Cluster Comput (2019) 22:S10145–S10162
https://doi.org/10.1007/s10586-017-1190-z

A case-based decision theory based process model to aid product conceptual design

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Received: 14 June 2017 / Revised: 10 September 2017 / Accepted: 12 September 2017 / Published online: 19 September 2017

Abstract In new product development, the rapid proposal of innovative solutions represents an important phase. This in turn relies on creative ideas, their evaluation, refinement and embodiment of worthwhile directions. This study aims to describe a CBDT based process model for product conceptual design that concentrates on rapidly generating innovations with the support of decision-making rationale. Case-based decision theory (CBDT), derived from case-based reasoning, is applied in this paper as a core method to aid design engineers to make an informed decision quickly, thus accelerating the design process. In the process of utilizing CBDT to support a decision, as for the similarity function, the proper value assignment methods to the selected attribute set for calculation are discussed. In order to assist with innovative solution, aspects of the theory of inventive problem solving (TRIZ) are integrated into the case-based reasoning process. Accordingly, a CBDT-TRIZ model is developed. Quality-function deployment is used to translate customer wants into relevant engineering design requirements and thus formulating the design specification. Image-Scale is used to offer an orthogonal coordinates system to aid evaluation. Finally, a case study is used to demonstrate the validity of the proposed process model based on the design of a cordless hand-tool for garden and lawn applications.

Keywords Product conceptual design · Decision-making · Case-based decision theory (CBDT) · Theory of inventive problem solving (TRIZ)

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1 Introduction

Speed to market and innovation are two of the most important factors that enable a manufacturer to be competitive. These two attributes can be contradicting, forcing compromises. A common activity which can benefit both attributes is speeding up the decision-making process. Decision-making occurs in many places within the design process from task clarification, specification definition, conceptual design, to embodiment design [1–4]. Decision-making and creativity play an important role in conceptual design [5–9] and this phase also tends to be time-consuming within an engineering product development cycle [10,11].

According to Wallace and Blessing [12] three related issues that need addressing in design research include: an overview of existing research; the lack of use of results in practice; and the lack of scientific rigor. Literature related to product concept design is relevant as it can help inform on how ideas are formulated, considered, evaluated and refined. Conceptual design is a critical phase during the design process, which can starts with design specifications, and ends with design solutions or concepts [1,2,6–8,10]. Conceptual design methods proposed in the literature can be classified into three categories based on focal points and tools used: (1) design models according to the design criterion of the product, such as the Axiomatic Design (AD) model proposed by Suh [13], the Technology System Forecasting model proposed by Mann [14]; (2) design models based on design strategies of product, such as the Function–Behaviour–Structure (FBS) model proposed by Gero and Kannengiesser [15], and the attribute-based decision-making model proposed by Wang [16]; (3) design models adopting artificial intelligence, such as the case-based reasoning model proposed by Madhusudan et al. [17], Tran et al. [18], Hassaniena et al. [19], Cho et al. [20], and the BRIGHT Process integrated with TRIZ proposed by Tsai and Childs [21], and Chechurin and Borgianni [22]. Speed and innovativeness are two key factors for the manufacturer or company, and the optimization of the decision-making process can satisfy these two attributes simultaneously. For design models based on design strategies of product, i.e. type (2), conceptual design can be regarded as a decision-making process, and the innovation process for the product can be implemented through various design strategies among design units [23–25]. There, the process model is developed by regarding the conceptual design process as a decision-making process.

To speed up design efficiency, product designers can choose to reuse past experiences to support decision making during the design process, which simplifies the cognitive task of creation to selection [26,27]. Coming from artificial intelligence (AI), case-based reasoning (CBR) is an approach to manage knowledge. The main principle in CBR is that similar problems have similar solutions [28], which is closer to the thinking model of the designer. Many researchers (e.g. Cho et al. [20], Ishikawa and Terano [29], Lee and Lee [30], Wu et al. [31], Jung et al. [32]) have applied CBR to provide decision support for designers and engineers during the conceptual design process of new product development projects. However, a criticism that can be levied is that CBR pays too much attention to the similarity between the new problem and existing cases while ignoring the human factor. CBDT which was established on the basis of CBR was proposed by Gilboa and Schmeidler [33], Pape and Kurtz [34], Yang et al. [35]. CBR and CBDT can both be helpful to assist the designer in rapidly acquiring solutions based on past experiences. However unlike CBR, CBDT considers not only the similarity between the new problem and existing cases, but also the utility of existing solutions effect on the new problem by means of evaluation. The problem solving process is more plausible as it is formed by both subjective and objective assessment. In addition, during the retrieval process, CBR just concerns the problem description, while CBDT concerns both the problem description and the solution involved in every case. Wang et al. [36] proposed a case-based decision (CBD) model at the background of product conceptual design. Focusing on the rationale analysis, they discussed the similarity calculation function on the basis of Euclid Distance, but they did not mention about attribute scope selection for the similarity calculation, as well as the dimensional effect of different attributes. However, these two aspects are significant for the results of the similarity calculation.

In this paper, a CBDT-based problem resolution model to support decisions during product conceptual design is proposed. In CBDT, the problem solving process is based on past solutions. Therefore, design may be accelerated but creativity limited to that experience and not necessarily stimulated. When facing an innovative problem (TRIZ regards a problem which includes at least one contradiction as an innovative problem), CBDT will be unable to propose a solution. The situation can be avoided by introducing TRIZ which can change the level of abstraction of the problem resolution. TRIZ has been described as a set of theoretical and methodological elements assisting the resolution of creative problems [37] and a short cut to experience. It has the capacity to considerably restrict the research space for innovative solutions and allows the passage from routine design to inventive design [38–41]. Accordingly, a CBDT-TRIZ model is proposed for rapidly undertaking innovative solution generation. With the CBDT-based problem resolution model and the CBDT-TRIZ model, we are able to address most of the decision issues during conceptual design, to solve ordinary decisions and rapidly give satisfactory solutions. In addition, Quality-function deployment (QFD), Image-Scale, and parametric modelling are integrated with those two models to formulate a complete process model to aid the conceptual design process. QFD is used to translate customer wishes into relevant engineering design requirements and thus formulating the design specification. Image Scale is used to offer an orthogonal coordinates system to aid evaluation, and parametric modelling is used to realize the design scheme by giving a solid model.

In Sect. 2 of this paper the methodological approach used in the research is introduced. Section 3 presents the overall process model for aiding conceptual design. Section 4 describes the CBDT-based model for general decision problem resolution during the conceptual design process, and the CBDT-TRIZ model for rapidly generating innovative solution. Section 5 seeks to provide some evidence for verification of the proposed overall conceptual design process model by means of a case study on the design of a cordless hand-tool.

2 Methodological approach

The overall approach taken in this research is aligned with Design Research Methodology (DRM). Some objectives of DRM are as follows: (1) to provide a framework for design research for individual researchers and teams; (2) to provide guidelines for more rigorous research; (3) to help select suitable methods and combinations of methods; (4) to provide a context for positioning research projects and programmes relative to other design research; and (5) to encourage reflection on the applied approach [42]. The relationship between the DRM and the methodology developed in this paper is illustrated in Fig. 1.

The DRM methodology consists of four stages, namely Research Clarification, Descriptive Study I, Prescriptive Study, and Descriptive Study II, see Fig. 1.

The first stage—research clarification, is to find the problem to discuss, and form a practical and valuable research goal. In this paper, goal and success criteria have been identified as improving the speed and innovativeness of product design.

The second stage—Descriptive Study I, is to thoroughly understand the problem determined in the first stage mainly through design practice observation. In this paper, the product conceptual design process is considered as a series of decision-making processes, and the means to achieve the research goal we determined is to optimize the decision-making process.

The third stage—Prescriptive Study, is to develop specific means to achieve the research goal and as a result to support design. Here, a CBDT based process model is proposed, and different methods and tools are organized properly to formulate the complete product conceptual design process model.

The fourth stage—Descriptive Study II, is to implement the specific means on design practice. In this study a case study was developed to verify the feasibility and the effectiveness of some aspects (such as the speed and innovativeness of the product design).

DRM is not a rigid and linear design science research methods, according to the practical needs, researchers can choose any one stage as a starting point, or focus on one or a few stages, or to join the corresponding iterative process.

3 An integrated process model for product conceptual design

In this paper, we regard the product conceptual design process as a series of decision-making activities to construct the process model, and simultaneously bearing the notion of customer-driven design. Then the process, as shown in Fig. 2, can be considered to include three main parts: (1) Design specification formulation. (2) Obtain solution through decision resolution. (3) Design embodiment. Part (2) is critical and the focus of attention here for that it is where most of the decision-making activities happen. In addition, how to optimize the decision-making process is also developed in this part.

Part (1)—design specification formulation

Usually, customer needs are the source and motive for product conceptual design. Each engineering design characteristic is maximized for product performance according to the level of customer satisfaction [43,44]. Therefore, the first step is to listen to voice of customers, thus acquiring customer needs of the product.

In order to realize customer-driven design, a way to integrate customer needs into the design process should be determined. QFD is a cross-functional planning methodology commonly used to ensure that customer expectations or requirements, often referred to as the voice of the customer, are deployed through product planning, part development, process planning and production planning [45]. Normally, it has four phases, and the first phase of QFD begins with the identification of customer requirements and their mapping into relevant engineering design requirements. The second phase of QFD can convert relevant engineering design requirements and into the components characteristics. In addition, these components can be ranked according to their importance degree. In this paper, we only implement the first two phases of QFD to process the customer needs.

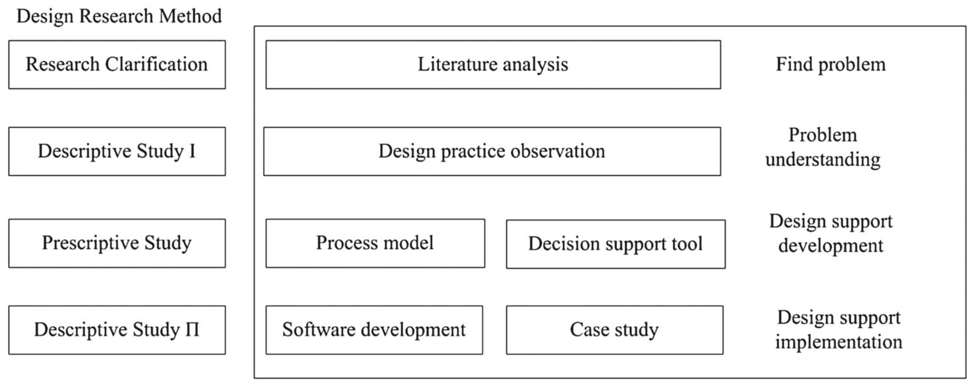
In any activity the specification is fundamental, as it should describe every attribute of every component of the product in unambiguous terms. It is based on the customers' perceived need and not on an in-house idea. When the design specification has been written, about 10% of the project spend will have been incurred but over 80% of all the project costs will have been determined. After the implementation of the second phase of QFD, the design specifications can be determined accordingly.

Part (2)—obtain solution through decision resolution

In this part, the main task is to complete the conceptual design of each component of the product through a series of decision problem resolution. The sequence of components design is arranged according to their importance degree which is obtained in the second phase of QFD analysis. Here, the decision problem is considered to have two types: general decision-making and decision-making related to innovative problem. For the two types of decision problem, a CBDT-based model and a CBDT-TRIZ model are respectively proposed for the resolution.

The CBDT-based model is a general method to support decision-making activities during product conceptual design. The model explores the advantage of case-based reasoning, as well as the utility evaluation to support decision problem resolution during product conceptual design process. However, some details, including case representation, index, evaluation criteria on decision results and similarity calculation between cases and target problem should be determined to make the application of CBDT more properly under the background of product conceptual design.

Fig. 1 Methodological diagram



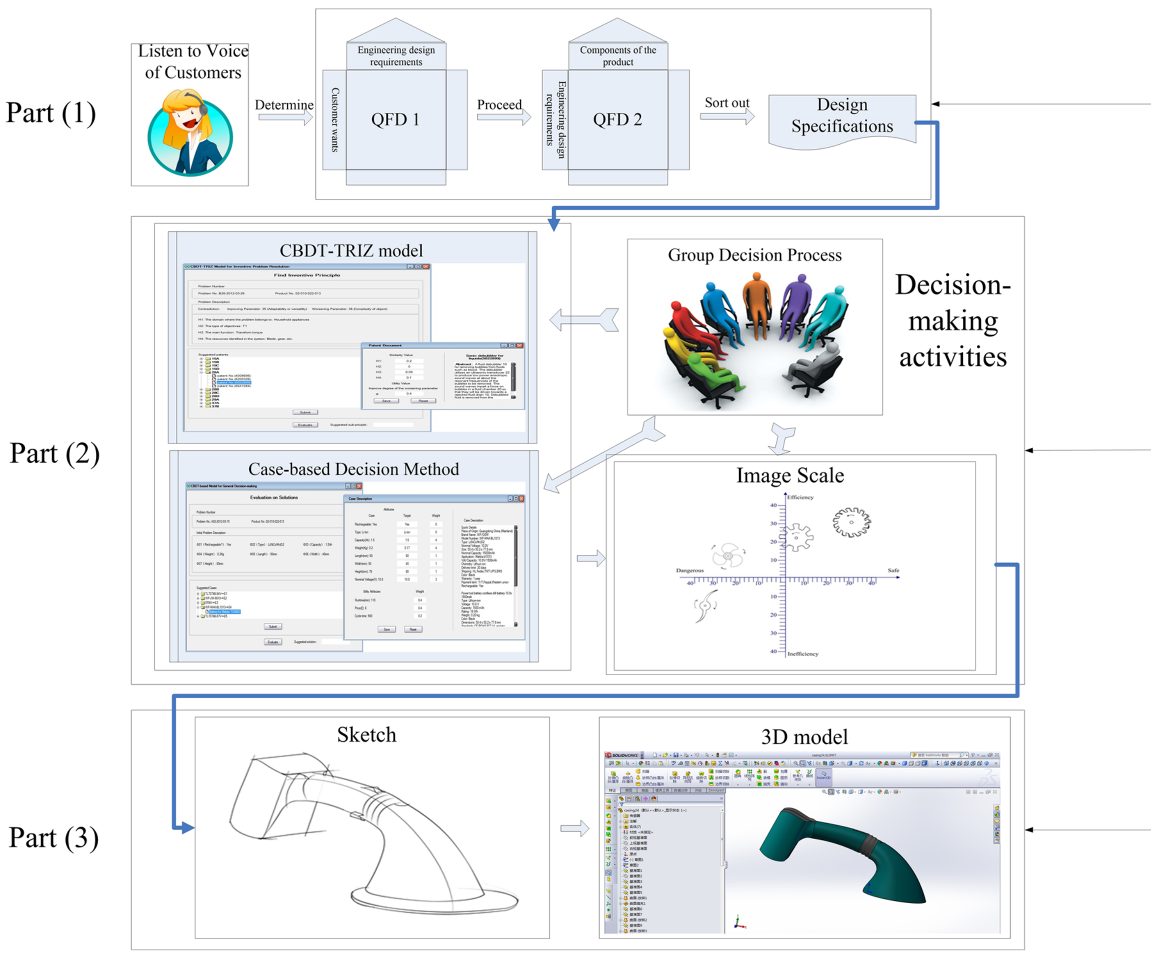


Fig. 2 The process model for product conceptual design

To improve the speed of decision-making and provide satisfactory solution, the CBDT-based model needs to be effective for general decision-making activities during the product conceptual design. However it is very limited for solving a decision problem concerned with a contradiction and accordingly proposing an innovative solution. Based on the CBDT-based model, as well as the synergy of CBDT and TRIZ, a CBDT-TRIZ model is developed specially for rapidly innovative solution generation. In addition, after the case-based decision method and the CBDT-TRIZ model have proposed a satisfactory solution, it is possible that several design schemes can be generated according to the same solution. Image scale, which provides an intuitive measurement, can help product designers to make a final decision.

In Fig. 2, "Case-based Decision Method" represents the software developed according to the CBDT-based model, and "CBDT-TRIZ model" represents the software developed according to the CBDT-TRIZ model. In this part, product designers can utilize these two models to help for most of the decision-making activities which the output are design solutions of parts or products. "Image Scale" is the method used to offer an orthogonal coordinates system to aid evaluation when it is needed. "Group Decision Process" could be implemented in all of the decision-making activities.

Part (3)—design embodiment

Design embodiment involves elaboration and detailing of aspects of the design (See Fig. 2). This can involve sketching and exploration of ideas and product form, followed by more detailed consideration of specific features and components.

4 The CBDT-based model and CBDT-TRIZ model to support decision-making

4.1 Fundamental of CBDT

The CBDT method which builds up the connection of solved problems and the problem to be solved was proposed by Gilboa and Schmeidler [33]. The application of the CBDT method depends on not only the similarity between the target problem and memory problems which retrieved from the database through specified index, but also the utility of every solution. The function to evaluate every solution can be given as below [36], and for all the solutions, the maximizer of the function is usually to be chosen.

$$U(a) = U_{q,M}(a) = \sum_{(q,a,r)\in M} \sigma_q(q_0, q_i)\left(\sum_{(q,a,r)\in M} \sigma_q(q_0, q)\right)^{-1} \cdot u(r) \quad (1)$$

where (q, a, r) represents a case, q, a and r, respectively represents the decision problem, the solution to the decision problem, and the result that was obtained. M is the memory. $\sigma_q(q_0, q_i)$ is the similarity between the target problem q_0 and a memory problem q_i.

4.2 The CBDT-based model

The CBDT-based model is a general method to support decision-making activities during product conceptual design, including the process of utilizing CBDT to support decision during product conceptual design and methodologies used during the process, such as case representation, index, evaluation criteria and similarity functions.

4.2.1 The process of utilizing CBDT to support decision

The process of utilizing CBDT to support decision during product conceptual design is shown in Fig. 3.

The process is described as follows:

(1) Determine the design task: Determine which component is to be discussed.
(2) Problem description: Use a problem vector to describe the task.
(3) Determine the attributes for index: Choose several main attributes from the problem vector and a proper mechanism as the index to retrieve similar cases.
(4) Retrieve similar cases according to the chosen index.
(5) Classify cases into case sets: According to retrieved similar cases, several solutions can be summarized to discriminate cases. During the process, similar solutions are regarded as the same. Then, retrieved similar cases will be classified into case sets, and each case set shares the same solution.
(6) Similarity calculation and utility evaluation on results: Calculate the utility of the decision results of these similar cases with proper evaluation criteria and the similarity between the target problem and cases with proper similarity function.
(7) Evaluation on solutions: Use function (1) to evaluate each solution.
(8) Obtain satisfactory solution and related cases: For all the solutions, the maximizer of function (1) is to be chosen as the satisfactory solution. Meantime, related cases can be referenced to help design.

4.2.2 Methodologies used during the process

(1) Case representation

As for CBDT, the central notion is a case. The case-base C is the set of products. The memory M contains all the finished products $\{c_1, c_2, \ldots, c_n\}$, where c_n denotes a case of product. Generally, a case in CBDT can be represented using the following three parts conceptually: problem description, solution description, and result. Suppose that there is a problem vector $\phi_i = (\phi_{i1}, \phi_{i2}, \ldots, \phi_{il})$ which denotes target product attributes, a solution vector $(\pi_{i1}, \pi_{i2}, \ldots, \pi_{ih})$ which denotes the technology attributes of the solution, and a utility attribute vector $(\gamma_{i1}, \gamma_{i2}, \ldots, \gamma_{ig})$ which denotes the utility attributes for each case's result evaluation, where φ_{il}, π_{ih} and γ_{ig} respectively denotes the value of each product attribute, technology attribute, and utility attribute. Then each case can be expressed as $c_i(\phi_i, \pi_i, \gamma_i)$, including product, technology attributes and utility attributes.

(2) Index

Indices are features which discriminate between cases. An index may point to a more specific set of cases, or directly to

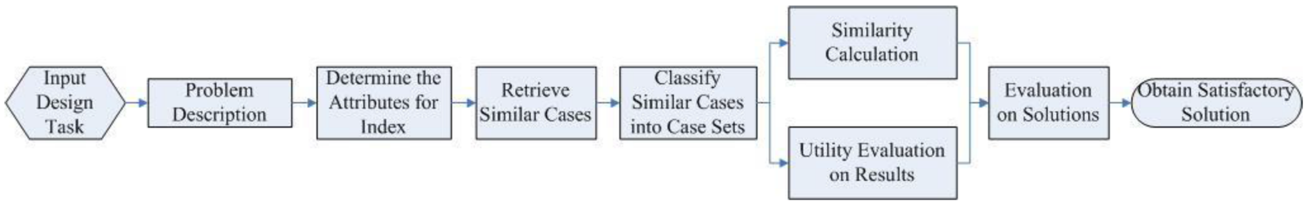


Fig. 3 The process of utilizing CBDT to support decision during product conceptual design

a case. Choose certain product attributes from the problem vector and corresponding mechanism as the index. Retrieve similar cases according to the index, which generally we can achieve it through cluster analysis, for that cluster analysis is helpful in identifying groups that both minimize within group variation for data in a cluster and maximize between-group variation to identify potential differences between clusters [46].

(3) Evaluation criteria

Suppose the utility attributes of case c_i are $(\gamma_{i1}, \gamma_{i2}, \ldots, \gamma_{ig})$, then the evaluation criteria can be represented as below:

$$g(c_i) = \sum_{e=1}^{g} \beta_e \cdot g_e(\gamma_{ie}) \tag{2}$$

where $\beta(\beta_1, \beta_2, \ldots, \beta_g)$ is the weight vector of $(\gamma_{i1}, \gamma_{i2}, \ldots, \gamma_{ig})$, and $g_e(\gamma_{ie})$ is the utility function of γ_{ie}.

(4) Similarity function

Normally in actual product design activities, the similarity between a target problem and a stored case is measured by the accumulated similarities on all counted attributes. On the one hand, the similarity is influenced by the counted attribute scope. On the other hand, the similarity is also influenced by different methods to calculate the similarity on each attribute. Accordingly, we will discuss attribute scope determination and methods to calculate the similarity on each single attribute respectively as below:

A. Attribute scope determination

The similarity measurement between a new problem and a stored case is based on the comparison of the problem description part of them. In our research, we assume that the problem description of a case takes the form of a set of $<$ attribute, value $>$ pairs. It is not necessary for both a new problem and a case to have the same attribute set. We further define that:

Np: set of attributes appearing in a new problem

Nc: set of attributes appearing in a stored case

One concept that is closely related to similarity is distance. The greater the distance between a new problem and a stored case, the less the similarity between them is. The main use of the similarity measurement in case-based reasoning is to sort the retrieved cases. From that point of view, the similarity and distance measurements have an inverse relationship, and either of them may be chosen. We adopt the distance measurement in our research, as defined by the following formula [47].

$$d_{(p,c)} = \sqrt{\sum\nolimits_{\phi\in\phi s} \omega_\phi d_\phi^2(p_\phi, c_\phi) / \sum\nolimits_{\phi\in\phi s} \omega_\phi} \tag{3}$$

where p, c, ϕ, ϕs and ω_ϕ respectively denote a new problem, a stored case, a particular attribute, a selected attribute set and the weight for the attribute ϕ respectively. In addition, $d_\phi(p_\phi, c_\phi)$ is a function used to compute the difference between a new problem and a stored case on an attribute ϕ. Then the similarity $s_{(p,c)}$ between a new problem and a stored case is defined by the following formula.

$$s_{(p,c)} = \frac{1}{d_{(p,c)}} \tag{4}$$

where $d_{(p,c)} \neq 0$. When $d_{(p,c)} = 0$, a new problem p is considered as the same as the stored case c.

Nominal attributes of the problem vector are always basic goals for new product design. We suppose these nominal attributes to be chosen for the index in the search, and other nominal attributes will be ignored as they make no difference on the whole evaluation process of CBDT. Therefore, after similar cases were retrieved through the index, the similarity evaluation between target problem and retrieved similar cases accordingly is developed among numerical attributes. Then $d_\phi(p_\phi, c_\phi)$ is defined as following in our research.

$$d_\phi(p_\phi, c_\phi) = \begin{cases} |p_\phi - c_\phi|, & \phi \text{ is a numerical attribute} \\ 1, & p \text{ or c has missing value on } \phi \end{cases} \tag{5}$$

Based on different types of value assignment methods to $\phi s(\phi s = Np, \phi s = Nc, \phi s = Np \cup Nc)$, in Function (3), the distance value in case-based reasoning will be different, and the result will influence the decision a lot. An example is given below, suppose there is a new problem and 4 similar cases, their problem vectors are shown in Table 1, and suppose that each attribute has the same weight. The distance measurement through different methods is shown in Table 2.

Table 1 Example-problem vectors of the new problem and 4 similar cases

	Attribute 1	Attribute 2	Attribute3	Attribute 4
New problem	0.4	0.5	0.7	
Case 1	0.4	0.5		
Case 2	0.4	0.6	0.2	
Case 3	0.4	0.6		
Case 4	0.4	0.6	0.2	0.5

Table 2 Example-distance measurement through different methods

	Case 1	Case 2	Case 3	Case 4
$\phi s = Np$	0.577	0.294	0.580	0.294
$\phi s = Nc$	0	0.294	0.070	0.561
$\phi s = Np \cup Nc$	0.577	0.294	0.580	0.561

For example, when we assign $\phi s = Np$, the distance measurement function will be $d_{(p,c)} = \sqrt{\sum_{\phi \in Np} \omega_\phi d_\phi^2(p_\phi, c_\phi) / \sum_{\phi \in Np} \omega_\phi}$, For case 1, according to Function (5) the distance between itself and the new problem related to attribute 1, attribute2, attribute 3 respectively is 0, 0, 1. The weight of attribute 1, attribute2, attribute 3, can all be assigned with 1. Then the distance between case 1 and the new problem can be computed as below:

$$d_{(p,c_1)} = \sqrt{(1 \times 0^2 + 1 \times 0^2 + 1 \times 1^2)/(1+1+1)} = 0.577.$$

So we need to take care with the value assignment methods for ϕs, according to the specific situation.

Scenario Building

After similar cases have been retrieved through the index, the similarity evaluation between target problem and retrieved similar cases can be developed. The attribute set of a stored case may be different from other cases. In design practice, after acquiring customer needs and QFD analysis, a designer generally knows the goal of a new product. If you propose an attribute, then designers can give a range of the value they wish the new product to achieve, but when the designer started the similarity evaluation, he/she did not know which attributes to give, so he/she just can initially give several attributes to stimulate the process. Following this process an experiment to verify which method is suitable can be undertaken.

Initial experiment design

The experiment set up here is designed with the objective to compare the ability of finding effective cases using different assignment methods to ϕs. Here, we use $F(2)$-value [48] in our experiments to evaluate the performance of different assignment methods to ϕs ($\phi s = Np$, $\phi s = Nc$, $\phi s = Np \cup Nc$).

$$F(2) - Value = \frac{(1+2^2)\,\mathrm{Pr}\,ecision^{*}\mathrm{Re}call}{2^2\mathrm{Re}call + \mathrm{Pr}\,ecision} \tag{6}$$

where Pr*ecision* is the fraction of effective cases which determined in the experiment among the retrieved cases, Re*call*is the fraction of the effective cases that have been retrieved over the total amount of the effective cases.

In the experiment, we use many sets of restricted random number to simulate the process. In the experiment, we determine that the full description of the target problem related topic consisted by 10 attributes, and the value of each attribute obeys normal distribution $N(0.5, 0.2^2)$ and is generated randomly between the interval (0,1). According to the supposed scenario, at the beginning of every trial of the experiment, we should firstly generate a full description of the target problem, namely 10 attributes all with assigned value, but only N ($N = 5, 6, 7$) attributes are chose for initial description. Then randomly generate 50 pieces of record, every record consists by any $M \sim 10 (M = 7, 8)$ attributes of the 10 attributes, and represents a retrieved similar case.

Experiment process

We implemented our experiment with Matlab, and according to the value of N and M, 6 groups of trials (Here we denote a trial as the process from Step 1 to Step 4) should be carried out. For each group, the experiment is developed as below:

Step 1: Determine the value of N and M.

Step 2: Generate the full description of the target problem and 50 pieces of record which represent 50 retrieved similar cases.

Step 3: Determine the effective cases and tag all the cases with their ranked sequence.

Step 4: Under the premise of the determined value of N and each attribute has the same weight, continue the trial with the generated full description of the target problem and 50 pieces of record which represent 50 retrieved similar cases. Find the first $K (K = 5, 10)$cases which are more closely to the target problem when assign ϕs as $\phi s = Np$ or $\phi s = Nc$ or $\phi s = Np \cup Nc$. According to the tag of each case, see how many effective cases are found, and respectively calculate the value of Pr*ecision* and Re*call* under different assigned ϕs.

Step 5: Repeat Step 2 to Step 4 for 10 times, for different assigned ϕs, regard the average value of the Pr*ecision* and Re*call* calculated through 10 times as the final Pr*ecision* and Re*call* value.

Effective cases determination

For each trial of the experiment, effective cases will be redetermined. In each trial, after the full description of the target problem and 50 pieces of record which represent 50 retrieved similar cases were generated, 1-NN algorithm is adopted to calculate the distance between the target new problem and a retrieved similar case, while ϕs is assigned as $\phi s = Np \cup Nc$. Then 50 similar cases can be ranked by the distance value, and the minimum will be ranked as 1. Every case will be tagged with the ranked sequence. Here, we define cases which ranked at the first five as effective cases.

Experiment results

The experiment results are listed from Tables 3, 4, 5, 6, 7, and 8. According to the results, we can see that $\phi s = Nc$ is more suitable to the supposed scenario.

B. Dimensional effect elimination

Generally, the final attribute set for similarity calculation includes attributes which their units are very different, and so are the numerical values. Thus calculated distance through simply subtraction related to each attribute can't perform the real contribution to the similarity. Here we use function (7) and (8) to eliminate the dimensional effect. Function (7) is for attributes which adopts accurate number value, and Function (8) is for attributes which adopts interval value. Function (7) and Function (8) are the specific implementation of Function (5) for different concrete situations.

$$d_\phi(p_\phi, c_\phi) = \frac{|c_\phi - p_\phi|}{\theta - \alpha}, \quad c_\phi, p_\phi \in [\alpha, \theta] \tag{7}$$

$$\begin{aligned} d_\phi(p_\phi, c_\phi) &= \left|\frac{a_1 + a_2}{2} - \frac{b_1 + b_2}{2}\right| \\ &\quad + \left|\frac{b_2 - b_1}{2} - \frac{a_2 - a_1}{2}\right| / (\theta - \alpha), \\ p_\phi &= [a_1, a_2] \in [\alpha, \theta], \quad c_\phi = [b_1, b_2] \in [\alpha, \theta] \end{aligned} \tag{8}$$

In function (7) and (8), α and θ respectively represents the lower limit and upper limit of each attribute.

4.3 The CBDT- TRIZ model for rapid innovative solution generation

Based on the framework of the CBDT-based model, a CBDT-TRIZ model is proposed for innovative problem (a problem which includes at least one contradiction) resolution. This exploits the synergy of CBDT and TRIZ. CBDT provides a means to model knowledge, a memory to store cases and a mechanism to reference past experience. TRIZ offers the ability to eliminate barriers between technical domains and consequently to propose inventive solutions. The CBDT-TRIZ model adopts the same process as that shown in Fig. 3, utilizes the contradiction matrix in TRIZ as the index for CBDT to find similar cases and discriminate cases, and utilizes CBDT to evaluate solutions suggested by the contradiction matrix. Some important issues, including problem description, index, case sets categorization, utility evaluation on decision results and similarity calculation are specially developed.

(1) Problem description

Here, the problem description is similar to that given in [49], but ignoring the attribute-"the goal to reach", which means this attribute will not be used for similarity calculation.

(2) Contradiction as the index

The 39×39 contradiction matrix proposed by Altshuller [50] and his colleagues is referred as the index here. Designers can use the contradiction formulation (problem formulation)-(worsening parameters, improving parameters) to find ways to solve it (principles) which indicated through the matrix.

(3) Classify cases into some case sets.

40 principles in TRIZ are detailed in sub-principles in order to increase their efficiency. These sub-principles can be regarded as the standard solution vector for the classification of similar cases.

(4) Utility evaluation on decision results.

For contradiction resolution, the conflict resolution degree should be concerned. According to TRIZ, a contradiction is expressed with two of the 39 parameters (an improving parameter and a worsening parameter), and the main purpose of conflict resolution is to improve the performance of the worsening parameter while not hurting the improving parameter. Here, we can regard the conflict resolution degree as the utility of decision results, and the value of the conflict resolution degree is given by experts through evaluating the performance of these two parameters. The value of the conflict resolution degree is processed in [0, 1], and 1 represents the best performance of the conflict resolution.

(5) Similarity calculation.

For this part, the similarity function is similar to that given in [49], the difference is that the attribute-"the goal to reach" is counted out for the similarity calculation. Accordingly, the weight is assigned among the remaining four attributes. The local similarity related to each remaining attribute is the same as that given in [49].

Table 3 Simulation results ($N = 5, M = 7$)

	Recall ($K = 5$)	Precision ($K = 5$)	$F(2)$-value ($K = 5$)	Recall ($K = 10$)	Precision ($K = 10$)	$F(2)$-value ($K = 10$)
$\phi s = Np$	0.38	0.38	0.38	0.54	0.27	0.3
$\phi s = Nc$	0.44	0.44	0.44	0.6	0.3	0.33
$\phi s = Np \cup Nc$	0.3	0.3	0.3	0.32	0.16	0.18

Table 4 Simulation results ($N = 6, M = 7$)

	Recall ($K = 5$)	Precision ($K = 5$)	F(2)-value ($K = 5$)	Recall ($K = 10$)	Precision ($K = 10$)	F(2)-value ($K = 10$)
$\phi s = Np$	0.4	0.4	0.4	0.6	0.3	0.33
$\phi s = Nc$	0.42	0.42	0.42	0.62	0.31	0.34
$\phi s = Np \cup Nc$	0.24	0.24	0.24	0.46	0.23	0.26

Table 5 Simulation results ($N = 7, M = 7$)

	Recall ($K = 5$)	Precision ($K = 5$)	$F(2)$-value ($K = 5$)	Recall ($K = 10$)	Precision ($K = 10$)	$F(2)$-value ($K = 10$)
$\phi s = Np$	0.46	0.46	0.46	0.66	0.33	0.37
$\phi s = Nc$	0.44	0.44	0.44	0.6	0.3	0.33
$\phi s = Np \cup Nc$	0.28	0.28	0.28	0.54	0.27	0.3

Table 6 Simulation results ($N = 5, M = 8$)

	Recall ($K = 5$)	Precision ($K = 5$)	$F(2)$-value ($K = 5$)	Recall ($K = 10$)	Precision ($K = 10$)	$F(2)$-value ($K = 10$)
$\phi s = Np$	0.24	0.24	0.24	0.7	0.35	0.39
$\phi s = Nc$	0.56	0.56	0.56	0.9	0.45	0.5
$\phi s = Np \cup Nc$	0.16	0.16	0.16	0.58	0.29	0.32

Table 7 Simulation results ($N = 6, M = 8$)

	Recall ($K = 5$)	Precision ($K = 5$)	$F(2)$-value ($K = 5$)	Recall ($K = 10$)	Precision ($K = 10$)	$F(2)$-value ($K = 10$)
$\phi s = Np$	0.46	0.46	0.46	0.56	0.28	0.31
$\phi s = Nc$	0.6	0.6	0.6	0.62	0.31	0.34
$\phi s = Np \cup Nc$	0.36	0.36	0.36	0.38	0.19	0.21

Table 8 Simulation results ($N = 7, M = 8$)

	Recall ($K = 5$)	Precision ($K = 5$)	$F(2)$-value ($K = 5$)	Recall ($K = 10$)	Precision ($K = 10$)	$F(2)$-value ($K = 10$)
$\phi s = Np$	0.34	0.34	0.34	0.74	0.37	0.41
$\phi s = Nc$	0.58	0.58	0.58	0.82	0.41	0.46
$\phi s = Np \cup Nc$	0.18	0.18	0.18	0.54	0.27	0.3

Fig. 4 Existing hand-tool products

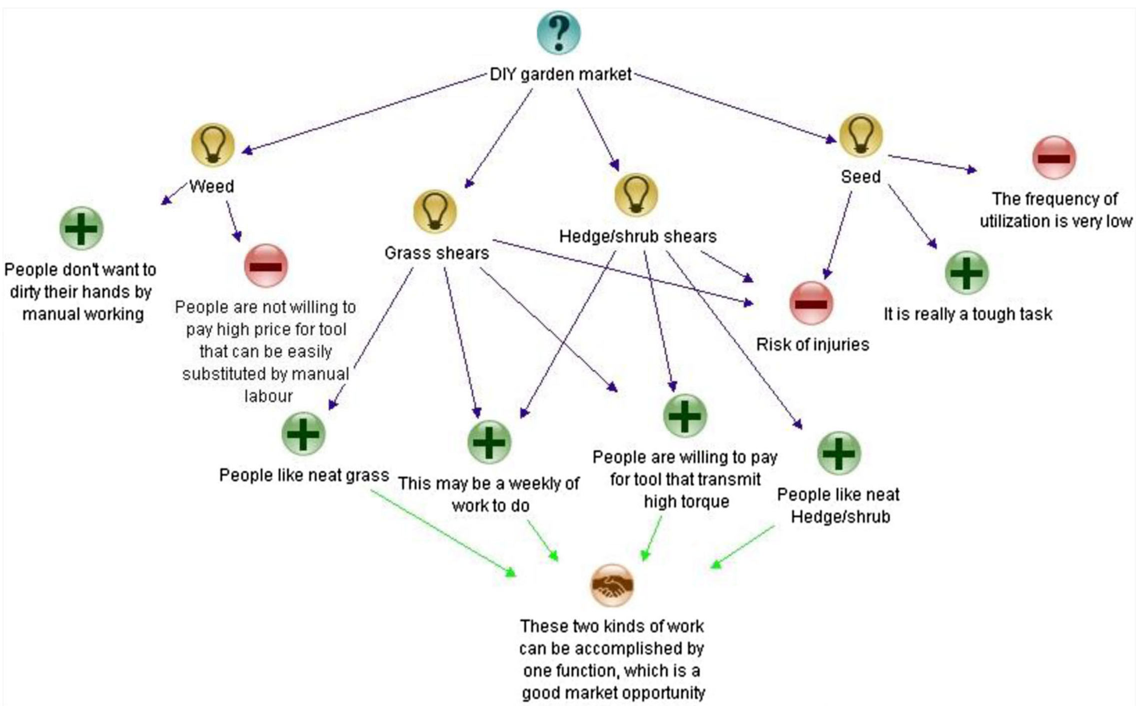
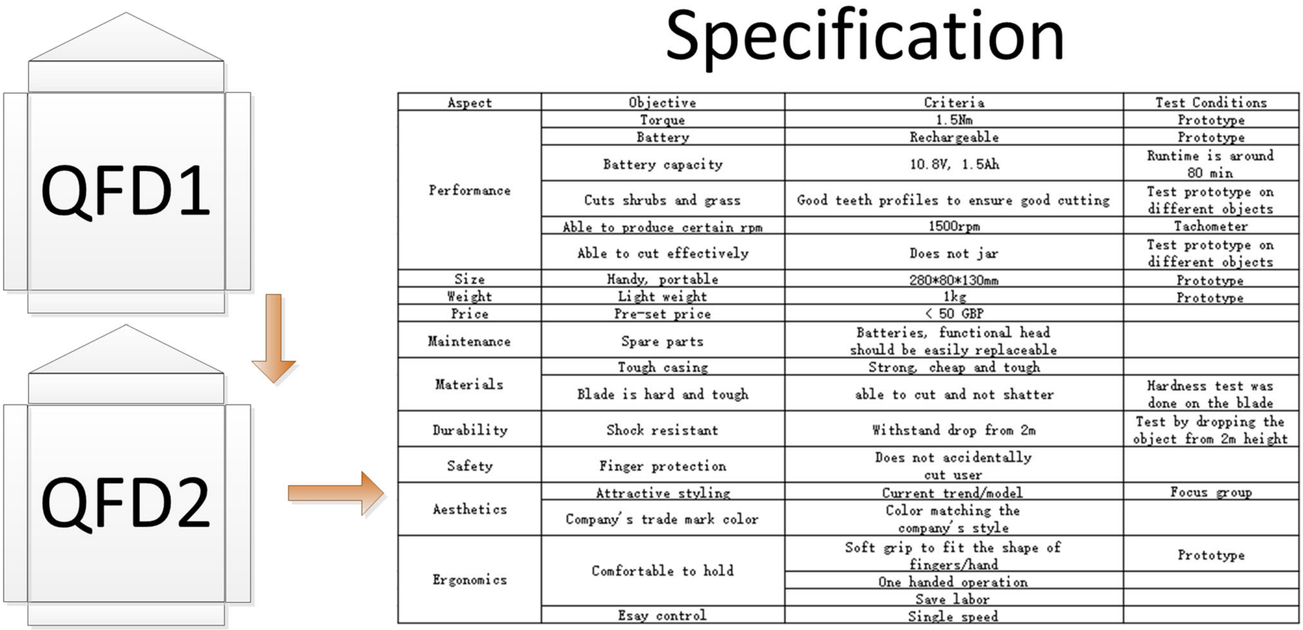


Fig. 5 IBIS map showing market analysis for DIY Garden tool

5 Innovative design for a hand-tool product

5.1 Description of the case

The aim of this case study was to design a hand-tool product for a lawn and garden hand-tool OEM based on components from two of their existing product lines. The project has been regularly set for the 2nd year of the Mechanical Engineering cohort of the MEng in Mechanical Engineering four year degree programme at Imperial College London over the last eight years, resulting in a substantial database of potential designs and knowhow. In this specific research study, the two hand-tools concerned have similar functions, as shown in Fig. 4, the longer functional head is for hedge/shrub shearing and the shorter functional head is for grass shearing. The OEM is an internationally recognized company and a multinational seller of tools in the DIY market, and is constantly searching for new and innovative designs for its product line.



Aspect	Objective	Criteria	Test Conditions
Performance	Torque	1.5Nm	Prototype
	Battery	Rechargeable	Prototype
	Battery capacity	10.8V, 1.5Ah	Runtime is around 80 min
	Cuts shrubs and grass	Good teeth profiles to ensure good cutting	Test prototype on different objects
	Able to produce certain rpm	1500rpm	Tachometer
	Able to cut effectively	Does not jar	Test prototype on different objects
Size	Handy, portable	280*80*130mm	Prototype
Weight	Light weight	1kg	Prototype
Price	Pre-set price	< 50 GBP	
Maintenance	Spare parts	Batteries, functional head should be easily replaceable	
Materials	Tough casing	Strong, cheap and tough	
	Blade is hard and tough	able to cut and not shatter	Hardness test was done on the blade
Durability	Shock resistant	Withstand drop from 2m	Test by dropping the object from 2m height
Safety	Finger protection	Does not accidentally cut user	
Aesthetics	Attractive styling	Current trend/model	Focus group
	Company's trade mark color	Color matching the company's style	
Ergonomics	Comfortable to hold	Soft grip to fit the shape of fingers/hand	Prototype
		One handed operation	
		Save labor	
	Esay control	Single speed	

Fig. 6 QFD analysis and specifications formulation

Table 9 Description of the contradiction problem related to the functional head

Attribute	Contradiction	H_1	H_2	H_3	H_4
Attribute value	(35,36)	Household appliances	T1	Transform torque	Blade, gear, etc
Weight		0.1	0.3	0.5	0.1

The main task was to conceive and develop a new functional head for a cordless hand tool which includes the adaptation of the existing handle, motor, battery and any other required components of the OEM's existing gardening power tools. In order to produce a new and innovative hand-tool that is market competitive, the first step is to do the market analysis. A market analysis is performed to find the most appropriate hand-tool to develop further. This analysis was captured in Issue-Based Information System format. As can be seen in Fig. 5, several proposals were considered, the final decision is to design a new product for both hedge/shrub and grass shearing with one functional head.

Based on the structure of the two existing product, the principle components list for the new product can be given as follows: Multiple part hand-held body; Functional head; Battery; Switch module; Motor; Power **transmission gearbox as appropriate; Charger.**

5.2 QFD analysis and specifications formulation

According to the proposed process model proposed in Sect. 3, we should firstly acquire the customer needs on the new product, and continue with QFD 1 and QFD 2 analysis. After that, the specification of the new product is formulated. The execution of the process is shown schematically in Fig. 6. In addition, the degree of importance of the parts from low to high order is: functional head; multiple part hand-held body; battery; switch module; motor; power transmission gearbox; charger.

5.3 Apply CBDT- TRIZ model for rapid innovative solution generation

According to the degree of importance, the design of the functional head is the primary focus as it defines the functionalities for the product. As shown in Fig 4, the two existing products both have two different functional heads respectively for grass shearing and hedge/shrub shearing, which result in two quality characteristics contradicting with each other. These two quality characteristics are "Complexity of the product" and "Cuts shrub and grass". The conflict can be translated into a standard TRIZ contradiction, where the improving parameter is 35 "Adaptability or versatility" and the worsening parameter is 36 "Complexity of object". The principles suggested by the contradiction matrix are **Principles** 15(Dynamics); 28(Mechanics Substitution); 29(Pneumatics and Hydraulics); 37(Thermal Expansion). These three inventive principles can be divided to 11 sub-principles in total according to [50].Then the full description of the contradiction problem can be given as in Table 9.

Table 10 Similar cases—related to sub-principle 15A

Case	Patent No.	H_1 (similarity value)	H_2 (similarity value)	H_3 (similarity value)	H_4 (similarity value)	g
c_1	5947791	Puppet toys (0.1)	T1 (1)	Replenish displacement (0.09)	Cloth, cotton, etc. (0.1)	0.1
c_2	6061835	Costume (0.1)	T2 (0)	Compact elastic-body (0.09)	Cloth, cavity, etc. (0.1)	0.3
c_3	6601472	Mechanical units (0.3)	T3 (0)	Absorb force (0.24)	Spring, bearing, etc. (0.4)	0.3

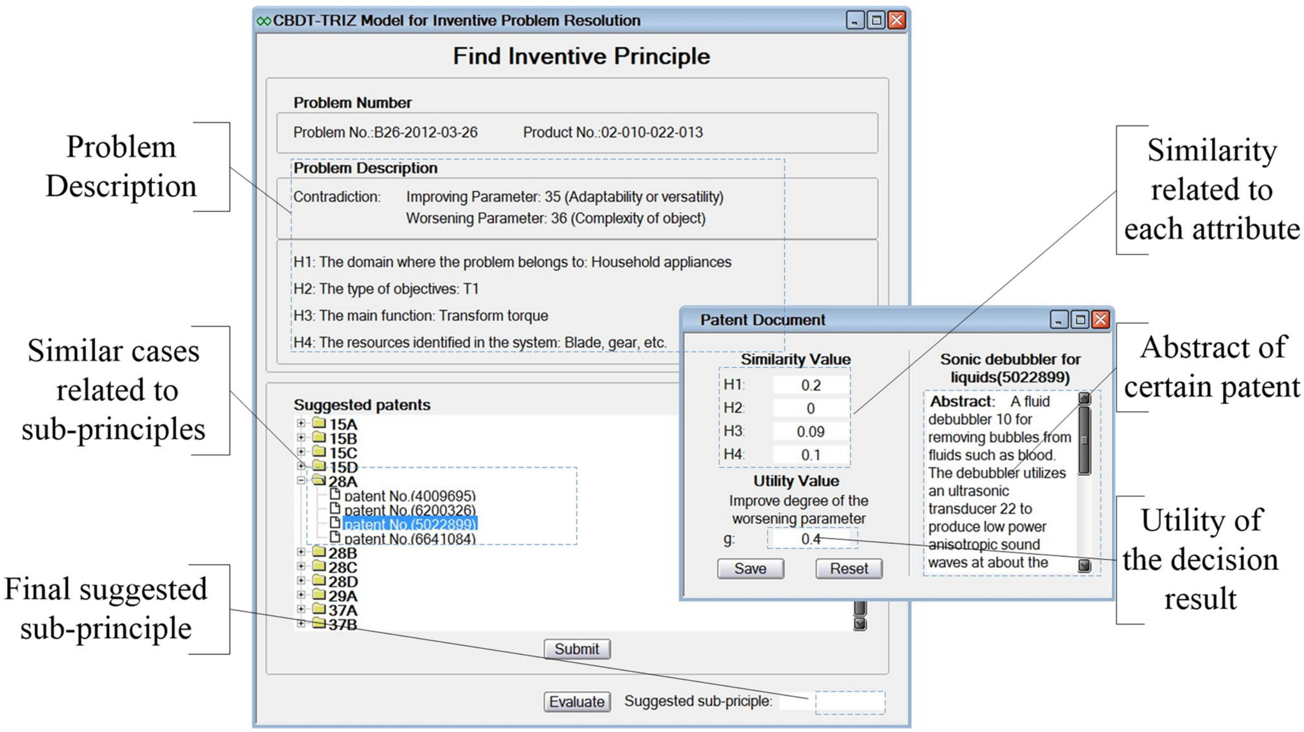
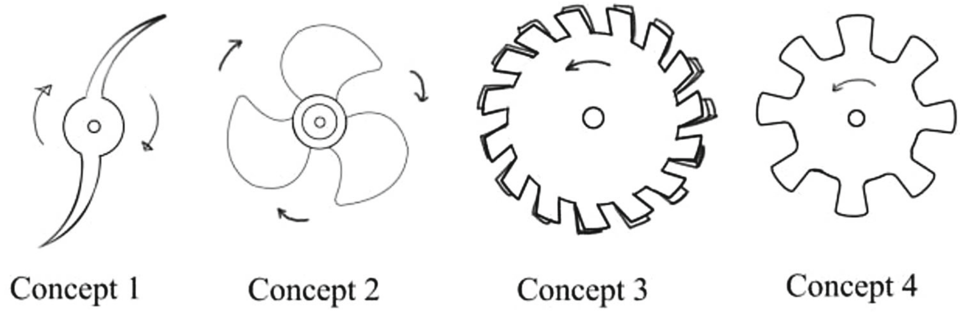


Fig. 7 Tool for finding inventive principle

According to the sub-principles, similar cases (these cases are all patents) are divided into 11 clusters (Here, cases are all collected from USPTO (United States Patent and Trademark Office) Patent Full-Text and Image Database). We use the patents related to 15A (Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition) which are shown in Table 10 to illustrate the evaluation process of each sub-principle. Table 10 presents the similar cases, with patents number, value of each attribute and calculated similarity value related to each attribute, utility of the decision result of each case-g. Here, the utility of the decision result of each case is given by experts through the evaluation of the performance of the improving parameter and the worsening parameter. A tool for finding inventive principle to support decision-making activities which involving innovative problem has been developed as shown in Fig. 7.

For c_1 (Case Description: Gender neutral doll body with replaceable photographic face), which comes from USPTO, its patent number is 5947791. According to the contents of the patent, properties are given: H_1- Puppet toys, H_2- T1, H_3- Replenish displacement, H_4- Cloth, cotton, rubber, etc. Similarity value related to H_1, H_4 and the utility of the decision result g are given by experts, and similarity value related to H_2 can be easily calculated through functions which are presented previously. For H_3, according to the functional basis by Hirtz et al, “Replenish” belongs to “Provision”,while “Transform” belongs to “Convert”, then sim_v is 0.3; “displacement” belongs to “Signal”, “torque” belongs to “Energy”, then sim_v is 0.3, so the similarity value

Fig. 8 Blade concepts



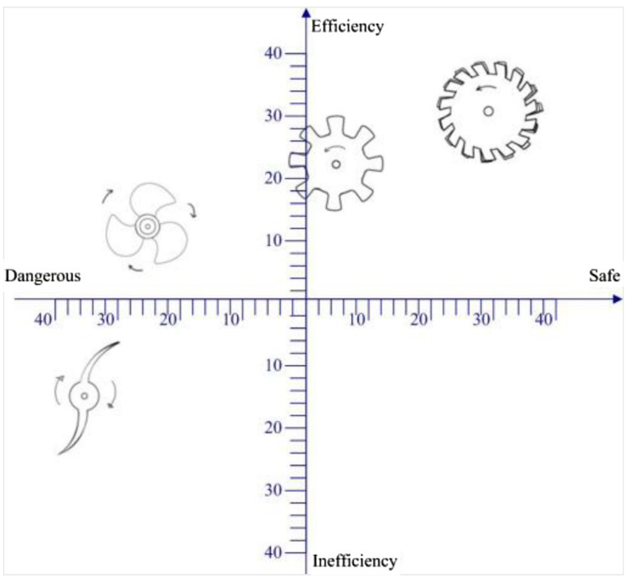


Fig. 9 Concept evaluation

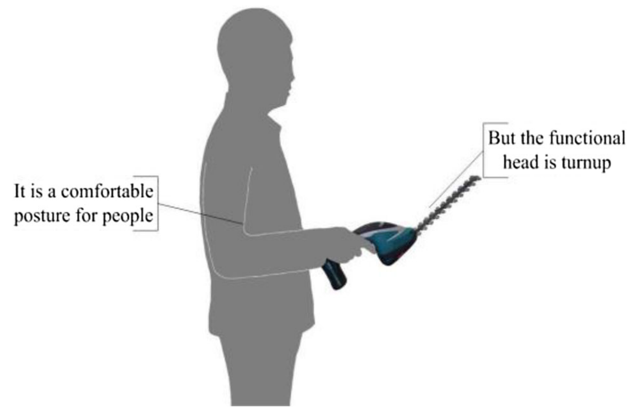


Fig. 10 Labor-saving posture

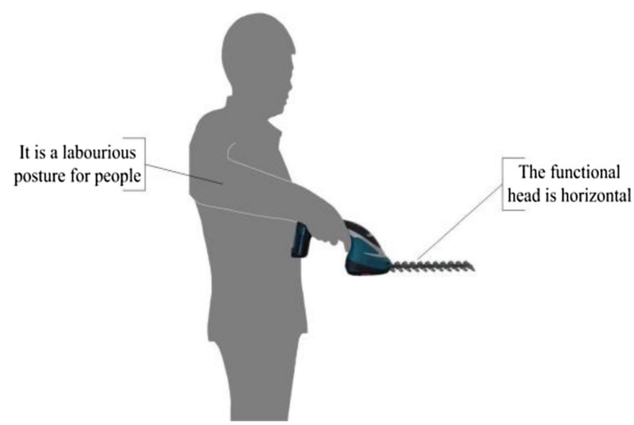


Fig. 11 Laborious posture

related to H_3 is 0.09. Combined with c_2 and c_3, the utility of the cluster sub-principle 15A can be calculated through function (1) which is 0.180.

With the help of the tool shown in Fig. 7, the evaluation of those 11 sub-principles can be developed. The final sub-principle suggested by the evaluation process is sub-principle 15D (Increase the degree of free motion). By referencing cases related to the sub-principle, a solution is given: the two different linear motions of the existing functional head of the handtools can be replaced by rotational motion. Four concept designs of blade are given in Fig. 8. These concept designs were evaluated by means of Image-Scale method as shown in Fig. 9. Two groups of factors: (Efficient, Inefficiency) and (Safe, Dangerous) are chose for the evaluation. According to Fig. 9, Concept 3 is the best, and it will be chose as the solution to the blade design.

The next concern is the multiple part hand-held body. "Convenience to use" is a very important customer need for the hand-held body, however as shown in Figs. 10 and 11, when the height of the shrub that we are shearing exceed a certain height, according to the existing products, it is a laborious work for people to cut the shrub in horizontal. There are also many other occasions that people cannot comfortably carry out their work. This relates to the contradiction between two quality characteristics: "Complexity of the product" and "Operation comfort". The conflict can be translated into a standard TRIZ contradiction, where the improving parameter is 36 "Complexity of object" and the worsening parameter is 33 "Convenience of use". The principles suggested by the contradiction matrix are Principles 9 (Preliminary Anti-Action); 24 ('Intermediary'); 26 (Copying); 27 (Cheap Short-Living Objects).

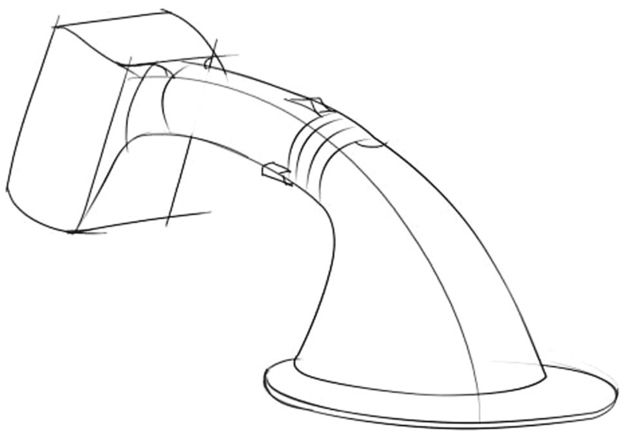


Fig. 12 Modification of hand-held body

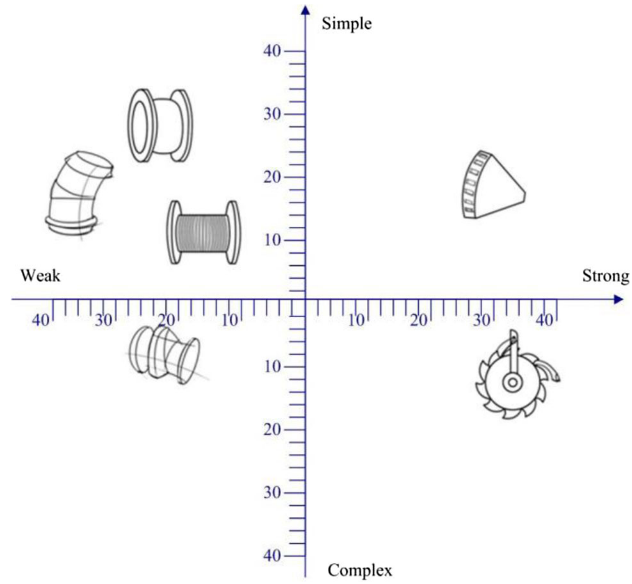


Fig. 14 Evaluation of concepts of the flexible joint

Suppose there is not a similar enough case related to these principles in the case-base. If so then the designer of designer can consider all of them. A possible solution is shown in Fig. 12: adding a flexible joint into the body. Accordingly, six concept designs of flexible joint are given in Fig. 13. These concept designs were evaluated by means of Image-Scale method as shown in Fig. 14. Two groups of factors: (Simple, Complex) and (Strong, Weak) are chose for the evaluation. According to Fig. 14, Concept 4 is the best, then it will be chose as the solution to the flexible joint design.

5.4 Apply CBDT-based model for general decision problem resolution

The specification for the battery is given in Table 11.

"Cordless hand-tool product", "Battery", "Rechargeable" and "Li-Ion" are used as index attributes to help designers find similar cases. Seven similar cases are found and their problem vectors and the weight of each attributes (http://www.alibaba.com/trade/) are shown in Table 12. According to the retrieved cases, the full description of the target problem is given in Table 12.

Case 1 and case 2 adopts the same battery E_1, case 3 and case 4 adopts the same battery E_2, case 4, case 5, case 5 respectively adopts battery E_3, E_4, E_5. The range of the value of "Capacity", "Weight", "Length", "Width", "Height", "Nominal Voltage", "Nominal Current", "Temperature Range" respectively are: [0.5, 3], [0.10, 0.50], [10, 80], [10, 80], [20, 100], [10, 12], [0.3, 0.6], [−50, 100].

In order to evaluate each similar case's utility on the decision results, "Runtime", "Price", "Cycle Time" are chose to be the utility attributes. Their weights are assigned respectively as 0.4, 0.4, 0.2. The values of utility attributes of the similar cases and the overall utility-g are shown in Table 13. The evaluation criteria related to each utility attribute are given below:

Runtime: Normally, after a full charge, the larger the runtime is, the better the performance is. Considering the range of the runtime is [50 min, 150 min], the utility of γ_{i1} can be calculated with $g_1(\gamma_{i1}) = \frac{\gamma_{i1}-50}{150-50}$, where γ_{i1} denotes the runtime.

Price: Suppose the highest price that users can accept is $pc = 10$, then the utility of γ_{i2} can be calculated with $g_2(\gamma_{i2}) = 1 - (\frac{\gamma_{i2}}{pc})^2$, where γ_{i2} denotes the price.

Cycle times: Normally, for the battery, the larger the cycle times is, the better the performance is. Then the utility of γ_{i3}

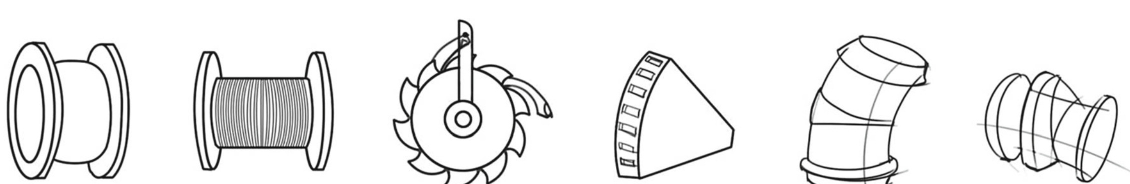


Fig. 13 Flexible joint concepts

Table 11 Specification of battery

Attribute	Rechargeable	Type	Capacity (Ah)	Weight (kg)	Length (mm)	Width (mm)	Height (mm)
Value	Yes	Li-ion	1.5	0.17	50	40	80

Table 12 Similar cases related to the battery design

Problem vector (Weight)	Capacity (Ah) (5)	Weight (kg) (4)	Length (mm) (1)	Width (mm) (1)	Height (mm) (1)	Nominal voltage (V) (4)	Nominal current (mA) (2)	Temperature range (°c) (1)
Target Problem	1.5	0.17	50	40	80	10.8	0.5	[−40,80]
Case 1	1.5	0.16	50	41	81	10.6	0.5	
Case 2	1.5	0.17	52	43	81	10.8	0.5	
Case 3	2	0.22	50	40	80	10.8		
Case 4	2		50	40	80	10.8		[−30,90]
Case 5	1.2	0.3	26	17	49	10.8	0.5	[−40,85]
Case 6	1.5	0.2	50	50	78	10.8		
Case 7	1.3	0.17	50	47	83	10.8		

Table 13 Utility attributes of the similar cases

Case	Runtime (min)	Price (£)	Cycle times	g
Case 1	120	6	1500	0.636
Case 2	118	6	1500	0.628
Case 3	130	7.2	2000	0.613
Case 4	128	£7.5	2000	0.587
Case 5	100	£6	900	0.536
Case 6	110	£6	900	0.576
Case 7	90	£6	1000	0.516

can be calculated with $g_3(\gamma_{i3}) = \begin{cases} 0.2, & \gamma_{i3} < 100 \\ 0.5, & 100 \le \gamma_{i3} < 500 \\ 0.8, & 500 \le \gamma_{i3} < 1000 \\ 1, & \gamma_{i3} \ge 1000 \end{cases}$, where γ_{i3} denotes the cycle times.

According to the information given in Tables 12 and 13, the utility of solution E_1, E_2, E_3, E_4, E_5 can be evaluated using function (1). A tool to help the evaluation process is also developed as shown in Fig. 15. The utility of E_1 is the maximum, so we choose E_1 as the sample design scheme of the battery.

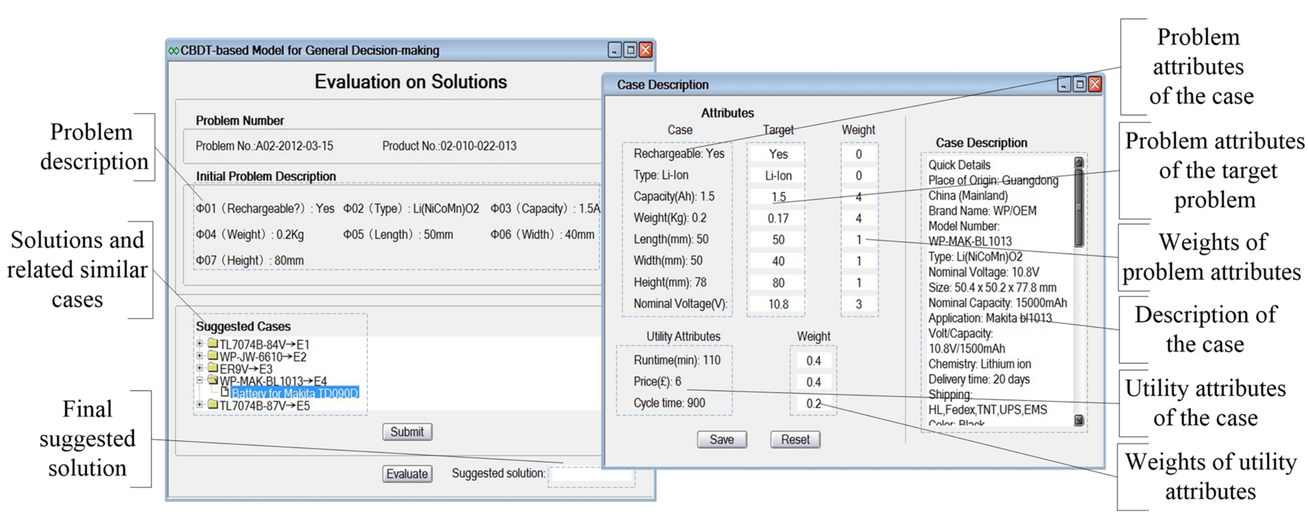


Fig. 15 Tool for evaluation based on CBDT

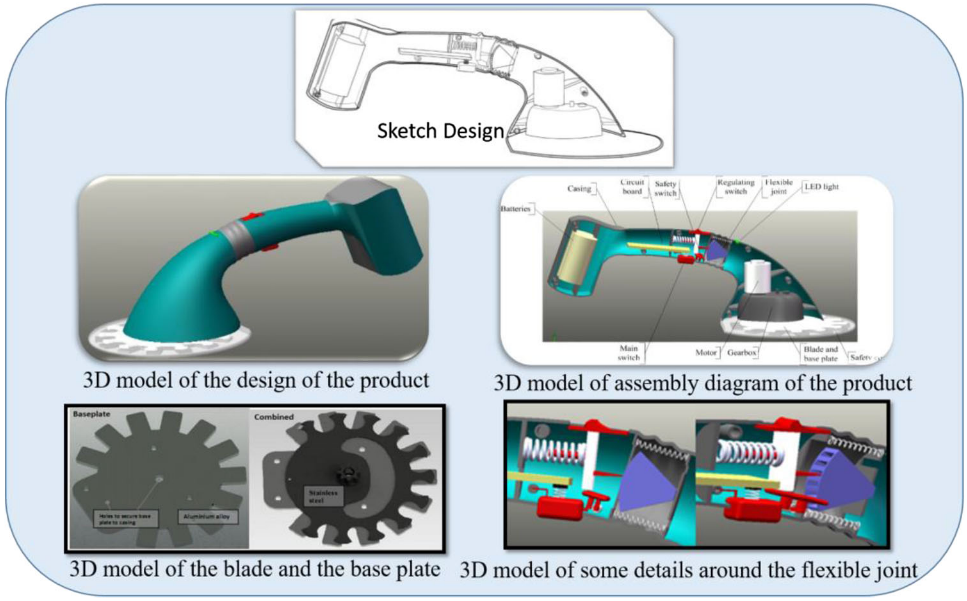


Fig. 16 Sketch design and corresponding solid models

5.5 The conceptual design of the hand-tool product

Other parts of the product, such as switch module, gearbox, shaft, etc. can be designed using the proposed methods. Finally, a sketch design for the product is shown in Fig. 16 along with corresponding solid models.

6 Conclusions

Considering the product conceptual design process as a series of decision-making processes, this paper proposes a CBDT based process model where quality function deployment, case-based decision theory (CBDT), the theory of inventive problem solving (TRIZ), Image-Scale, and solid-modelling are integrated together to help product conceptual design. A CBDT-based problem resolution model to support general decision-making during product conceptual design, and a CBDT-TRIZ model for rapidly undertaking innovative solution generation are proposed. Accordingly, case representation, index, evaluation criteria on decision results and similarity calculation between cases and target problem have been explored. Although the CBDT-based model and the CBDT-TRIZ model adopts the same reasoning and process framework, there are important differences. The similarity calculation function for general decision-making has been a specific area of focus. In the CBDT-based model, the similarity is influenced by the counted attribute scope and different methods to calculate the similarity on each attribute. Therefore, an experiment was carried out with Matlab which verified that assigning the set of attributes appearing in a stored case as the attribute set for similarity calculation is more plausible to the supposed scenario, and similarity calculation functions related to each attribute are also determined according to the supposed scenario. In addition, the proposed process model also utilizes QFD to translate customer wants into relevant engineering design requirements and thus formulating the design specification, and Image Scale to offer an orthogonal coordinates system to aid evaluation.

Based on the proposed product conceptual design process model, software was developed including a tool for general decision problem resolution based on CBDT, and a tool for the application of the CBDT-TRIZ model. The feasibility and effectiveness of the proposed product conceptual design process model which are supposed to not only help obtaining design solutions quickly through existing cases but also stimulate generating innovative solutions are supported by these software tools, as well as by a "cordless hand-tool design" case study.

There are aspects that can be further improved in the proposed process model. Firstly, additional tools from TRIZ and creative problem solving can be introduced into the model. For example, Substance-Field analysis would be very useful because under certain conditions it gives more precise directions for problem solving. Secondly, further research can be carried out with the evaluation criteria on decision results. How to establish the case-base which can automatically classify cases is another key point for the future work.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Nos. 61703317, 71671135, 71371148, and 71603197), the Fundamental Research Funds for the Central Universities (WUT: 2017VI026), the National Social Science Foundation of China (No. 16ZDA045).

References

1. Pahl, G., Beitz, W., Schulz, H., Jarecki, U.: Engineering Design: A Systematic Approach. Springer, Berlin (2007)
2. Ma, H.Z., Chu, X.N., Xue, D.Y., Chen, D.P.: A systematic decision making approach for product conceptual design based on fuzzy morphological matrix. Expert Syst. Appl. **81**(15), 444–456 (2017)
3. Rao, C.J., Zheng, J.J., Wang, C., Xiao, X.P.: A hybrid multi-attribute group decision making method based on grey linguistic 2-tuple. Iran. J. Fuzzy Syst. **13**(2), 37–59 (2016)
4. Hu, Z., Rao, C.J., Zheng, Y., Huang, D.: Optimization decision of supplier selection in green procurement under the mode of low carbon economy. Int. J. Comput. Intell. Syst. **8**(3), 407–421 (2015)
5. Gero, J.S.: Creativity, emergence and evolution in design. Knowl. Based Syst. **9**(7), 435–448 (1996)
6. Hinckeldeyn, J., Dekkers, R., Altfeld, N., Kreutzfeldt, J.: Expanding bottleneck management from manufacturing to product design and engineering processes. Comput. Ind. Eng. **76**, 415–428 (2014)
7. Lin, K.Y., Chien, C.F., Kerh, R.: UNISON framework of data-driven innovation for extracting user experience of product design of wearable devices. Comput. Ind. Eng. **99**, 487–502 (2016)
8. Ko, Y.T.: Modeling a hybrid-compact design matrix for new product innovation. Comput. Ind. Eng. **107**, 345–359 (2017)
9. Rao, C.J., Peng, J.: Fuzzy group decision making model based on credibility theory and gray relative degree. Int. J. Inform. Technol. Decis. Mak. **8**(3), 515–527 (2009)
10. Tan, R., Ma, J., Liu, F., Wei, Z.: UXDs-driven conceptual design process model for contradiction solving using CAIs. Comput. Ind. **60**(8), 584–591 (2009)
11. Fu, X.X., Niu, Z.W., Yeh, M.K.: Research trends in sustainable operation: a bibliographic coupling clustering analysis from 1988 to 2016. Clust. Comput. **19**, 2211–2223 (2016)
12. Wallace, K.M., Blessing, L.T.: Observations on some German contributions to engineering design in memory of professor Wolfgang Beitz. Res. Eng. Des. **12**(1), 2–7 (2000)
13. Suh, N.P.: Axiomatic Design: Advances and Applications (The Oxford Series on Advanced Manufacturing) (2001)
14. Mann, D.L.: Better technology forecasting using systematic innovation methods. Technol. Forecast. Soc. Chang. **70**(8), 779–795 (2003)
15. Gero, J.S., Kannengiesser, U.: A function-behavior-structure ontology of processes. Artif. Intell. Eng. Des. Anal. Manuf. **21**(4), 379 (2007)
16. Wang, J.R.: Ranking engineering design concepts using a fuzzy outranking preference model. Fuzzy Sets Syst. **119**(1), 161–170 (2001)
17. Madhusudan, T., Zhao, J.L., Marshall, B.: A case-based reasoning framework for workflow model management. Data Knowl. Eng. **50**(1), 87–115 (2004)
18. Tran, H.M., Schnwlder, J.: DisCaRia–distributed case-based reasoning system for fault management. IEEE Trans. Netw. Serv. Manag. **12**(4), 540–553 (2015)
19. Hassaniena, A.E., El-Bendaryb, N., Sweidan, A.H., Mohamed, A.E., Hegazyaa, O.M.: Hybrid-biomarker case-based reasoning system for water pollution assessment in Abou Hammad Sharkia. Egypt. Appl. Soft Comput. **46**, 1043–1055 (2016)
20. Cho, B., Kim, K.J., Chung, J.W.: CBR-based network performance management with multi-agent approach. Clust. Comput. **20**(1), 757–767 (2017)
21. Tsai, S., Childs, P.R.N.: TRIZ: incorporating the bright process in design. TRIZ Futur. Conf. **8**, 243–250 (2008)
22. Chechurin, L., Borgianni, Y.: Understanding TRIZ through the review of top cited publications. Comput. Ind. **82**, 119–134 (2016)
23. Li, W., Li, Y., Wang, J., Liu, X.: The process model to aid innovation of products conceptual design. Expert Syst. Appl. **37**(5), 3574–3587 (2010)
24. Rao, C.J., Goh, M., Zhao, Y., Zheng, J.J.: Location selection of sustainability city logistics centers. Transp. Res. Part D **36**, 29–44 (2015)
25. Rao, C.J., Xiao, X.P., Goh, M., Zheng, J.J., Wen, J.H.: Compound mechanism design of supplier selection based on multi-attribute auction and risk management of supply chain. Comput. Ind. Eng. **105**, 63–75 (2017)
26. Cortes Robles, G., Negny, S., Le Lann, J.M.: Case-based reasoning and TRIZ: a coupling for innovative conception in Chemical Engineering. Chem. Eng. Process. **48**(1), 239–249 (2009)
27. Baysan, D., Durmusoglu, M.B., Cinar, D.: Team based labour assignment methodology for new product development projects. Comput. Ind. Eng. **106**, 83–104 (2017)
28. Aamodt, A., Plaza, E.: Case-based reasoning: foundational issues, methodological variations, and system approaches. AI Commun. **7**(1), 39–59 (1994)
29. Ishikawa, T., Terano, T.: Analogy by abstraction: case retrieval and adaptation for inventive design expert systems. Expert Syst. Appl. **10**(3), 351–356 (1996)
30. Lee, D., Lee, K.: An approach to case-based system for conceptual ship design assistant. Expert Syst. Appl. **16**(2), 97–104 (1999)
31. Wu, M., Lo, Y., Hsu, S.: A fuzzy CBR technique for generating product ideas. Expert Syst. Appl. **34**(1), 530–540 (2008)
32. Jung, S., Lim, T., Kim, D.: Integrating radial basis function networks with case-based reasoning for product design. Expert Syst. Appl. **36**(3), 5695–5701 (2009)
33. Gilboa, I., Schmeidler, D.: Case-based decision theory. Q. J. Econ. **110**(3), 605–639 (1995)
34. Pape, A.D., Kurtz, K.J.: Evaluating case-based decision theory: predicting empirical patterns of human classification learning. Games Econ. Behav. **82**, 52–65 (2013)
35. Yan, A., Shao, H.S., Wang, P.: A soft-sensing method of dissolved oxygen concentration by group genetic case-based reasoning with integrating group decision making. Neurocomputing **169**, 422–429 (2015)
36. Wang, Q., Zhao, Y., Rao, C.J.: Analyses and improvement of case-based decision model of product conceptual design. Adv. Neural Netw. ISNN **2009**, 1131–1137 (2009)
37. Childs, P.R.N., Tsai, S.: Creativity in the design process in the turbomachinery industry. J. Des. Res. **8**(2), 145–164 (2010)
38. Zanni-Merk, C., Cavallucci, D., Rousselot, F.: An ontological basis for computer aided innovation. Comput. Ind. **60**(8), 563–574 (2009)
39. Wang, F.K., Yeh, C.T., Chu, T.P.: Using the design for six sigma approach with TRIZ for new product development. Comput. Ind. Eng. **98**, 522–530 (2016)
40. Wang, Y.H., Lee, C.H., Trappey, A.J.C.: Service design blueprint approach incorporating TRIZ and service QFD for a meal ordering system: a case study. Comput. Ind. Eng. (in Press) (2017)
41. Rao, C.J., Goh, M., Zheng, J.J.: Decision mechanism for supplier selection under sustainability. Int. J. Inf. Technol. Decis. Mak. **16**(1), 87–115 (2017)
42. Blessing, L.T., Chakrabarti, A.: DRM, a Design Research Methodology. Springer, Berlin (2009)
43. Lau, H.C., Jiang, B., Chan, F.T., Ip, R.W.: An innovative scheme for product and process design. J. Mater. Process. Technol. **123**(1), 85–92 (2002)
44. Zhao, L., Chen, W., Ma, J., Yang, Y.: Structural bionic design and experimental verification of a machine tool column. J. Bionic Eng. **5**, 46–52 (2008)
45. Chin, K., Wang, Y., Yang, J., Gary Poon, K.K.: An evidential reasoning based approach for quality function deployment under uncertainty. Expert Syst. Appl. **36**(3), 5684–5694 (2009)

46. Anderberg, M.R.: Cluster analysis for applications, DTIC Document (1973)
47. Gu, M., Tong, X., Aamodt, A.: Comparing similarity calculation methods in conversational cbr. In: IEEE International Conference on Information Reuse and Integration (IRI-2005) (2005)
48. Maicher, L., Witschel, H.F.: Merging of distributed topic maps based on the subject identity measure (SIM) approach. Proc. Berl. XML Tags **4**, 301–307 (2004)
49. Hu, Z., Zhao, Y., Chen, Y.: CBDT-TRIZ model for product conceptual design. J. Comput. Inf. Syst. **9**(7), 2575–2585 (2013)
50. Altshuller, G.S.: Creativity as an Exact Science: The Theory of the Solution of Inventive Problems. CRC, Boca Raton (1984)

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