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Handle ID: .http://hdl.handle.net/10985/9062

To cite this version :

Jing XU, Yang XU, Alain BERNARD, Jing XU, Shigeo SUGIMOTO, Nicolas PERRY - Knowledge evaluation in product lifecycle design and support - Knowledge-Based Systems - Vol. 70, p.256–267 - 2014

Knowledge evaluation in product lifecycle design and support

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ABSTRACT

Enterprises are focusing more and more on knowledge issues for global product development. This paper describes knowledge evolution processes in product development activities and proposes a knowledge evaluation method in product lifecycle design. The paper also theoretically analyzes the evaluation model and illustrates how knowledge values can be assessed by case study. The case study shows how knowledge values calculated by the model can provide suggestions about which knowledge to choose and what to do next. The knowledge evaluation model serves as a useful tool for managing knowledge in product lifecycle design and support.

Keywords:
Knowledge management
Knowledge value
Product design
Life cycle management
Evaluation

1. Introduction

The current commercial environment necessitates that enterprise to adapt to the requirement of more innovation, fewer errors, less time-to-market, lower manufacturing cost, better operational performance and better cooperation among partners [4]. In such situations, more and more enterprises consider their production processes as knowledge management (KM) processes, and they are paying attention to the crucial competence: knowledge [25,32,21]. Meanwhile, the whole lifecycle plays an important role in production activities. So product lifecycle management (PLM), from the initial conception to the end of life, is a strategic approach in production management [26].

A variety of intelligent solutions have been proposed in knowledge management concerning product development. Karacapilidis [19]proposed a computerized knowledge management system for the collaborative development of a manufacturing strategy. Their system supports collaborative strategy development by integrating a domain-specific modeling formalism based on the resource view of the firm, an associated structured dialogue scheme, an argumentation-enabling mechanism, and an efficient algorithm for the evaluation of alternatives. He et al. [16] proposed a unified product structure management model to integrate product structure information and enterprise business processes and to ensure people of various disciplines can access product information throughout the entire product lifecycle. Hung et al. [18] have developed a novel framework supported by a knowledge-based database to support product design planning, considering quality function deployment and design structure matrix. Chen [12] has presented a five-step approach using knowledge integration and sharing mechanism for collaborative modeling product design and process development. It can satisfy participants' demands for product knowledge, increase product development capability, reduce product development cycle time and cost, and ultimately increase product marketability. Gunendran and Young [15] have conducted surveys on how to organize manufacturing best practice knowledge in product development, and they have explored a system design tool to model the relationship between knowledge and product information so as to reuse system design models. Chang et al. [9] have studied organizational knowledge structure in the context of new product development (NPD) and illustrated that one must possess enough working experience within product development process to have the skills to accomplish cross-functional knowledge conversion. Al-Ashaab et al. [2] have implemented the knowledge-based environment framework KBE-ProVal (Knowledge-Based Environment to Support Product Design Validation) to support product design validation. Akasaka et al. [1] have extend product design to Product-Service-System (PSS) and proposed a knowledge-based PSS design support method.

Those results show that when production is tightly linked with knowledge, product development solutions do not focus just on the

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"product" but extend to knowledge management. As a result, product designers should not only combine enterprise business processes with product development processes but also integrate all functional elements which could be identified, especially knowledge. Effective models are expected to be a unified platform for creation, sharing and application of knowledge that is related to product and production activities [23]. In other words, product design should consider all knowledge in all stages of a product lifecycle processed by all participants, linking to enterprise lifecycle management, technology lifecycle management and associated to a global knowledge lifecycle management.

However, knowledge evaluation is a topic within KM that is not well studied especially when integrated with product development. Evaluation is crucial for knowledge management in both research and practice, however, the intangibility of knowledge make evaluation very complex. Only by developing a standardized and quantitative approach can we establish a method of knowledge evaluation that can be applied in practice. Xu and Bernard [32] have proposed a basic knowledge quantification approach which evaluates how knowledge can make changes in product state evolution. Based on the idea and approach, this paper addresses the problem of knowledge evaluation for further application, discusses how knowledge can improve product lifecycle design process, validate the efficiency of knowledge evaluation process, determine the optimized sequence of in knowledge acquisition, and provide enterprises with a global view on product design.

2. Knowledge evaluation modeling

2.1. Product development process description

In a product development process, a product may be considered to start from its initial state and arrive to a required state (final state), and a task T is supposed to be accomplished to realize this product evolution from that initial state P_0 to the final state P_n. For example, to produce a car (product), here is one step of the product development process: the car is to change from version 1.0 (initial state) to version 2.0 (final state), and a task T can bridge the gap between these two product states.

T is the total task which may include several sub-tasks (t_i) and sub-sub-tasks (t_{ij}), for example:

- The first sub-task t_1: increment of the wheel number: $4 \rightarrow 8$
- The second sub-task t_2: to meet a higher standard of environment protection: Standard 1.0 → Standard 2.0
- The sub-sub-tasks of t_2 are:
  - The first sub-sub-task t_{21}: utilization of another type of power mode: petrol power → hybrid power of petrol and electricity
  - The second sub-sub-task t_{22}: realization of a better equipment for emissions
- Etc.

Consequently, the product development process can be described by a series of state changes. Given an initial state P_0, the product development process can be characterized by a sequence of product states « $P_0 \rightarrow P_1 \rightarrow P_2 \rightarrow \cdots \rightarrow P_n$ », where:

- P_1: The product state when t_1 is accomplished.
- P_2: The product state when t_2 is accomplished.
- P_3, P_4, etc.
- The final state P_n: all the sub-tasks are accomplished, in other words, the entire task T is accomplished.

Formally, task T can be characterized by a directed graph, defined as follow.

Definition 1. Task T is represented by a weighted directed graph $G(T) = (H, A, \Omega)$, where:

- H is a set of tasks, whose elements are the task T, the non-atom tasks t_m and the atom-tasks at_n, i.e., $H = \{h_i\} = \{T, t_1, t_2, \ldots, t_m, at_1, at_2, \ldots, at_n\}$;
- A is a set of directed arcs α_{pq}, i.e. h_p and h_q are linked by α_{pq}, from h_p to h_q;
- Ω is a set of weights ω_{pq} which are assigned to each arc α_{pq}.

In particular, the sub-tasks which do not have successors are named atom-tasks, noted as at_i.

A product development chain is illustrated by Fig. 1.

The task T is characterized by a graph, not a tree. In fact, there may be several sub-tasks which are not independent and they may have one or several sub-tasks in common. Characterization of knowledge K is based on the approach from Xu and Bernard [31]. The approach considers both the static features and dynamic changes of knowledge. For the static features of knowledge, a vector is used to help characterizing different aspects of knowledge such as quantity, granularity, compatibility and maturity. Such characterization mainly helps in dealing with explicit knowledge, for example, design knowledge organization, knowledge acquisition and storage. For the dynamic issues concerning knowledge evolution, the concept of knowledge state is applied. It describes the knowledge activities with state sequences. This is especially useful for processing product designers' knowledge, both explicit and tacit.

2.2. Knowledge value for product development

Supposing that knowledge K is necessary to accomplish the task T and a knowledge fragment k_i is needed to accomplish sub-task t_i, thus, k_i is the solution for the sub-task t_i, and knowledge K can be considered as a set of solutions which together can accomplish the task T. A knowledge fragment k_i can be a person, a book, a plan or any type of solutions provided.

Given this model, some questions may be: What knowledge K can accomplish the task T completely? If knowledge K can only solve a part of the task T, which part is solved? What knowledge fragments k_i have to be added in order to solve the remaining parts? How to choose the knowledge fragments k_i to accomplish the unsolved sub-tasks?

In order to answer these questions, some hypotheses are presented:

Hypothesis 1. The atom-tasks are noted as at_i, and all atom-tasks correspond to an explicit answer "yes" or "no" which shows whether it can be solved or not. In other words, the atom-tasks cannot be solved partially.

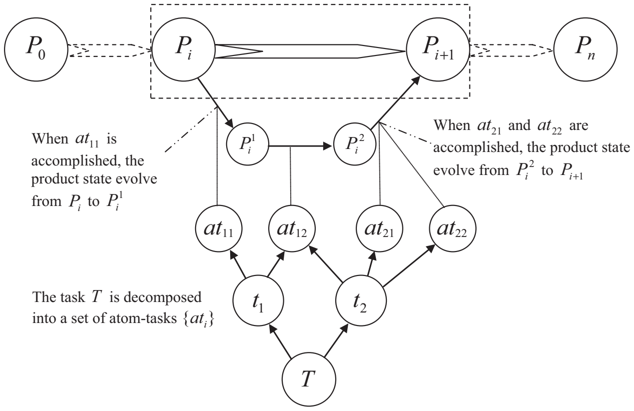

Fig. 1. A product development chain.

Hypothesis 2. The principles of task decomposition are as follows. If the task T is decomposed into T_1, T_2, …, T_n, we have:

(a) $T \subseteq (T_1 \cup T_2 \cup \ldots \cup T_n)$ (the combination of the sub-tasks should cover the original task T)
(b) $T \neg \subset T_i$ (any sub-task T_i cannot cover the original task T)
(c) The task T is decomposed with weights, noted as: T: $\omega_1 T_1 + \omega_2 T_2 + \cdots + \omega_n T_n$, and $\sum_{i=1}^{n} \omega_i = 1$ (the weights indicate the importance of the sub-tasks to the original task, for example, if the design of a car of version 2.0 focuses more on speed improvement, then the sub-task of speed improvement will have a higher weight than the sub-task of cost diminution)

The value of knowledge K_i to the task T_i is noted as $V(T_i, K_i)$. This notation indicates that knowledge is always in context, in other words, knowledge evaluation is linked with specific tasks. Knowledge value thus varies according to different tasks. For example, given a same knowledge fragment "to adjust the height of a chair", it could have a high value to the task "to consider the ergonomics" and have a low value to the task "to control the cost". The value of knowledge K to the atom-task at_i is defined as follows.

Definition 2.

$$V(at_i, K) = \begin{cases} 1, & at_i \text{ can be solved by } K \\ 0, & at_i \text{ cannot be solved by } K \end{cases}$$

Based on the two hypotheses and Definition 2, knowledge value can be measured by the procedure as follow.

Procedure for knowledge value measurement:

- Step 1: The value of knowledge K for the atom-tasks is obtained according to Definition 2.
- Step 2: For any $h_i \in H$, find all the (h_i, h_j) and their associate ω_{ij}, then:

$$V(h_i, K) = \sum_j \omega_{ij} \cdot V(h_j, K)$$

From Step 1 we can obtain all the $V(at_i, K)$ and from Step 2 we can obtain $V(T, K)$. When $V(T, K) \neq 1$, there are one or several sub-tasks which are not accomplished, so additional knowledge is necessary to make $V(T, K) = 1$. During this process of knowledge addition, both explicit knowledge and tacit knowledge might be needed. Usually, explicit knowledge comes from databases, publications, rules, etc. and tacit knowledge comes from experience, expertise, wisdom, judgment, etc.

If K_i can solve at_i and at_i is linked to T by a sequence of arcs with weights of ω_1, ω_2, …, ω_m, then $V(T, K_i) = \prod_{u=1}^{m} \omega_u \cdot V(at_i, K_i) = \omega_{at_i} \cdot V(at_i, K_i)$.

Consequently, a knowledge integrated product development system can be modeled as follows.

Definition 3. A knowledge integrated product development system is a quintuplet <$\mathcal{P}$, $\mathcal{K}$, H, Ω, V>:

- $\mathcal{P}$ is the set of all possible product states, including the initial state P_0 and the final state P_n;
- $\mathcal{K}$ is the set of all possible knowledge, $\mathcal{K} = \{K_0, K_1, \ldots, K_n\}$;
- H is the set of all possible tasks, including the atom-tasks at_i, the non-atom-tasks t_i and the total task T;
- Ω is the set of weights which are assigned during task decomposition;
- V is a function, and $V(T_i, K_j)$ means the knowledge value.

If another knowledge K'_0 is also available, $V(T, K'_0)$ can be calculated and compared with $V(T, K_0)$. The knowledge that has a higher value is usually chosen. As collaborative networks is regarded as a critical success factor to achieve product innovation [24], it is always useful to choose the most valuable knowledge to be exchanged and shared.

2.3. Model characteristics

Based on the definitions above, this section will propose and demonstrate several useful and important model characteristics.

Definition 4. Given <$\mathcal{P}$, $\mathcal{K}$, H, Ω, V>, $\forall K_1, K_2 \in \mathcal{K}$, K_1 can solve a set of tasks $X \subseteq H$, K_2 can solve a set of task $Y \subseteq H$, if:

$$X \subseteq Y \subseteq H \rightarrow V(T, K_1) \leqslant V(T, K_2)$$

then V is monotonic.

Definition 5. Given <$\mathcal{P}$, $\mathcal{K}$, H, Ω, V>, $\forall X, Y \subseteq H$, $\forall K \in \mathcal{K}$, if:

$$V(X \cup Y, K) \leqslant V(X, K) + V(Y, K)$$

then V is additive.

Note: $X \cup Y$ is the union of the two tasks.

Theorem 1. *Knowledge value is monotonic.*

Proof. Given <$\mathcal{P}$, $\mathcal{K}$, H, Ω, V>, $\forall K_1, K_2 \in \mathcal{K}$, K_1 can solve a set of tasks $X \subseteq H$, K_2 can solve a set of tasks $Y \subseteq H$. Suppose that $X = \{x_1, x_2, \ldots, x_p\}$ and $Y = \{y_1, y_2, \ldots, y_q\}$, where $x_1, x_2, \ldots, x_p$, $y_1, y_2, \ldots, y_q$ are the atom-tasks.

From $X \subseteq Y \subseteq H$
We have: $\neg \exists x_i \notin \{y_1, y_2, \ldots, y_q\}$, $\exists y_j \notin \{x_1, x_2, \ldots, x_p\}$, $i \in \{1, 2, \ldots, p\}$, $j \in \{1, 2, \ldots, q\}$
Suppose that $y_{a_i} \in \{x_1, x_2, \ldots, x_p\}$, $y_{b_i} \notin \{x_1, x_2, \ldots, x_p\}$, $a_i, b_i \in \{1, 2, \ldots, q\}$
Then $\{y_{a_1}, y_{a_2}, \ldots, y_{a_p}\} = \{x_1, x_2, \ldots, x_p\}$
Suppose that x_i is linked to T by the sequence of α_1^x, α_2^x, …, $\alpha_{m_i}^x$, y_j is linked to T by the sequence of α_1^y, α_2^y, …, $\alpha_{m_j}^y$

$$V(T, K_1) = \sum_{i=1}^{p} \prod_{u=1}^{m_i} \omega_u^x \cdot V(x_i, K_1) = \sum_{i=1}^{p} \prod_{u=1}^{m_i} \omega_u^x$$

$$\begin{aligned} V(T, K_2) &= \sum_{j=1}^{q} \prod_{u=1}^{m_j} \omega_u^y V(y_j, K_2) \\ &= \sum \prod \omega_u^y V(y_{a_i}, K_2) + \sum \prod \omega_u^y V(y_{b_i}, K_2) \\ &= \sum \prod \omega_u^x V(x_i, K_2) + \sum \prod \omega_u^y V(y_{b_i}, K_2) \\ &= \sum \prod \omega_u^x + \sum \prod \omega_u^y V(y_{b_i}, K_2) \\ &= V(T, K_1) + \sum \prod \omega_u^y V(y_{b_i}, K_2) \end{aligned}$$

$$\because \sum \prod \omega_u^y V(y_{b_i}, K_2) \geqslant 0$$

$$\therefore V(T, K_1) \leqslant V(T, K_2)$$

As a result, it is concluded that V is monotonic. □

Theorem 1 indicates that if the value of knowledge K to the task T is V, then its value to any sub-task of T is not lower than V. This guarantees that the knowledge value is always increasing, or at least remaining the same, when the tasks that it can solve increase, in other words, knowledge value does not decrease during the forward process of product development.

Theorem 2. *Knowledge value is additive.*

Proof. Given a <$\mathcal{P}$, $\mathcal{K}$, H, Ω, V>, $\forall X, Y \subseteq H$, similar to the proof process of Theorem 1, X is replaced by $\{x_1, x_2, \ldots, x_p\}$ and Y is replaced by $\{y_1, y_2, \ldots, y_q\}$.

(1) If X and Y do not have atom-tasks in common, so:

$$V(X \cup Y, K) = \sum_{i=1}^{p} \prod \omega_u^x V(x_i, K) + \sum_{j=1}^{q} \prod \omega_u^y V(y_j, K)$$
$$= V(X, K) + V(Y, K)$$

(2) If X and Y have atom-tasks in common, and suppose that $\{c_1, c_2, \ldots, c_m\}$ are the atom-tasks in common, so:

$$V(X \cup Y, K) = \sum_{i=1}^{p} \prod \omega_u^x V(x_i, K) + \sum_{j=1}^{q} \prod \omega_u^y V(y_j, K)$$
$$- \sum_{k=1}^{m} \prod \omega_u^c V(c_k, K) = V(X, K) + V(Y, K) - \sum V(c_k, K)$$
$$\because \sum V(c_k, K) \geqslant 0$$
$$\therefore V(X \cup Y, K) \leqslant V(X, K) + V(Y, K)$$

As result, it is concluded that V is additive. □

Theorem 2 indicates that if one task T is decomposed into several sub-tasks $\{t_1, t_2, \ldots, t_n\}$, then $V(T, K) \leqslant \sum_{i=1}^{n} V(t_i, K)$, in other words, if knowledge K can accomplish all sub-tasks of the task T, it can accomplish this task T.

The conclusion of Theorem 1 and 2 can be easily tested in real life examples. As a simple test, we have assigned a task of designing a chair for office use to a set of 9 students. The students are divided into 3 groups to design 3 different aspects of the chair — form, color and material, and the three tasks are named task F, task C and task M. Their design results, which are regarded as representation of their design knowledge (k_1, k_2 and k_3), are quantified according to the proposed method. By integrating the design results of Group 1 and Group 2, we get a new design result representing their combined knowledge k_4. In the test, we have $V(F, k_1) = 0.7$, $V(C, k_2) = 0.8$, $V(T, k_1) = 0.5$, $V(T, k_2) = 0.3$, $V(T, k_3) = 0.4$, $V(T, k_4) = 0.7$, $V(F, k_4) = 0.7$, $V(C, k_4) = 0.8$, $V(F \cup C, k_4) = 0.95$. So we have $V(T, k_1) \leqslant V(T, k_4)$ which matches the conclusion of Theorem 1 and $V(F \cup C, k_4) \leqslant V(F, k_4) + V(C, k_4)$ which matches the conclusion of Theorem 2.

Theorem 1 and Theorem 2 guarantee the efficiency of the proposed knowledge evaluation process. By proving that "knowledge value is monotonic", we may conclude that knowledge value does not decrease during the forward process of product development, in other words, negative knowledge (knowledge that may damage the accomplished tasks) can be detected. By proving that "knowledge value is additive", we may conclude that when all sub-tasks are accomplished, the task T is accomplished. Without Theorem 2, it may happen that the task T is not solved even all sub-tasks are accomplished.

3. Knowledge evaluation in product design support

During product lifecycle design, both tacit and explicit knowledge may be required to accomplish the tasks at_i, so these two kinds of knowledge can add value to the knowledge of design K and thus make knowledge evolution [5].

Here are the main steps to take during the procedure of knowledge evaluation in supporting product design.

1. To decompose of the product development process into simpler processes, in other words, to realize the decomposition of the task T into atom-tasks at_i.
2. To evaluate the value of the existing knowledge using the evaluation model introduced in the previous section.
3. If not all the atom-tasks are solved, find out which at_i should be solved next.
4. To add appropriate knowledge, explicit and/or tacit, to accomplish at_i.
5. Repeat Step 3 and Step 4 until all atom-tasks are solved.

In a general point of view, Fig. 2 illustrates the process of knowledge evolution and product development with a double-helix structure. During this process, knowledge and product add values to each other mutually at every reaction point.

Xu and Bernard [32] have described the « reaction point » in detail, c.f. Fig. 3. Knowledge is regarded as the interaction between designers and products which results in the change of product states. In our context, it means that knowledge I can solve at_i.

Meanwhile, by adding knowledge I, K-state I changes to K-state II. In the case for a product designer, experience could be regarded as tacit knowledge which could make his/her K-state change, c.f. Fig. 4, which illustrates the mutual effect of production development and knowledge evolution.

The case given in the following section illustrates how knowledge evaluation can serve in product lifecycle design and support.

4. Case study

How to apply the knowledge quantification approach in real life cases is crucial to show its usefulness, and this section illustrates how the proposed knowledge evaluation method is applied.

This paper has chosen a case of chair design, which is a part extracted from the product lifecycle of a chair. The knowledge evaluation model is implemented on the phase of design as it is a key phase where major decisions are made concerning knowledge. In this example, the task « design a chair » should be accomplished in order to make the product (chair) evolves in the development process. Fig. 5 illustrates how the task is decomposed. Although the decomposition is not complete, for example, several tasks such as market study, packaging and logistics matters and particular optimization, are neglected, it can serve as a demonstration.

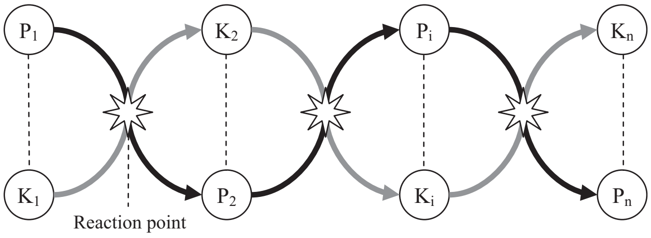

Fig. 2. The structure of the interaction process between knowledge and product.

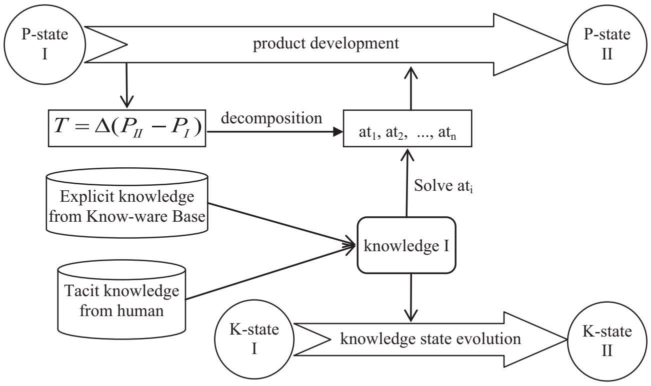

Fig. 3. Details of « reaction point ».

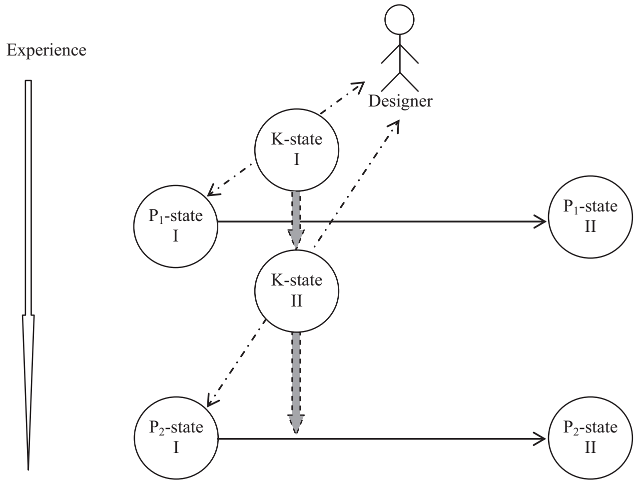

Fig. 4. Mutual effect of product development and knowledge evolution.

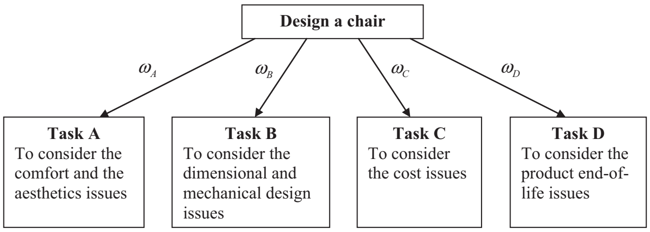

Fig. 5. Decomposition of the task « design a chair ».

Based on the criteria obtained from experience in product design, the principle task « design a chair » is decomposed into four sub-tasks.

The weights ω_i are given by the experts of different roles who have different points of view in design activities. Table 1 shows the weights given to each sub-task by experts of different roles. To determine a weight, we have taken into account the results given by a group of experts for each given role. How to improve the results of collecting and analyzing the weight values given by different people is another complicated topic, which needs further research on statistical techniques, human behaviors, etc., and in this paper, we simply take the average of the weights proposed by all the experts assigned in each group as the weight value.

The following sections will analyze the different sub-tasks in details.

4.1. Details of Task A

Fig. 6 shows the decomposition of the task « To consider the comfort and the aesthetics issues ».

Here are some illustrations of Fig. 6.

- « Perception test » and « To consider the psychological comfort issues » can be solved by questionnaire surveys.

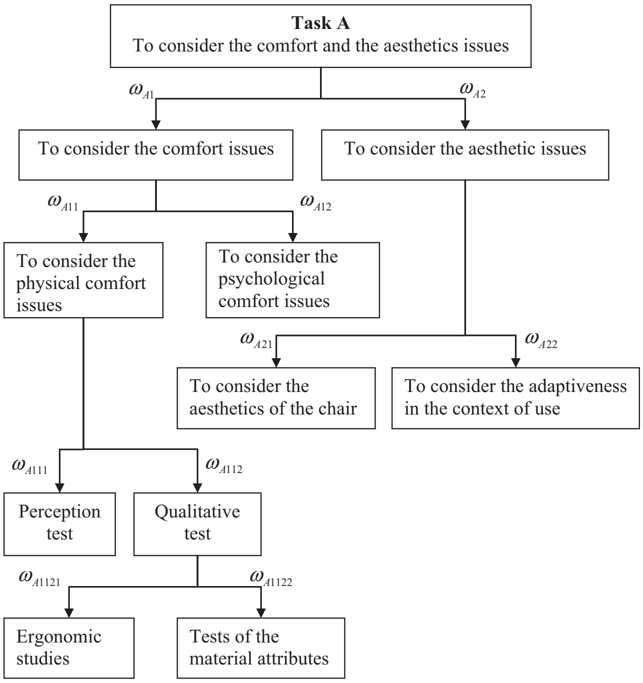

Fig. 6. Decomposition of Task A.

- « Ergonomic studies » mainly focus on examining the degree of fatigue of different parts of the body (muscle, bone, joint, etc.) of a person who sits in the chair for a period of time or by simulations.
- « Tests of the material attributes » may include the thermal conductivity (in winter, people do not like to sit in a chair with a surface of iron, because its too cold), the sensation of the material (for example, smooth or rough, soft or hard), etc.
- « To consider the aesthetics of the chair » considers the intrinsic beauty of the chair, which depends on the cultural and social context. In other words, for a same chair, it may vary from beautiful to disgusting due to different tastes of people from different countries or groups.
- « To consider the adaptiveness in the context of use » considers whether the chair matches the environment of use. For example, in a fast-food restaurant, sofas are not suitable to the environment although they are very beautiful.

4.2. Details of Task B

Fig. 7 illustrates the decomposition of the task « To consider the dimensional and mechanical design issues ».

Here are some illustrations to Fig. 7.

- The architectural design is considered before the design in details.
- For the assignments of the values of the weights ω_{B1} and ω_{B2}, they depend on whether the designer take optimization into account. Table 2 shows two examples in determining ω_{B1} and ω_{B2}. In an

Table 1
The values of weights (in percentage).

Experts of different roles	ω_A Comfort/aesthetics	ω_B Dimension/mechanics	ω_C Costs	ω_D End of life
Client	50	10	30	10
Designer	10	50	30	10
Manufacturer	0	30	50	20
Seller	30	10	40	20
Transporter	0	60	30	10
Recycler	0	0	30	70

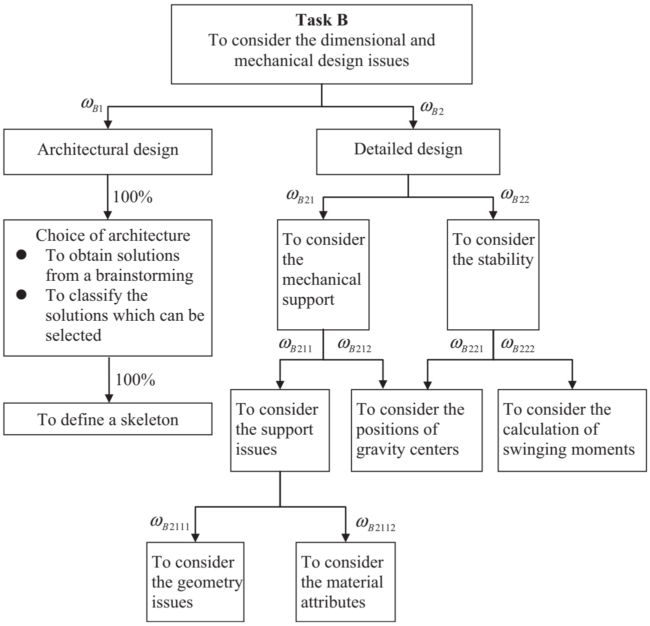

Fig. 7. Decomposition of Task B.

extreme situation, when a designer assigns ω_{B1} = 100%, it means the designer will simply look for a solution in a database of archived designs.

- The tasks « To consider the mechanical holding issues » and « To consider the stability » have a same sub-task « To consider the positions of gravity centers ». Such situation that several tasks may have a same sub-task in common is acceptable according to Definition 1 which defined the Task *T* as a graph.
- Here are two weights which have the value « 100% ». They mean that the tasks linked by an arrow of a weight of « 100% » are « equal ». In this case, when people have accomplished « to define a skeleton », they have accomplished the « architectural design » at the same time.

4.3. Details of Task C

Fig. 8 illustrates the decomposition of the task « To consider the cost issues ».

Here are some illustrations to Fig. 8:

- To determine the values of the weights ω_{C1} and ω_{C2}, the context of design should be considered, in other words, they depend on the amount of production of the chairs provided by customers. Table 3 gives two examples. In the condition that the chair is designed to be produced in large quantities, the cost of materials has a weight of greater importance. When it is a case of custom design, the weight of materials is lower. The client is willing to pay the extra cost for differentiation even if the materials used are more expensive.
- If several tasks have the relations of inclusion, an arrow with a weight of "100%" is used. Design optimizations are often made retrospectively by taking into account new knowledge (Chenouard, 2007)

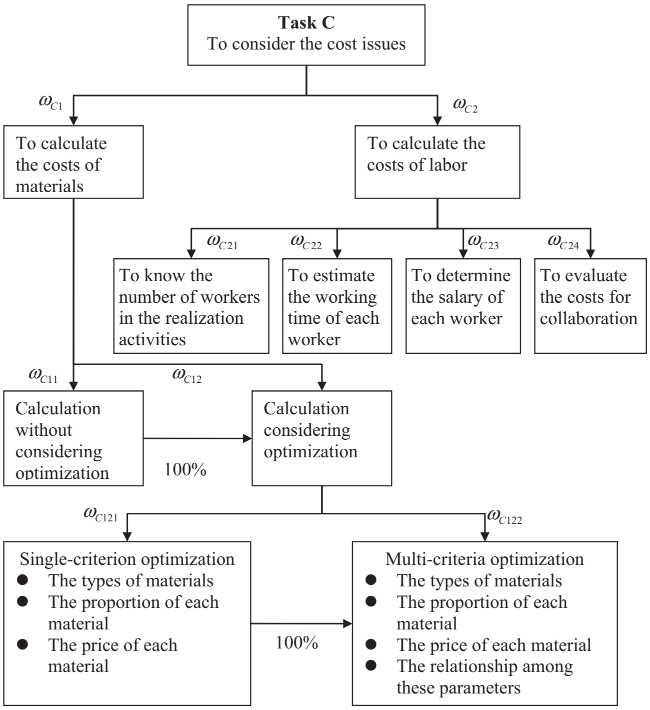

Fig. 8. Decomposition of Task C.

- Why the arrow from the task "Single-criterion optimization" to the task "Multi-criteria optimization" has a weight of "100%"? Obviously, when people can perform the task of "Multi-criteria optimization", they are able to accomplish the task of "Single-criterion optimization". In other words, these two tasks have a containment relationship. In case when two tasks have a containment relationship, an arrow of a weight of "100%" is used. Optimizations of the design are often made retrospectively, taking new knowledge into account, [14].

4.4. Details of Task D

Fig. 9 illustrates the decomposition of the task « To consider the product end-of-life issues ».

Here are some illustrations to Fig. 9:

- Management of product end-of-life and recycling are critical issues in environment treatment for manufacturing enterprises so they should be considered in product lifecycle design [29,7]. The task « To consider the recycling issues» needs knowledge about the possibilities of recycling the materials used.
- The number of materials to be considered is not limited to three, and it may differ from case to case. In other words, this number depends on how many principal types of materials are used to build the chair.
- The three weights ω_{D11}, ω_{D12} and ω_{D13} are determined by several factors of the chair, for example
  - The proportion of each material used
  - The cost of each material used

Table 2
The values of the weights ω_{B1} and ω_{B2}.

	ω_{B1} (%)	ω_{B2} (%)
If the designer pays special attention in optimization issues during the design process	30	70
If the designer does not spend too much time in searching for optimization solutions for Task B	50	50

Table 3
The values of the weights ω_{C1} and ω_{C2}.

	ω_{C1} (%)	ω_{C2} (%)
If the chair is designed to be produced in large quantities	80	20
If the chair need a custom design with a small amount of production expectation	20	80

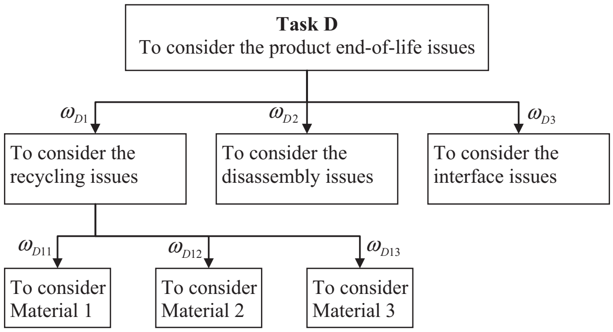

Fig. 9. Decomposition of Task D.

We propose a formula to calculate the weight ω_{D1i}:

$$\omega_{D1i} = \frac{\left(\frac{weight_i}{WEIGHT} + \frac{price_i}{PRICE}\right)}{3}$$

In this formula, *weight*$_i$ and *price*$_i$ are the weight and the price per weight unit of Material *i*; *WEIGHT* and *PRICE* are the total weight and total price of the chair.

- The task « To consider the disassembly issues » evaluate whether the designed chair can be disassembled. The easy disassembly of a product will facilitate the recycling of material used and the reuse of different parts of the chair.
- The task « To consider the interface issues » mainly considers the reuse issues of different parts of the chair. For example, if a chair has a leg broken, instead of throwing it away and replacing it by a new one, people can simply substitute the broken leg. But in order to realize the substitution of the broken leg, the interface between the leg and the body of the chair should be well designed. In such cases, the design of the interface should be given special attention.

4.5. Test on a specific case

In product lifecycle design, various sub-tasks are often not totally independent, in other words, they may be linked to a same task. For example, the task "ergonomic studies" may affect the task "architectural design", because a very "beautiful" chair may not be comfortable. How to solve this type of problem? The solution lies in adding a constraint of the two weights, for example, $\omega_{A1121} + \omega_{B1} = 0.8$, and this will serve to balance the different requirements and preferences. For example, according to customers' requirements, in case designers should pay more attention to "ergonomic studies", we can increase the weight of this task from 0.3 to 0.6, and the weight of the other task "architectural design" has to be reduced from 0.5 to 0.2. Therefore, when determining the weights, experts must consider the probable mutual affects among tasks.

Based on the study above, we are addressing the following specific case.

In order to solve the problem of "design a chair", people need knowledge. In this case, knowledge is represented in the form of "design solutions". Suppose we have obtained several solutions, so we must choose a solution that is more valuable, that is to say, the knowledge which is most valuable. In the next step, we have to evolve the chosen knowledge so that it reaches to the final state, i.e. the state that it can solve the task of "design a chair" completely.

- Knowledge K_1: the chair is described by Fig. 10, and the additional content of K_1 are as follows.
  - The chair is composed of three parts;
  - The materials used are wood, leather and cotton.
- Knowledge K_2: the chair is described by Fig. 11, and the additional contents of K_2 are as follows:
  - The chair is made of only one piece;
  - The material used is the thermoplastic polytetrafluoroethylene (acronym PTFE)

To evaluate the knowledge which corresponds to each type of chair, decision makers must determine the weights of Table 4 and complete the table of atom-tasks (Table 5).

The calculations of the knowledge values are performed using the evaluation model of knowledge introduced in Section 2. "$\surd$" in Table 5 means the knowledge can solve the corresponding atom-task. The results of knowledge values are as follows.

- $V(T, K_1) = 73.45\%$
- $V(T, K_2) = 68.84\%$

Consequentially, K_1 is chosen as it has a higher value.

Based on K_1, we will evolve the knowledge to a new state so that it can solve the task *T* completely.

By comparing values of different knowledge, the proposed model allows us to know which tasks should be accomplished next. In order to accomplished the task *T*, sub-tasks can be solved in different orders, so different knowledge are required in different sequence. As knowledge value is context related, knowledge is evaluated differently in different product development stages, and people are suggested to choose the optimized sequence of knowledge acquisition according to knowledge value and knowledge cost (knowledge cost is beyond discussion of this paper, so is supposed to be constant).

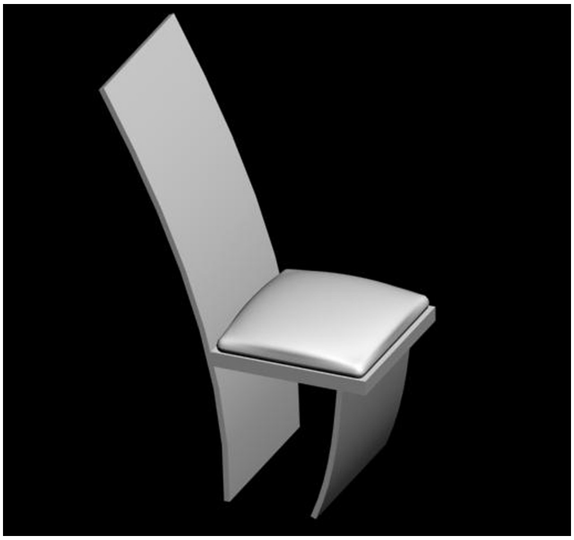

Fig. 10. The chair described by K_1.

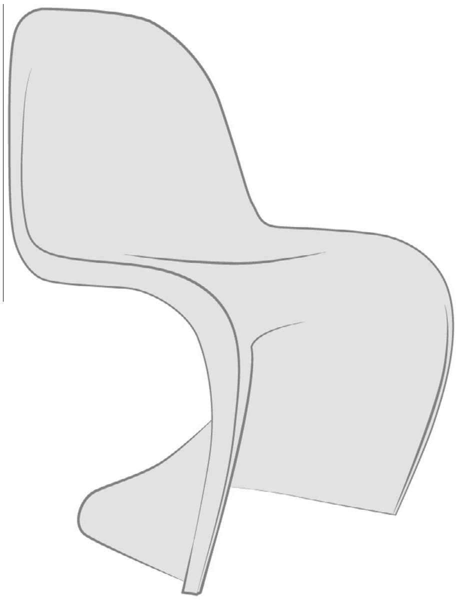

Fig. 11. The chair described by K_2.

For K_1, according to $V(at_i, K_1)$, the sequence of tasks to be accomplished is:

$$at_{B222} \to at_{D3} \to at_{C122} \to at_{C121} \to at_{D12} \to at_{A22} \to at_{C21} \to at_{C22} \to at_{C23} \to at_{C24} \to at_{D13}$$

This sequence of problem solving serves as a suggestion, not a requirement.

As $V(at_{B222}, K_1)$ is the biggest of all unsolved $V(at_i, K_1)$, we begin by looking for knowledge that can solve at_{B222}. In order that K_1 arrives to a state that it can accomplish the task "To consider the calculation of swinging moments", an additional knowledge k_{B222} should be introduced. k_{B222} is likely to be a tacit knowledge that comes from the designer's experience. After this process, K_1 is improved, c.f. Fig. 12.

Take another task at_{A22} as example. In order to make K_1 arrive to a state that it can accomplish the task "To consider the adaptiveness in the context of use", an additional knowledge k_{A22} should be introduced. k_{A22} is likely to an explicit knowledge, which is characterized by a series of responses to the questions "who will use the chair", "where the chair will be used", etc.

Every time that K_1 reaches a state that can solve one more task, its value increases.

When knowledge reaches its final state, its value may not always be 100%, but it is not critical if people are already satisfied

Table 4
Values of the weights.

ω_A	ω_{A1}	ω_{A2}	ω_{A11}	ω_{A12}	ω_{A21}	ω_{A22}	ω_{A111}	ω_{A112}	ω_{A1121}	ω_{A1122}
(1) The values of the weights of Task A										
10%	70%	30%	80%	20%	60%	40%	30%	70%	50%	50%
ω_B	ω_{B1}	ω_{B2}	ω_{B21}	ω_{B22}	ω_{B211}	ω_{B212}	ω_{B221}	ω_{B222}	ω_{B2111}	ω_{B2112}
(2) The values of the weights of Task B										
50%	30%	70%	50%	50%	70%	30%	50%	50%	50%	50%
ω_C	ω_{C1}	ω_{C2}	ω_{C11}	ω_{C12}	ω_{C21}	ω_{C22}	ω_{C23}	ω_{C24}	ω_{C121}	ω_{C122}
(3) The values of the weights of Task C										
10%	60%	40%	50%	50%	25%	25%	25%	25%	50%	50%
ω_D	ω_{D1}	ω_{D2}	ω_{D3}	ω_{D11}	ω_{D12}	ω_{D13}				
(4) The values of the weights of Task D										
30%	30%	50%	20%	60%	30%	10%				

Table 5
The list of atom-tasks.

	Descriptions		K_1	K_2
at_{A111}	Perception test for the comfort issues		√	√
at_{A1121}	Ergonomic studies		√	√
at_{A1122}	Tests of the material attributes for the comfort issues		√	
at_{A12}	To consider the psychological comfort issues		√	√
at_{A21}	To consider the aesthetics of the chair		√	√
at_{A22}	To consider the adaptiveness in the context of use			
at_{B1}	To define a skeleton		√	√
at_{B2111}	To consider the geometry issues		√	√
at_{B2112}	To consider the material attributes for the structure issues		√	√
at_{B212}	To consider the positions of gravity centers		√	√
at_{B222}	To consider the calculation of swinging moments			√
at_{C11}	To calculate the costs of materials without considering optimization		√	√
at_{C121}	To calculate the costs of materials considering single-criterion optimization			
at_{C122}	To calculate the costs of materials considering multi-criteria optimization			
at_{C21}	To know the number of workers in the realization activities			
at_{C22}	To estimate the working time of each worker			
at_{C23}	To determine the salary of each worker			
at_{C24}	To evaluate the costs for collaboration			
at_{D1}	To consider the recycling issues	Material 1	√	√
		Material 2		√
		Material 3		√
at_{D2}	To consider the disassembly issues		√	
at_{D3}	To consider the interface issues			

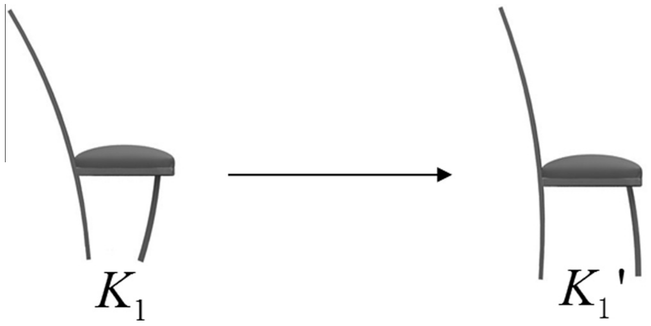

Fig. 12. Knowledge evolution: $K_1 \rightarrow K_1'$.

with its current value. In the given example, if we do not have to accomplish the task of "To calculate the cost of labor", knowledge can remain in a state that its value is not 100%. In such cases, people have to take some risks when they are going to the next stage of the product lifecycle.

5. Discussions

Compared to existing approaches existed, the quantitative measurement method proposed by this paper is the most distinguished feature. Table 6 shows the comparison among some existing methods.

Based on the comparison of existed methods shown in Table 6, we have implemented several tests to compare our approach using quantitative measurement method (Method 1) with approaches mainly based on questionnaire (Method 2 from Karacapilidis [19]) and designer experience (Method 3 from Hung et al. [18]). Test 1 is to design a T-shirt for our student football team, Test 2 is to design a cover of the admission brochure for 2014 autumn semester, Test 3 is to design a solution for business process reengineering (BPR) in medical care. We have selected 27 students, who are designers in the tests, and they are grouped randomly. Each group has 3 members, and the 9 groups are assigned to 9 cases (3 tests × 3 methods). The design results are evaluated by a group of 3 experts by scoring from 1 to 9. Table 7 shows the results of the tests.

In this set of tests, we simply invite several experts to give scores in order to evaluate the quality of results, because we do not have a quantification scoring system to judge the design results which greatly depend on human preference. Our quantification model can be used to choose the most valuable knowledge during the design process, but not applied in the judgment process when comparing different results from different methods. We may infer from the comparison results that in Test 3, Method 1 shows its advantage better. This is because BPR design relies more on engineering methods than artistic innovation, and in such case, the quantification method can better show its advantage.

Table 7
Tests results.

Average score	Method 1	Method 2	Method 3
Test 1	8.3	7.3	8
Test 2	8.3	8.3	8
Test 3	9	8	7.7

In order to make further study, we have extended Test 1 to a competition of T-shirt pattern design on the theme of graduation, and then compare the results of our knowledge evaluation method and subjective judgments from 110 experts and students, and each participant can vote for at most 2 candidate design solutions. In all, we have 171 votes. Table 8 shows the results of knowledge value obtained by the evaluation method and the subjective judgments.

The results indicate that values obtained from the proposed method basically meet people's subjective judgments in real life, which represents a rational link between "how much the knowledge value is", which is calculated from the knowledge evaluation method, and "how useful the knowledge is" in people's mind.

The proposed approach mainly operates with formal modeling of knowledge and deals with engineering modeling (requirements) and engineering preferences (decision making). In case of preferences, utility function is often considered as well. Utility can be regarded as the usefulness of a product in response to the expectations of the customers. It is the measure of how a product can meet the customers' requirements and is the sum of the individual performance characteristics of a particular product. In product design process, designers are assumed to have in mind a utility function that he/she maximizes to make the selection in multi-attribute decision making. For more complex cases, Maddulapalli et al. [22] have presented an algorithm for calculating the "robustness index" in case where decision makers give estimates of the end users' needs preferences. The algorithm is applicable to cases where product designers do not have enough information about the precise end users' preferences or decision makers' value function is implicit. In the case where customer involvement is considered in product lifecycle design and support, Chen and Yan [10] have proposed a customer utility prediction system, which comprises design knowledge acquisition module and customer utility evaluation module. In the former module, design options can be generated from a design knowledge hierarchy, and customer-sensitive design criteria are solicited from customer requirements. In the later module, a measurement for customer desirability called customer utility index is introduced, and it is proved to be useful to represent multicultural customer preference towards various design options. Karande et al. [20] have proposed an approach based on utility concept and desirability function to help designer make the right choices for particular engineering applications. To better combine utility issue with our approach, future research may aim at improving our

Table 6
Comparison of different methods.

Method proposed by	Basic content	Evaluation	Effectiveness
Karacapilidis [19]	A web-based knowledge management system for assisting the manufacturing strategy process	Based on questionnaire testing user's perceived usefulness and the perceived ease of use	Aiding a team of managers to reach a decision
Hung et al. [18]	A framework which integrates quality function deployment and design structure matrix to support product design planning	Based on many years of experience of working in industry	Providing a spectrum perspective for an early new product design project from needs analysis to design plan
Chen [12]	An architecture for integrating knowledge management systems and business process management systems	No quantitative evaluation	Process designers can use existing process templates and execution results stored in a process repository when design or redesign processes; Process/activity performers can be provided with the right knowledge at the right time
Our method	Effects between knowledge and product are analyzed, and knowledge values are assessed	Based on a theoretically proved model	Assisting designers to decide which knowledge to choose and what problem to solve next

Table 8
Results of the T-shirt pattern design competition.

	Number of vote for the candidate	Value obtained from the proposed method
Candidate 1 	48 (48/171 ≈ 28.1%) Rank: 1	0.80 Rank: 1
Candidate 2 	24 (24/171 ≈ 14.0%) Rank: 5	0.60 Rank: 5
Candidate 3 	29 (29/171 ≈ 17.0%) Rank: 4	0.65 Rank: 4
Candidate 4 	32 (32/171 ≈ 18.7%) Rank: 3	0.75 Rank: 2
Candidate 5 	38 (38/171 ≈ 22.2%) Rank: 2	0.75 Rank: 2

model by taking into accounts not only engineering requirements but also personalized preferences characterized by utility function. Possible correlation of utility function based on various criteria is worth being studied as well.

Multi-Disciplinary Design is also an advanced area of application for the approach proposed in the paper. It is a very challenging problem because it includes both the complexity of design and the intrinsic complexity of multi-disciplinarity, where unpredictable coupling of design parameters usually happens [28]. For many complex products, such as electromechanical complies and e-Business systems, the demands posed on the performance are quite exhaustive, and these demands from different disciplines (mechanics, networks, systems engineering, marketing, management, etc.) have to be integrated together in close harmony. In such situations, design issues often require more than one simple optimization of a number of parameters [13]. Chen et al. [11] have proposed a knowledge-based framework for conceptual design of multi-disciplinary systems. Through reusing and synthesizing known principle solutions in various disciplines together, it can help designers who are lack of sufficient multi-disciplinary knowledge. When applying the approach introduced in this paper, knowledge from different disciplines can be evaluated and compared though a domain-independent method, which may reduce the complexity when designers determine the optimized solution.

In real life application, effective software is more and more used to help designers make better-informed decisions in the complex and iterative process in product lifecycle design and support. The computer-based intelligent assistants are quite useful to simultaneous and collaborative design processes which depend on effective transfer of knowledge between persons/teams. These tools are useful to study the traceability of product design and foresee future developments [8]. Design rationale can be effectively re-used across design generations [17]. Tang et al. [27] have introduced a rationale-based architecture model (AREL) to capture design rationale and help people understand architecture design. The AREL model, constructed by UML, uses motivational reasons and design rationale, which is comprised of qualitative rationale, quantitative rationale and alternative design options. For industrial practice, Bracewell et al. [6] have developed a simple and unobtrusive software tool, Design Rationale editor (DRed), which allows engineering designers to record their rationale as the design proceeds. It is implemented in a multinational aerospace company and allows the issues addressed, options considered, associated pro and con arguments, etc., to be captured. Possible integration of the proposed approach of this paper with software used in real-life design will be quite meaningful. The quantification model may help designers choose the most valuable knowledge from the knowledge base (or the knowledge network if various stakeholders are involved in) and explore the push service and prompt function of the existed software. By calculating the most (or the top-N) valuable knowledge in the current state, the system could remind the designer which knowledge he/she may need, and this will help product design, development and innovation.

6. Conclusions

Knowledge evaluation is a key issue in knowledge management. This paper has presented a novel knowledge evaluation model for product lifecycle design. The quantitative approach set a measurable standard to determine which a "better" design is. Although product design has its subjective aspect, an objective standard can help designers evaluate their design plans at an early stage. The model integrates the process of knowledge evolution and product development, and the mutual effects between knowledge and product are analyzed. Based on the theoretical definitions and models, this paper illustrates how knowledge value can be assessed by studying a specific case. In the applications of product lifecycle design, knowledge values calculated by the model can serve as important factors in a decision making system that decides which knowledge to choose and what to do next. Moreover, as there is lack of unified standard of knowledge evaluation in product design process, which brings a barrier to communications among different design platforms, this paper has addressed this problem and set an evaluation framework that can be widely used in product design activities. The model could serve as a base to describe the knowledge related activities and could be a useful tool for managing knowledge in product lifecycle design and support.

One limitation of the model is that it mainly deals with single-loop learning [3] and thus is lack of double-loop learning and innovation. Innovation issues are not much discussed either, although the role of innovation is stressed in successful enterprises and knowledge creation is positioned at the core of it [30]. As knowledge is often described as a coherent web of claims and statements, the problem of "knowledge fragments dependencies" is often discussed, because one specific idea (regarded as a knowledge fragment) may easily stimulate another idea (regarded as another knowledge fragment). This topic is related to innovation, which is not much discussed in this paper, and it could be a very interesting and valuable research in the next step. Interesting perspectives may also include deeper analysis about the optimization issues of weights, dynamic product development processes, parallel and distributed product development systems, etc. Implemented in a decision support system (DSS) and integration with existing product design tool such as Rhinoceros and AutoCAD also need further research and collaboration.

Acknowledgements

This work is partly supported by the National Social Science Foundation of China (No. 13CTQ022) and the National Natural Science Foundation of China (No. 51205344). We would like to appreciate Prof. Robert B. Allen from Research Center for Knowledge Communities (RCKC) of University of Tsukuba, for his helpful suggestions and support.

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