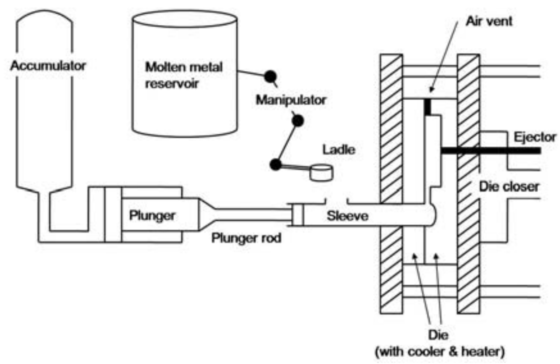

Figure 1. Example die-casting machine.

3.2 Assumptions on function and mechanism structure

It is also assumed that the function and mechanism structure of the existing base product has been deployed as a corresponding pair of a function tree and a mechanism tree. This deployment is not a new practice, and has been introduced and utilised, for example, in axiomatic design [17].

The current die-casting machine we consider consists of a molten metal reservoir, a molten metal feeder, a molten metal injector, an ejector, a moulding mechanism, and a die lubricator (which is omitted in Figure 1). The molten metal reservoir further comprises a pot which reserves molten metal, a heater which raises its temperature, and a lid which maintains the temperature. The molten metal feeder is composed of a ladle which ladles molten metal, and a manipulator which manipulates the ladle. The subsystems of the molten metal injector include a sleeve which reserves molten metal and keeps its temperature, an accumulator which generates a force, a plunger rod which conveys the force, and the plunger which injects molten metal into a die and eliminates voids. The subsystems of the moulding mechanism contain the die which moulds molten metal, a die-cooler which cools down the die, a die heater – which heats the die, a die closer – which shuts the die, and air vents, which exhaust gas from the die. Further, the die lubricator is composed of a spray, which sprays lubricant and cools down the die, and a tank, which reserves lubricant.

Thus, the function and mechanism structure of the base product can be captured by the function tree shown in Figure 2 and the mechanism tree shown in Figure 3. Hereafter, we refer to each sub-function corresponding to a leaf node of the function tree and each sub-mechanism represented by a leaf node of the mechanism tree as an elemental function and an elemental mechanism respectively. In the die-casting machine example, dividing those elemental functions and mechanisms further down to smaller constituents was judged to be meaningless for devising innovation.

Further, we term it an engineering solution to utilise a specific elemental mechanism for performing each elemental function. Then, a product can be deemed as a set of engineering solutions $\{a_1, a_2, \ldots\}$. For example, the current die-casting machine can be captured as the set of the below engineering solutions:

a_1: reserve molten metal by a pot,
a_2: raise molten metal temperature by a heater,
a_3: maintain molten metal temperature by a lid,
a_4: ladle molten metal by a ladle,
a_5: manipulate the ladle by a manipulator,
a_6: reserve molten metal by a sleeve,
a_7: generate a force by an accumulator,
a_8: convey the force by a plunger rod,

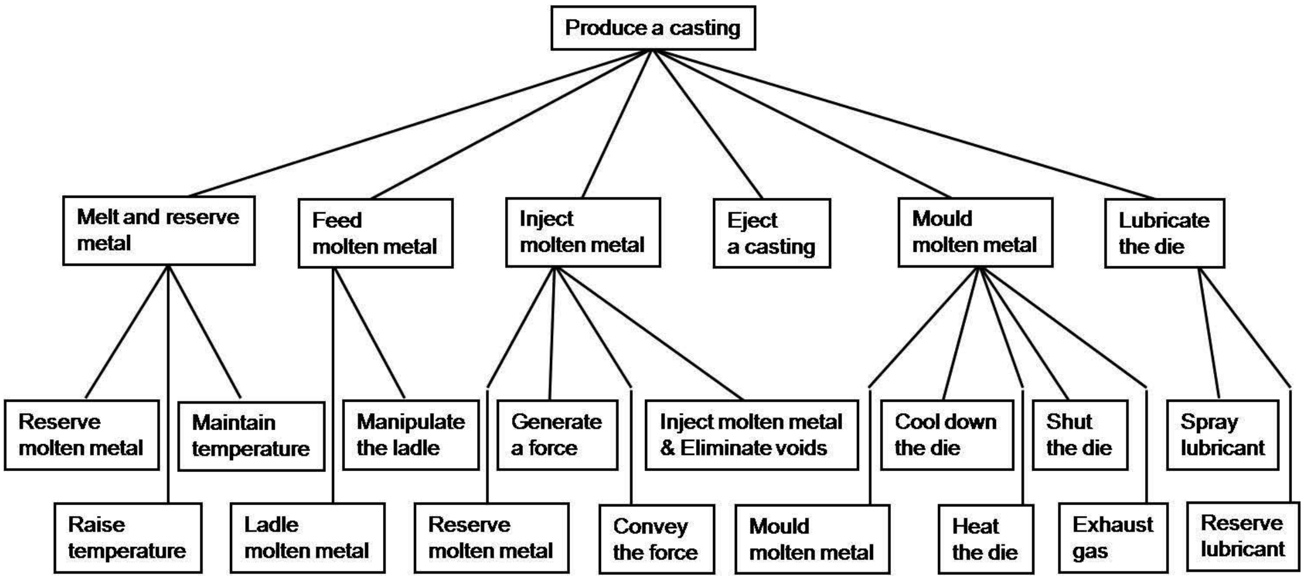

Figure 2. Function tree of example die-casting machine.

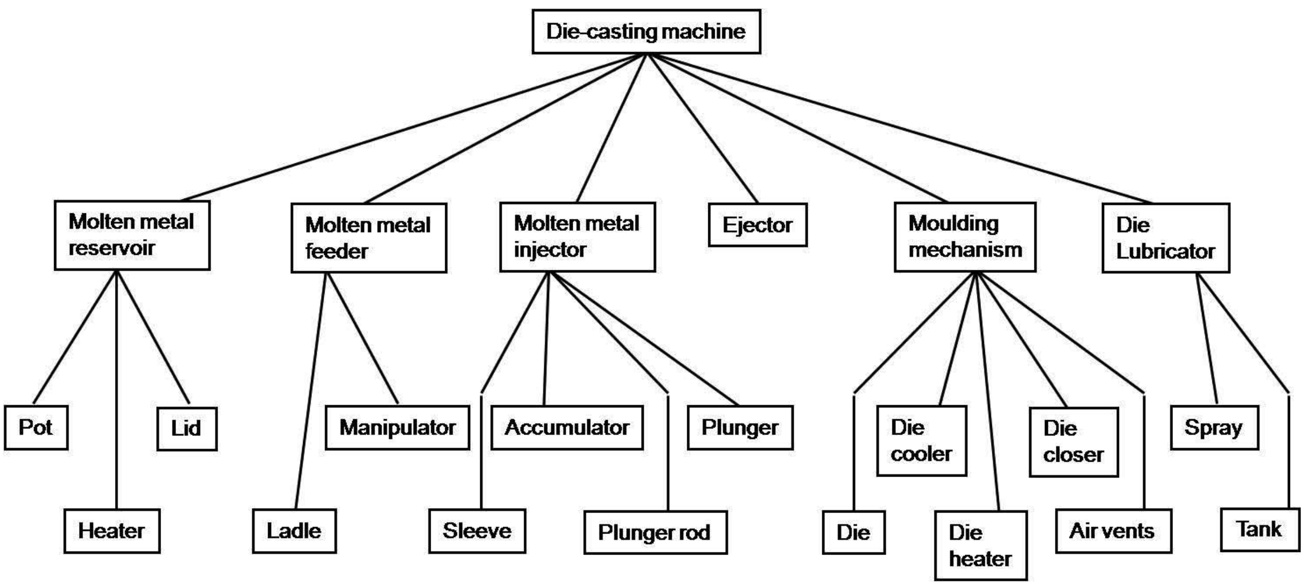

Figure 3. Mechanism tree of example die-casting machine.

a_9: inject molten metal and eliminate voids by a plunger,
a_{10}: eject a casting by an ejector,
a_{11}: mould molten metal by a die,
a_{12}: cool down the die by a die cooler,
a_{13}: heat the die by a die heater,
a_{14}: shut the die by a die closer,
a_{15}: exhaust gas by air vents,
a_{16}: spray lubricant and cool down the die by a spray,
a_{17}: reserve lubricant by a tank.

3.3 Product innovation using TRIZ

The target quality, i.e. the set of the target values assigned to the quality characteristics, must be able to clearly differentiate the resultant product from competing ones in the mature market environment, and hence will be difficult to attain with the function and mechanism structure of the base product. This paper does not compromise the target quality, but instead aims at deriving a new innovative conceptual design solution by changing the function and mechanism structure through an appropriate technical innovation. What is required to accomplish this product innovation will be to determine what changes should be made to which parts of the base product to reach the target quality.

This paper uses a TRIZ-based approach to this problem. The TRIZ tools that we can use to derive an innovation concept for an engineering solution include the 40 principles of innovation, the principle of separation, the effect database, etc. The 40 principles of innovation are a collection of typical principles for resolving a technical contradiction, which is a situation that improving an attribute degrades another attribute. The principle of separation resolves a physical contradiction, which is a situation that mutually conflicting target values are given to a certain single attribute, by separation in space, time, etc. The effects database shows utilizable physical, chemical and geometrical effects that can substitute for a current engineering solution having a contradiction, when the function to be realised by the solution is specified.

Thus, what TRIZ tools try to accomplish is not to reach a given target quality but to resolve contradictions. Therefore, in order to attain the target quality by the help of TRIZ, we need first to study the contradictions in the function and mechanism structure of the base product that block the target quality from being reached, and then to pose an appropriate contradiction to a suitable TRIZ tool in a proper form. The next section proposes a structured decision making process for this purpose.

4. Proposed decision making process for product innovation

4.1 Capturing elemental conflicts

The outline of the proposed approach is shown by a diagrammatic presentation in Figure 4. The first step reveals the technical problems preventing the quality characteristics from being enhanced as prescribed, each in the form of a contradiction, on the engineering solutions of the base product. We start this step by enumerating major phenomena $\{p_{i1}, p_{i2}, \ldots\}$ that affect each quality characteristic y_i, and clarifying the relationships between the phenomena and the engineering solutions $\{a_1, a_2, \ldots\}$. Then, we grasp the technical problems concerning each engineering solution in the form of a contradiction; *the engineering solution gives a desirable effect to a phenomenon and at the same time an undesirable effect to another phenomenon*.

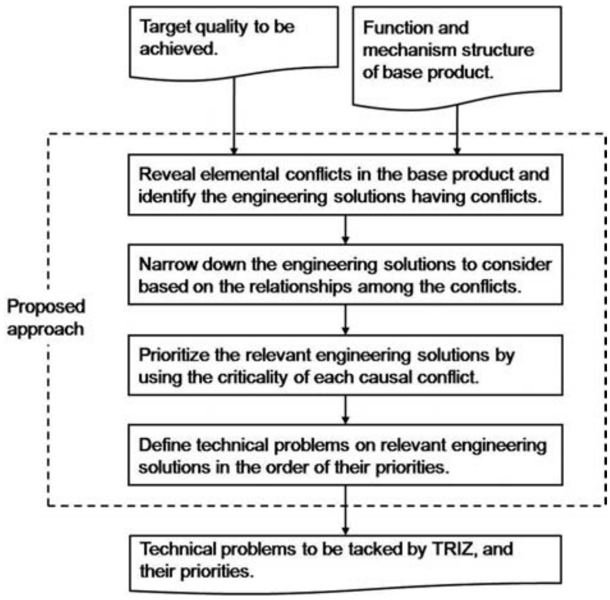

Figure 4. Diagrammatic presentation of proposed approach.

Hereafter, we call the contradictions the elemental conflicts, and denote them by $\{c_1, c_2, \ldots\}$. When the former phenomenon of an elemental conflict concerns the quality characteristic y_i and the latter phenomenon influences y_j, then the elemental conflict will cause a trade-off relationship between the characteristics y_i and y_j and as a result will make the innovative target quality difficult to attain. Thus, the elemental conflict must be resolved so as to reach the target quality.

In the die-casting machine example, the major phenomena concerning the quality characteristics are the followings:

p_{11}: generation of voids from remaining air in the die,
p_{12}: generation of voids from die lubricant,
p_{21}: soldering between the die and molten metal,
p_{22}: temperature drop and incomplete filling of molten metal,
p_{31}: molten metal consumption in the runner of the die,
p_{32}: molten metal leakage from the parting surface of the die,
p_{41}: time consumption by spraying lubricant,
p_{42}: time consumption by injecting molten metal,
p_{51}: die fatigue due to temperature stress,
p_{52}: die fatigue due to the closing force.

We can capture the elemental conflicts of the base product according to the relationships between those phenomena and each engineering solution.

Each elemental conflict has a structure that an engineering solution gives a desirable effect to a phenomenon and at the same time an undesirable effect to another phenomenon. We refer to the former phenomenon as the upstream phenomenon and the latter one as the downstream phenomenon of the conflict. Then, the elemental conflict can be expressed by a model: an upstream phenomenon

-> an engineering solution -> a downstream phenomenon. For example, the engineering solution a_9 (inject molten metal and eliminate voids by a plunger) gives a desirable effect to the phenomenon p_{11} (generation of voids from remaining air in the die) and at the same time an undesirable effect to the phenomenon p_{32} (molten metal leakage from the parting surface of the die). Hence, the current die-casting machine has the elemental conflict:

$$c_1: p_{11} \text{ -> } a_9 \text{ -> } p_{32} .$$

Similarly, the below nine elemental conflicts have been captured in the example die-casting machine:

- c_1: generation of voids from remaining air in the die (p_{11}) -> inject molten metal and eliminate voids by a plunger (a_9) -> molten metal leakage from the parting surface of the die (p_{32}),
- c_2: generation of voids from die lubricant (p_{12}) -> inject molten metal and eliminate voids by a plunger (a_9) -> molten metal leakage from the parting surface of the die (p_{32}),
- c_3: soldering between the die and molten metal (p_{21}) -> spray lubricant and cool down the die by a spray (a_{16}) -> generation of voids from die lubricant (p_{12}),
- c_4: soldering between the die and molten metal (p_{21}) -> spray lubricant and cool down the die by a spray (a_{16}) -> time consumption by spraying lubricant (p_{41}),
- c_5: soldering between the die and molten metal (p_{21}) -> cool down the die by a die cooler (a_{12}) -> die fatigue due to temperature stress (p_{51}),
- c_6: temperature drop and incomplete filling of molten metal (p_{22}) -> mould molten metal by a die (a_{11}) -> molten metal consumption in the runner of the die (p_{31}),
- c_7: temperature drop and incomplete filling of molten metal (p_{22}) -> inject molten metal and eliminate voids by a plunger (a_9) -> generation of voids from remaining air in the die (p_{11}),
- c_8: time consumption by injecting molten metal (p_{42}) -> inject molten metal and eliminate voids by a plunger (a_9) -> generation of voids from remaining air in the die (p_{11}),
- c_9: molten metal leakage from the parting surface of the die (p_{32}) -> shut the die by a die closer (a_{14}) -> die fatigue due to the closing force (p_{52}).

The elemental conflicts $c_1, c_2, ..., c_5$ and c_9 are straightforward to understand. The conflict c_6 occurs because of enlarging the runner cross section of the die to slow down the temperature drop. Whereas, the conflicts c_7 and c_8 arise due to increasing the speed and the pressure of molten metal injection.

These elemental conflicts are the technical problems that prevent the target quality from being reached. By revealing which engineering solution causes each elemental conflict, we have the set of the engineering solutions having technical problems. We denote the set by A_C. In the die-casting machine example, this set is given by:

$$A_C = \{a_9, a_{11}, a_{12}, a_{14}, a_{16}\} \qquad (2)$$

4.2 Structuring elemental conflicts

When there are many elemental conflicts, we should pay attention to the causal conflicts but the resultant ones that are brought about by the causal ones. Hence, our product innovation approach next clarifies the relationships among the elemental conflicts and highlights the causal ones to be considered according to the relationships.

If eliminating an elemental conflict will make it unnecessary for another elemental conflict to be resolved, we say that these conflicts are in an influential relationship. There can be the following two types of influential relationships between elemental conflicts:

Serial influential relationship: It is the influential relationship that occurs between elemental conflicts c_m and c_n when the downstream phenomenon of c_m is identical to the upstream phenomenon of c_n and resolving c_m will make the engineering solution itself or its condition that causes c_n unnecessary. In this case, c_n needs not to be dealt with any more if c_m is resolved.

Parallel influential relationship: It is the influential relationship that occurs between elemental conflicts c_m and c_n when they have a same upstream phenomenon and resolving c_m will make the engineering solution itself or its condition that causes c_n unnecessary. In this case as well, c_n needs not to be dealt with if c_m is resolved.

Hereafter, we represent these influential relationships by:

c_m -> c_n,

and call c_m the elemental conflict on the cause-side and c_n the one on the effect-side.

In the die-casting machine example, the downstream phenomenon of c_3 is p_{12} and which is also the upstream phenomenon of c_2, and resolving c_3 will make it unnecessary to consider c_2. That is, if the conflict c_3 is resolved and the phenomenon p_{12} is no longer problematic, the engineering solution a_9 will not need to deal with the voids generated by p_{12}. Thus, there is a serial influential relationship c_3 -> c_2 . Whereas, the elemental conflicts c_6 and c_7 share the same upstream phenomenon p_{22} and the solution a_9, which causes c_7, is the primary engineering solution to this phenomenon p_{22}. If a_9 does not cause the conflict, the engineering solution a_{11}, which causes c_6, will become unnecessary. Hence, there is a parallel influential relationship c_7 -> c_6. Similarly, the following eight influential relationships can be obtained in this example:

c_1 -> c_9, c_2 -> c_9, c_3 -> c_2, c_5 -> c_3,
c_5 -> c_4, c_7 -> c_1, c_7 -> c_6, c_8 -> c_1.

As we can see in this example, when there are many elemental conflicts, the influential relationships among them are likely to be complicated. Since the influential relationships defined above satisfy the transitive law, not only the direct influential relationships but also indirect ones must be grasped and unified into the aggregate relationships. They can be captured by structuring the influential relationships among the elemental conflicts through DEMATEL (Decision Making Trial and Evaluation Laboratory) [18][19]. DEMATEL is a matrix-based approach for quantifying the overall relationships among multiple items and has been used for structural modelling in various fields [20][21].

We first set the direct influence $r_{mn} = 0$ for each pair of elemental conflicts c_m and c_n that has no direct influential relationship between them. Since no elemental conflict has a direct influential relationship with itself, $r_{mm} = 0$ holds for every c_m. If c_n is directly influenced only by c_m, we set $r_{mn} = 1$. In the die-casting machine example, we have:

$$r_{32} = r_{53} = r_{54} = r_{76} = 1 \tag{3}$$

Further, if c_n is directly influenced by more than two elemental conflicts, we define the value of each corresponding r_{mn} according to the relative degree of its influence so that the below condition should be satisfied:

$$\sum_m r_{mn} = 1 \tag{4}$$

In our example, c_1 is directly influenced by c_7 and c_8, and c_9 is affected by c_1 and c_2. Hence, we set:

$$r_{71} = r_{81} = r_{19} = r_{29} = 0.5 \tag{5}$$

We now have the direct influence matrix $\boldsymbol{R} = (r_{mn})$, which then will be used to derive the aggregate influence matrix $\tilde{\mathbf{R}} = (\tilde{r}_{mn})$ as below:

$$\tilde{\mathbf{R}} = \sum_{k=1}^{\infty} \mathbf{R}^k = \mathbf{R}(\mathbf{I} - \mathbf{R})^{-1} \tag{6}$$

where $\boldsymbol{I}$ is an identity matrix. Each element $\tilde{r}_{mn}$ of the obtained matrix $\tilde{\mathbf{R}}$ expresses the aggregate influence from c_m to c_n.

In the die-casting machine example, the direct influence matrix is given by:

$$\mathbf{R} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{7}$$

Accordingly, the aggregate influence matrix is obtained as:

$$\tilde{\mathbf{R}} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0.5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0.25 \\ 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.25 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{8}$$

When, and only when, the elemental conflict c_m is a causal conflict which is not influenced by any other elemental conflicts, the mth column of the aggregate influence matrix will become a zero vector. Thus, we can identify the causal elemental conflicts by extracting every column of a zero vector from the aggregate influence matrix. In our die-casting machine example, as shown in Figure 5, the causal conflicts to be really resolved have been revealed as $\{c_5, c_7, c_8\}$.

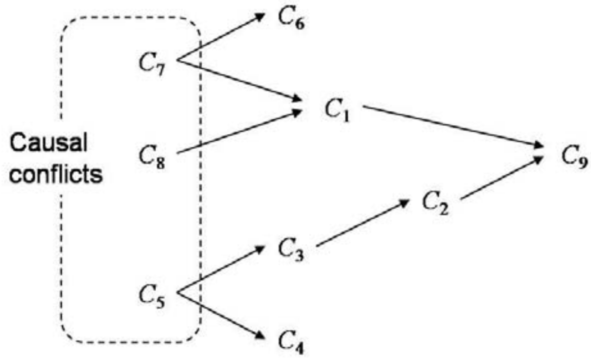

Figure 5. Relationships among elemental conflicts.

By checking which engineering solution brings about each causal elemental conflict, we can further narrow down the set of the engineering solutions to be considered from the above A_C. We denote the obtained subset of A_C by $\tilde{A}_C$. In the die-casting machine example, this set is given by:

$$\tilde{A}_C = \{ a_9, a_{12} \} \tag{9}$$

That is, the engineering solutions to be really considered were successfully narrowed from the above five down to only two engineering solutions.

4.3 Criticality analysis of elemental conflicts

When more than two engineering solutions have been found to have a causal conflict as in the case of the die-casting machine, the proposed approach next prioritises the engineering solutions.

We first quantify how important it is to resolve each elemental conflict so as to satisfy customers' requirements. For this purpose, we define the phenomenon weight $w_P(p_{ij})$ of each phenomenon p_{ij} concerning the quality characteristic y_i by distributing the relative weight u_i of the quality characteristic to every phenomenon p_{ij} according to the magnitude of its effect on the characteristic. Then, we define the raw conflict weight $w_C(c_m)$ of each elemental conflict as below:

$$w_C(c_m) = w_P(p_{ij}) + w_P(p_{kl}) \tag{10}$$

where p_{ij} and p_{kl} represent the upstream phenomenon and the downstream one of the elemental conflict c_m respectively. Accordingly, we can obtain the aggregate conflict weight $\tilde{w}_C(c_m)$ of the same elemental conflict c_m by the below equation:

$$\tilde{w}_C(c_m) = w_C(c_m) + \sum_n \tilde{r}_{mn} \, w_C(c_n) \tag{11}$$

This aggregate conflict weight $\tilde{w}_C(c_m)$ represents that the greater its value, the higher the number and/or the larger the relative weights of the quality characteristics to be improved by resolving the elemental conflict c_m.

Next, we prioritise the engineering solutions that we should focus on as the target of innovation, according to the aggregate conflict weights calculated above. When a_k is included in the set of the relevant engineering solutions $\tilde{A}_C$, we define its solution weight $w_A(a_k)$ as below:

$$w_A(a_k) = \sum_{es(c_m)=a_k} \tilde{w}_C(c_m) \quad (12)$$

where $es(c_m)$ expresses the engineering solution $(\in \{a_1, a_2, \ldots\})$ that causes the elemental conflict c_m.

This is the sum of the aggregate weights of the elemental conflicts located in the engineering solution. We can prioritise the engineering solutions to be considered in the decreasing order of this value. For convenience, we can deem that the weight of any engineering solution that is not included in the set $\tilde{A}_C$ is zero.

In the die-casting machine example, the process of this criticality analysis has been undergone as shown in Figure 6, and the relevant engineering solutions were prioritised as:

$$w_A(a_9) > w_A(a_{12}) \quad (13)$$

4.4 How to pose technical problems to TRIZ

When the relevant engineering solutions are determined and prioritised through the above criticality analysis, our product innovation approach will pose a technical problem concerning the chosen engineering solution in one of the following forms:

- formulate an elemental conflict of the chosen engineering solution as a technical contradiction, and apply one of the suggested principles of innovation,
- formulate an elemental conflict of the chosen engineering solution as a physical contradiction, and apply the principle of separation, and
- describe the elemental function of the selected engineering solution as a function to be realised, and obtain an applicable one from the physical, chemical and geometric effects in the effects database.

Thus, the procedure of posing technical problems to TRIZ and deriving innovation concepts to be introduced to the function and mechanism structure of the base product can be summarised as below, where A_0 is the set of the candidate engineering solutions to be focused on as the target of innovation:

Step 1: Set $A_0 = \tilde{A}_C$.

Step 2: If $A_0 = \phi$ holds, then select the most satisfactory innovation concept among those which have been devised, and end the procedure.

Step 3: Select the engineering solution a_i having the highest solution weight from the set A_0, and update the set as:

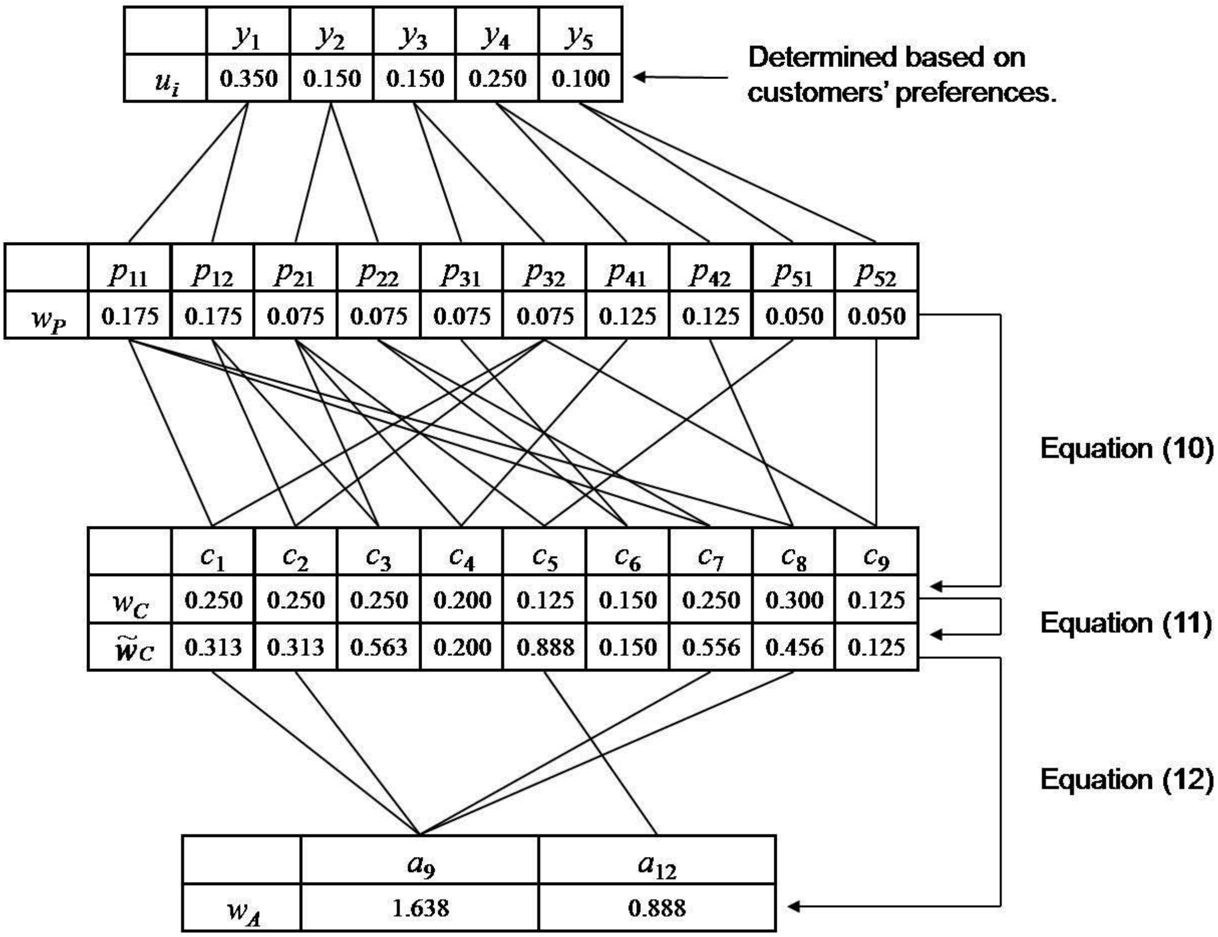

Figure 6. Process of criticality analysis.

$$A_0 = A_0 - \{a_i\} \quad (14)$$

Step 4: Derive innovation concepts by attempting innovation through TRIZ focusing on the chosen engineering solution a_i. If a satisfactory concept is obtained, then end the procedure.

Step 5: Examine possible combinations among the innovation concepts obtained so far. If a satisfactory concept is obtained through combination, then end the procedure. Otherwise, go back to **Step 2**.

4.5 Example application results

This subsection presents some results of applying the proposed approach to the die-casting machine example. As shown earlier in Figure 4, the role of the proposed approach itself is to define appropriate technical problems for TRIZ and applying TRIZ to the problems is outside the scope of the approach. However, in this subsection, how TRIZ handles the problems derived by the proposed approach is also described briefly for illustrative purpose. For the sake of intellectual property preservation, the innovation concepts that are not regarded as a part of the common knowledge cannot be disclosed here and hence those described below are only a part of the obtained innovation concepts. Despite this, we can still see in the below how the proposed approach guides the process of deriving innovation concepts.

According to the above criticality analysis, we first select the engineering solution a_9 (inject molten metal and eliminate voids by a plunger) as the target of innovation. It has two causal elemental conflicts c_7 and c_8. Since the effect database is not to resolve these conflicts directly, here we give some results of applying the 40 principles of innovation and the principle of separation.

Suppose that we took up the elemental conflict c_7 concerning the chosen engineering solution a_9. Then, we can formulate it into a technical contradiction. When we choose *durability of moving object* as the attribute to improve and *harmful side effects* as the attribute to be degraded, TRIZ will recommend the principle of *skipping* (*rushing through*). By applying this principle, we can obtain an innovation concept that radically shortens the route to the gate of the die and injects molten metal at a high speed without causing a significant temperature drop. This innovation concept will shorten the cycle time without increasing the fraction of defectives due to voids.

Instead of a technical contradiction, we can formulate the same elemental conflict c_7 into a physical contradiction:

"*molten metal injection should be at a high speed and a high pressure to prevent incomplete filling, and should be at a low speed and a low pressure not to generate voids*"

and utilise the principle of separation. However, *separation in time* has been already adopted by many die-casting machines through changing the plunger speed in the middle of the injecting process. Hence, here we apply *separation in space* to this technical problem. Accordingly, we can obtain an innovation concept that raises the pressure of the molten metal only in some areas in the die after completing injection.

At this step, we can also take up the other elemental conflict c_8 concerning the engineering solution a_9. When formulating it into a technical contradiction by choosing *speed* as the attribute to improve and *accuracy of manufacturing* as the attribute to be degraded, TRIZ will suggest the principle of *preliminary action* and the principle of *self-service and self-organization*. Applying the principle of *preliminary action* will lead to an innovation concept that exhausts the gas from the die prior to molten metal injection through a vacuum pump, and utilizing the principle of *self-service and self-organization* will result in an innovation concept that eliminates the gas through a reaction with the injected molten metal itself, instead of exhausting it, by fulfilling the die with a reactive gas before starting injection. These innovation concepts will significantly decrease the fraction of defectives due to voids.

We can further combine the above innovation concept obtained by the principle of *skipping* (*rushing through*) with the innovation concept achieved by the principle of *self-service and self-organization* into the function and mechanism structure of the product to be developed.

As demonstrated above, the proposed approach enabled to highlight the target of innovation systematically within the whole function and mechanism structure of the current base product, and the above die-casting machine example suggested that the proposed approach will be actually able to guide us to methodically derive some innovative conceptual design solutions. When dealing with a product having a small number of engineering solutions and elemental conflicts, a simple drawing like Figure 5 can also guide the decision making process instead of DEMATEL analysis. Hence, the full version of the proposed approach will be more effective for a large-scale product. However, it is also true that, the larger the scale of the product, the more time-consuming to rigidly follow the proposed decision making process. In order to use the proposed approach efficiently for a large-scale product, a conventional approach, such as Yamashina *et al.* [14], can be used as a pre-processor to narrow down in advance the engineering solutions and elemental conflicts to be considered.

5. Conclusions

This paper proposed a systematic decision making process for identifying the contradictions to be tackled by TRIZ to accomplish product innovation in a target-quality-oriented way. An illustrative example showed that it is capable of systematically guiding the conceptual design process of an innovative product. The approach utilises the engineers' knowledge on the base product, for example, the knowledge on the phenomena taking place while the product is performing its function. Thus, when the engineer using this approach is not so familiar with the base product and hence some of the phenomena were remained unknown, the available innovation concepts may be limited. However, it is also true that the knowledge on the phenomena only is often not sufficient for effective product innovation. Therefore, the proposed approach and a deep understanding of the base product should go hand in hand to make the most of the approach.

How to handle a large-scale product efficiently is an important future research topic. Further, we need to note that the proposed approach is not the one and only way to define contradictions, which prevent the given target quality from being reached, in the base product. Thus, it is also an interesting future research topic to establish other approaches for capturing contradictions. A same contradiction may be described in a different form, and it may result in a different innovation concept. It is not astonishment since the conceptual design problem treated in this paper is not a problem with a single right answer. That is, the main objective of a systematic innovation approach, as the one proposed here, is not to derive one right answer, but to enhance the efficiency of the innovation process.

AUTHORS

Hajime Mizuyama* and **Kenichi Ishida** – Department of Mechanical Engineering and Science, Kyoto University, Kyoto 606-8501, Japan. Tel.: +81-75-753-5237, Fax: +81-75-753-5239.
E-mail: mizuyama@mbox.kudpc.kyoto-u.ac.jp
* Corresponding author

References

[1] Hauser J. R. and Clausing D., "The House of Quality", *Harvard Business Review*, no. 66, 1988, pp. 63-73.
[2] Chan L. K. and Wu M. L., "Quality Function Deployment: A Literature Review", *European Journal of Operational Research*, vol. 143, 2002, pp. 463-497.
[3] Altshuller G., *40 Principles: TRIZ Keys to Technical Innovation*, Technical Innovation Center, Worcester, MA, 1998.
[4] Altshuller G., *Innovation Algorithm*, Technical Innovation Center, Worcester, MA, 1999.
[5] Kim Y. S. and Cochran D. S., "Reviewing TRIZ from the Perspective of Axiomatic Design", *Journal of Engineering Design*, no. 11, 2000, pp. 79-94.
[6] Savransky S. D., *Engineering of Creativity: Introduction to TRIZ Methodology of Inventive Problem Solving*, CRC Pr I Llc, Boca Raton, 2000.
[7] Orloff M. A., *Inventive Thinking through TRIZ: a Practical Guide*, Springer Verlag, New York, 2003.
[8] Bariani P. F., Berti G. A. and Lucchetta G., "A Combined DFMA and TRIZ Approach to the Simplification of Product Structure", *Proceedings of the I MECH E. Part B. Journal of Engineering Manufacture*, no. 218 B8, 2004, pp. 1023-1027.
[9] Chang H. T. and Chen J. L., "The Conflict-Problem-Solving CAD Software Integrating TRIZ into Eco-Innovation", *Advances in Engineering Software*, no. 35, 2004, pp. 553-566.
[10] Mao Y. J. and Tseng C. H., "An Innovative Piston Retractor for Bicycle Hydraulic Disc Braking Systems", *Proceedings of the I MECH E. Part D. Journal of Automobile Engineering*, no. 218 D3, 2004, pp. 295-303.
[11] Tsai C. C., Chang C. Y. and Tseng C. H., "Optimal Design of Metal Seated Ball Valve Mechanism", *Structural and Multidisciplinary Optimization*, no. 26, 2004, pp. 249-255.
[12] Terninko J., "The QFD, TRIZ and Taguchi Connection: Customer-Driven Robust Innovation". In: Proceed*ings of the 9th Symposium on Quality Function Deployment*, 1997, pp. 441-445.
[13] Hua Z., Yang J., Coulibaly S. and Zhang B., "Integrating TRIZ with Problem-Solving Tools: A Literature Review from 1995 to 2006", *International Journal of Business Innovation and Research*, no. 1, 2006, pp. 111-128.
[14] Yamashina H., Ito T. and Kawada H., "Innovative Product Development Process by Integrating QFD and TRIZ", *International Journal of Production Research*, no. 40, 2002, pp. 1031-1050.
[15] Hua Z., Huang F. and Wang W., "A Method of Product Improvement by Integrating FA with TRIZ Software Tools", *International Journal of Product Development*, no. 4, 2007, pp. 122-135.
[16] Wang, H., Chen, G., Lin, Z. and Wang, H., "Algorithm of Integrating QFD and TRIZ for the Innovative Design Process", *International Journal of Computer Applications in Technology*, no. 23, 2005, pp. 41-52.
[17] Suh N. P., *The Principles of Design*, Oxford University Press, New York, 1990.
[18] Fontela E. and Gabus A., "DEMATEL - Progress Achieved", *Futures*, no. 6, 1974, pp. 361-363.
[19] Fontela E. and Gabus A., "World Crisis - Decision Making Trial and Evaluation Laboratory", *Futuribles*, no. 14, 1978, pp. 211-221.
[20] Tamura H. and Akazawa K., "Structural Modeling and Systems Analysis of Uneasy Factors for Realizing Safe, Secure and Reliable Society", *Journal of Telecommunications and Information Technology*, no. 3, 2005, pp. 64-72.
[21] Tamura H. and Akazawa K., "Stochastic DEMATEL for Structural Modeling of a Complex Problematique for Realizing Safe, Secure and Reliable Society", *Journal of Telecommunications and Information Technology*, no. 4, 2005, pp. 139-146.