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Robustness Analysis of Super Network Consisting of Product Development Tasks, Customers and Customers' Knowledge

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Abstract

Collaboration with customers is increasingly important for the new products development. The process of new product development can be seen as the process of tasks completion. During this process, customers use their specific knowledge to support the completion of product development tasks. Tasks, customers and their knowledge, which are interrelated and interacted, can form a network. In this paper, the characteristics of tasks, customers and their knowledge are analyzed. Moreover, the relationship among them are described and analyzed by using the super network approach. Based on this, we propose the method of associated node removal to analyze the robustness of network. Unique knowledge, the proportion of unique knowledge, invulnerability of network and core knowledge are three indicators to measure the robustness of this network. The results of this paper can help the firm to judge the importance of different customers and their knowledge, find the easy-to-lose knowledge and evaluate the safety of knowledge resources.

Key words: *product development, customer, super network, knowledge, robustness*

1. Introduction

With the increasing competition in markets today, firms are gradually recognizing the importance of being better and faster to develop new products than their competitors, which can help them to obtain market competitive advantage and earn more revenue returns [1]. However, the rapid changes of external environment, such as economy and technology, force firms to rely on not only its own resources but also external knowledge, resources and technology. Customers as one of the most important external resources [2], it is valuable to integrate them into new product development. Customer collaboration can help firms to get the knowledge and ability about product innovation from the customers, and achieve the target of improving the quality and market satisfaction of new products [3-5].

Firms need to complete a series of tasks when they develop a new product. To a certain extent, the process of product development can be seen as the course of fulfilling a few tasks. During this process, many different resources are needed, such as knowledge, funds, and material. As a result, customers are needed to collaborate with the firm during the development of new product. Because they have some knowledge [6], which technical staffs of firms do not have, such as demand information, knowledge and the experience of using products etc. By using the above knowledge, customers can support and fulfill the certain tasks of product development. In this paper, customers' knowledge only refers to the knowledge that related to product development.

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These customers collaboratived in product development have different knowledge storage and structure [7]. Moreover, different tasks make different requests for the customers' knowledge. These two aspects decide the fact that customers play different role in the process of product development. Some customers may be critical for the development of new product. At the same time, some customers may not be so important relatively. The important customers and their knowledge are critical to complete product development tasks. If they are drain or not want to participate in product development, their knowledge will lost at the same time. This problem could cause the result that tasks cannot be completed in time. So, for the firms, which want to collaborate with customers in the process of product development, the following problems are needed to analyze and solve urgently. How to analyze the importance of different customers and their knowledge? How to prevent the loss of knowledge resources, and improve the ability of response to knowledge loss that caused by customers drain? How to evaluate the effect of customers drain to product development? In this paper, these problems are boiled down to the problem of the robustness of the network, which consist of product development tasks, customers and their knowledge. This paper defines this network as TKC .

The purposes of this study analyzes the robustness of the TKC network include three aspects. First, evaluate the importance of customers. Second, analyze the proportion of unique knowledge that owned by a customer. Third, analyze the invulnerability of the network. In other words, for each product development task, it's to analyze the minimum number of customers who are removed that result in a certain percentage of knowledge loss.

Currently, a number of researches discussed the robustness of network. The main research objects are focus on biological network[8-10], Internet, and WWW [11, 12] *etc*. The common methods that used to analyze the robustness of these networks are no different, *i.e.*, analyze the variation of the topology and functional of the network when remove nodes or edges from the network randomly and selective. However, in this paper, for the network consisting of tasks, customers and their knowledge, it is different from the above networks. (1) Customer is different from other objects in the network like biological network, Internet, and WWW. (2) Knowledge, as a kind of information resource, is owed by customers and in a state of dynamic change. The change of customers' position, learning ability, experience etc. will lead to the change of their knowledge. Therefore, the change of customers influence on the knowledge that supports the completion of product development tasks. (3) Compared to the network that consist of individual or knowledge alone, customers and their knowledge in the network are interconnected. If we remove customers from the network, the corresponding knowledge will be loss at the same time. Therefore, the common method has limitation to analyze the robustness of the TKC network.

In this paper, we study the product development tasks, customers and their knowledge comprehensively and jointly. Moreover, the method of associated node remove is adopted to analyze the robustness of TKC network, *i.e.*, a customer is removed, the corresponding knowledge will be removed then. The characteristics of product development tasks, customers and their knowledge are illustrated, and the model of the Super-network TKC is constructed in section 2. Section 3 analyzes the robustness of TKC . There is an illustrative example followed by in section 4. The final section concludes the paper.

2. Establishment of the Super Network TKC

2.1. The Hierarchical Network of Product Development Tasks

Product development is a complex project, which consists of a number of tasks. To improve the efficiency and effectiveness of the tasks completion, task decomposition is a practical way [13]. There are many advantages for task decomposition. Firstly, let customers and product developers understand the number of tasks needed to complete. Secondly, let them know the relationship among these tasks. Thirdly, compared with analyzing the resources and material of product development work, it is more convenient and accurate to analyze the requirements of each task. This paper uses work breakdown structure to decompose product development tasks [14].

The entire product development work is decomposed into multiple main tasks based on workflow or content. Then each main task is decomposed into subtasks continually, until it cannot be broken down. The procedure of task decomposition is shown in Figure 1.

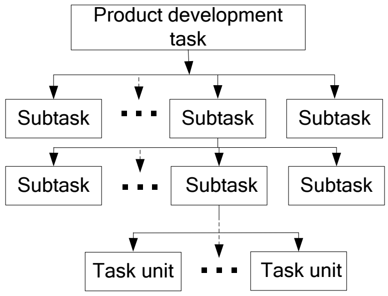

Figure 1. The Breakdown Structure of Product Development Tasks

There are three types of relationship among these subtasks. The first is the time sequence of tasks, namely the serial and parallel relationship. The second is the containment relationship. The superior task is decomposed into multiple subordinate tasks. This study calls the superior tasks as the parent tasks, and the subordinate tasks as subtasks. The third is the overlapping relationship. A subtask may belong to multiple different parent tasks. The minimum level of indecomposable subtasks is called task unit. Task units are relatively independent, whose contents are simple and easy to account and understand for product developers and customers.

There are multiple levels of tasks in Figure 1. Tasks at each level represent the different scale. This paper regards the minimum level task unit as a task point. The tasks at the different levels can be measured by the number of task points it contains. These task points, which are interrelated and interacting, constitute a network of product development tasks. This study uses a hierarchical network model to represent the structure of tasks.

In the network, the task points are seen as the network nodes, the direct affiliation relationship among tasks act as edge. Based on this, the hierarchical network of product development tasks is built, and denoted as $T-T$ network:

$$G_T = (T, E_{t-t}) \tag{1}$$

$T=\{t_1, t_2, ..., t_n\}$ is the set of task points. $E_{t-t}=\{(t_i, t_j) \mid \alpha(t_i, t_j)=1\}$ is the set of edges. $\alpha(t_i, t_j)=1$ represents that there is a direct affiliation relationship between task t_i and task t_j. On the contrary, $\alpha(t_i, t_j)=0$ represents no direct affiliation relationship between them.

2.2. The Hierarchical Network of Customer's Knowledge

In the product development process, customers will form an organization, with sharing and integrating their knowledge. And it will develop a set of knowledge [15]. The knowledge refers to the demand information, using knowledge, creative ideas, and solutions of product.

Due to the complexity of knowledge structure. The common methods like Product Data Management (PDM) and Extensible Markup Language (XML) are difficult to describe the knowledge in the semantic information level. Meanwhile, different customers have different comprehension for the same concept according to their preferences or expression under different backgrounds and environments, which is not conducive to the matching between customers' knowledge and tasks, likewise with the sharing of knowledge. Ontology theory can effectively compensate for these shortcomings. The ontology is a kind of conceptualize description for concepts and relationships. The ontology theory can contribute to the sharing and analysis of customers' knowledge. This study describes the customers' knowledge, and build ontology tree of them based on the ontology theory. It is shown in Figure 2.

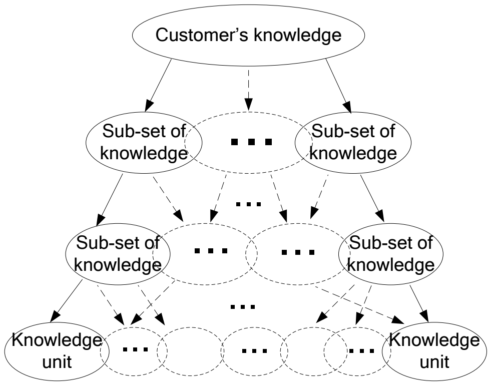

Figure 2. The Ontology Tree Model of Customer's Knowledge

In the ontology tree model, there are various types of complex relationship between knowledge elements. Firstly, inclusion relationship, the lower set of knowledge is a part of the higher set of knowledge. Moreover, the lower set of knowledge is called as sub-set of knowledge, the higher set of knowledge is called as parent set of knowledge. Secondly, cross relationship, a sub-set of knowledge may belong to different parent set of knowledge. Thirdly, there is a link on the contents, two different knowledge points may related to the same object, things, events and others.

In this paper, the minimum sub-set of knowledge is called knowledge unit. These knowledge units are belonging to the small domain, relative independent and have clear meaning. Moreover, it's easy to understand without additional definition or description for customers and product developers. These knowledge units act as knowledge points in this paper. Therefore, the set of customer's knowledge containing many knowledge points forms a network. We use a hierarchical network model to represent the structure of customers' knowledge.

In the network, setting knowledge points act as the network nodes, the directly affiliation relationship among tasks act as edge. Based on this, customer's knowledge network is built, and denoted as $K-K$ network:

$$G_K = (K, E_{k-k}) \tag{2}$$

$K=\{k_1,k_2,...,k_m\}$ represents the set of knowledge points, $E_{k-k}=\{(k_i,k_j)\,|\,\alpha(k_i,k_j)=1\}$ represents the set of edges. $\alpha(k_i,k_j)=1$ represents that there is direct affiliation between knowledge point k_i and k_j. On the contrary, $\alpha(k_i,k_j)=0$ represents no direct affiliation between two knowledge points.

2.3. The Network of Customers

According to the analysis of chapter 2.2, customers who collaborate in product development can be seen as a smart client unit [16]. These customers are interrelated and interacted with each other and constitute a relationship network. In this network, the nodes represent customers. The edges represent the relationship among them. This study establish a network of customers:

$$G_C = (C, E_{c-c}) \quad (3)$$

$C = \{c_1, c_2, ..., c_s\}$ represents the set of customers. $E_{c-c} = \{(c_i, c_j) | \alpha(c_i, c_j) = 1\}$ represents the set of edges. $\alpha(c_i, c_j) = 1$ represents that there is a direct interaction between customer c_i and c_j.

2.4. The Super Network Model of TKC

The above three kinds of networks are correlative. The relationship between the $T-T$ network and $K-K$ network can be expressed as demand and support. Each task in the $T-T$ network requires different types and values of knowledge from the $K-K$ network. Each knowledge point supports and facilitates the completion of one or several tasks in the $T-T$ network.

The relationship between the $K-K$ network and $C-C$ network is mainly mapped and integrated. There exists mapping relationship between each knowledge point and the customer. Each knowledge point has its owners that may be one customer or many customers. Integrating, classifying and decomposing knowledge from all customers are in the $C-C$ network, and each knowledge point will be got in the $K-K$ network.

The relationship between the $T-T$ network and $C-C$ network can be depicted as assigning and promoting. Each task in the $T-T$ network is assigned to different type of customers in the $C-C$ network by considering its characteristics. At the same time, customers in the $C-C$ network use their knowledge to promote the completion of single task or multiple tasks.

In the customer collaborative product development process, these three networks have multi-level features, and linkages among them. This paper studies the relationship of these three networks by using the ideas and methods of the super network. Super network is proposed by American scientists Nagurney et al. when they are solving the interweave problem of logistics network, information networks and financial networks[17]. Based on the above analysis, the super network consisting of $T-T$ network, $K-K$ network and $C-C$ network is shown in Figure 3. We named this network as TKC super network.

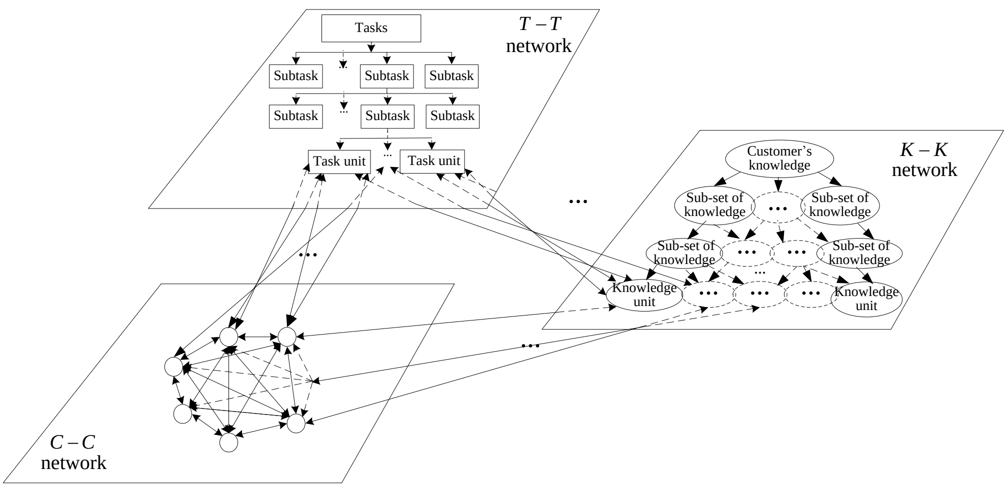

Figure 3. The Super-Network of TKC

In Figure 3, the relationship between the $T-T$ network and $K-K$ network is expressed as follows:

Boolean variable $\beta(t_i, k_j)$ represents the relationship between tasks t_i and knowledge k_j. If task t_i requires knowledge k_j, then $\beta(t_i, k_j) = 1$. Otherwise, $\beta(t_i, k_j) = 0$. For task t_i, the set of needful knowledge can be expressed as:

$$K(t_i) = \{k_j | k_j \in K, \beta(t_i, k_j) = 1\} \quad (4)$$

Boolean variable $\beta(k_i, t_j)$ represents the relationship between knowledge k_i and task t_j. If knowledge k_i can support the task t_j, then $\beta(k_i, t_j) = 1$. On the contrary, $\beta(k_i, t_j) = 0$. For knowledge k_i, the set of supported tasks can be expressed as:

$$T(k_i) = \{t_j | t_j \in T, \beta(k_i, t_j) = 1\} \quad (5)$$

Based on the above analysis, this study synthesizes the $T-T$ network and $K-K$ network, and builds the super network model of task-knowledge:

$$TK = (G_t, G_k, E_{t-k}) = (T, K, E_{t-t}, E_{k-k}, E_{t-k}) \quad (6)$$

E_{t-k} represents the relationship between tasks and knowledge.

The relationship between the $K-K$ network and $C-C$ network is expressed as follows:

Boolean variable $\gamma(k_i, c_j)$ represents the relationship between knowledge k_i and customer c_j. If knowledge k_i is a part of the knowledge system of customer c_j, then $\gamma(k_i, c_j) = 1$. Otherwise, $\gamma(k_i, c_j) = 0$. For knowledge k_i, the set of customers who own it can express as:

$$C(k_i) = \{c_j | c_j \in C, \gamma(k_i, c_j) = 1\} \quad (7)$$

Boolean variable $\gamma(c_i, k_j)$ represents the relationship between customer c_i and knowledge k_j, If customer owns knowledge k_j, then $\gamma(c_i, k_j) = 1$. Otherwise, $\gamma(c_i, k_j) = 0$. For customer c_i, the set of knowledge that he owns can be expressed as:

$$K(c_i) = \{k_j | k_j \in K, \gamma(c_i, k_j) = 1\} \quad (8)$$

Based on the above analysis, this study synthesizes the $K-K$ network and $C-C$ network, and gets the super network model of knowledge-customer:

$$KC = (G_k, G_c, E_{k-c}) = (K, C, E_{k-k}, E_{c-c}, E_{k-c}) \quad (9)$$

E_{k-c} represent the relationship knowledge and customers.

The relationship between the $T-T$ network and $C-C$ network is expressed as follows:

Boolean variable $\phi(t_i, c_s)$ represents the relationship task t_i and customer c_s. If the task need involvement of customer c_s, then $\phi(t_i, c_s) = 1$. Otherwise, $\phi(t_i, c_s) = 0$. For the task t_i, the set of customers that it needs can be expressed as:

$$C(t_i) = \{c_s | c_s \in C, \phi(t_i, c_s) = 1\} \quad (10)$$

Setting Boolean variable $\phi(c_s, t_j)$ represents the relationship between c_s and task t_j. If customer c_s participates in task t_j, then $\phi(c_s, t_j) = 1$. Otherwise, $\phi(c_s, t_j) = 0$. For customer c_s, the set of tasks that he collaborative is expressed as:

$$T(c_s) = \{t_j | t_j \in T, \phi(c_s, t_j) = 1\} \quad (11)$$

Based on the above analysis, this study synthesizes the $T-T$ network and $C-C$ network, and gets the super network model of task-customer:

$$TC = (G_t, G_c, E_{t-c}) = (T, C, E_{t-t}, E_{c-c}, E_{t-c}) \quad (12)$$

E_{t-c} represents the relationship between tasks and customers.

In summary, the super-network model that consists of task, customer's knowledge and customer is built, which denote as TKC :

$$TKC = (G_t, G_k, G_c, E_{t-k-c}) = (T, K, C, E_{t-t}, E_{k-k}, E_{c-c}, E_{t-k}, E_{t-c}, E_{k-c}) \quad (13)$$

3. Analysis of the Robustness of TKC Network

For each task in product development process, its completion needs some customers to collaborate and provide their knowledge. Customers and their knowledge are correlative, it is infeasible to remove customers from $C-C$ network or remove knowledge from $K-K$ network separately. In this study, we adopt the method of associated node remove. A customer in the $C-C$ network first is removed, and then his corresponding knowledge in the $K-K$ network is removed follow. After that, the effect is analyzed.

Based on the above method, three indicators are used to measure the robustness of TKC network.

(1) Unique Knowledge (UK)

In this paper, unique knowledge represents those knowledge that is only owed by a customer in the customer organization.

Let t_i denotes a product development task. $C=\{c_1,c_2,...,c_s,...,c_n\}$ is the set of customers that needed in the process of task t_i completion, n is the number of customers. c_s is s th customer. $K=\{k_1,k_2,...,k_j,...,k_m\}$ is the set of knowledge that owned by these n customers. Where m is the number of knowledge points. k_j is j th knowledge point. The set of knowledge can be collected through interview, test and other methods.

Step 1: Analyze the degree of task demand for knowledge

Since different tasks have different contents, characteristic, and quality demands etc. Therefore, it needs different knowledge, and different knowledge plays different roles.

This study defines φ_{ij} as the effect of knowledge point k_j to the task t_i. The larger of φ_{ij}, the more critical the knowledge point k_j to the task t_i. The value of φ_{ij} is determined by the knowledge domain experts and firm personnel.

Step 2: Analyze the stock of knowledge mastered by a customer

Customer's knowledge system is composed of different types of knowledge, which belongs to different fields and used to solve different problems. At the same time, for the different knowledge, the degrees of customer master are different. This study uses the stock of knowledge in customer's knowledge system to denote the degree of mastery of this knowledge.

Let $KS(c_s)$ represents the set of knowledge that mastered by customer c_s. w_{sj} denotes the stock of knowledge k_j in customer c_s knowledge system. So $KS(c_s)$ can be defined as:

$$KS(c_s) = f(c_s, K) = \left\{(k_j, w_{sj}) \middle| k_j \in K, \gamma(c_s, k_j) = 1\right\} \tag{14}$$

The stock of knowledge k_j in all customers is defined as $w(k_j)$, and it's calculated by equation (15).

$$w(k_j) = \sum_{s=1}^{n} w_{sj} \tag{15}$$

Step 3: analyze unique knowledge

For customer c_s, the unique knowledge can be represented as:

$$UK(c_s) = \left\{k_j \middle| k_j \in K, \gamma(c_s, k_j) = 1, w(k_j) = w_{sj}\right\} \tag{16}$$

The number of knowledge points which are only owned by customer c_s is

$$NUK(c_s) = \sum_{j=1}^{m} \left[\gamma(c_s, k_j) = 1 \middle| w(k_j) = w_{sj}\right] \tag{17}$$

The set of unique knowledge of all customers can be expressed as:

$$UK = UK(c_1) \cup UK(c_2) \cup ... \cup UK(c_n) \tag{18}$$

The total number of unique knowledge of all customers defined as:

$$NUK = \sum_{s=1}^{n}\sum_{j=1}^{m}\left[\gamma(c_s,k_j)=1 \middle| w(k_j)=w_{sj}\right] \tag{19}$$

Therefore, the effect of unique knowledge of customer c_s to the task t_i is calculated by equation (20).

$$E_{is} = \sum_{j=1}^{m}\varphi_{ij}UK(c_s) \tag{20}$$

It's important to note that the above equations and models must be analyzed based on the same standard and the same environment. Without the specific environment, the all mathematical calculation and analysis are meaningless.

(2) The proportion of unique knowledge

For the task t_i, the proportion of unique knowledge can be denoted as r_i. Moreover, it represents the proportion of unique knowledge in the set of knowledge, which can be expressed as:

$$r_i = NUK/n = \sum_{s=1}^{n}\sum_{j=1}^{m}\left[\gamma(c_s,k_j)=1 \middle| w(k_j)=w_{sj}\right]/n \tag{21}$$

The unique knowledge and the proportion of unique knowledge reflect the knowledge that owned by one customer. The unique knowledge is easy to lose when these customers drain. So the higher proportion of unique knowledge, the lower robustness of TKC network.

In terms of firm which develop new product with collaborative customers, it is important to take steps to protect unique knowledge, For example, encouraging communication and sharing among customers and firm personnel, recording these unique knowledge, learning and translating into the own assets of the firm. Through these actions, the safety of these knowledge can be guaranteed. In addition, the above methods and process are also used to measure the important of each customer from perspective of knowledge. Let η_s denotes the knowledge of customer c_s accounts for the knowledge set K. The higher η_s is, the more important of customer c_s will be.

$$\eta_s = \sum_{j=1}^{m}w_{sj} / \sum_{j=1}^{m}w(k_j) = \sum_{j=1}^{m}w_{sj} / \sum_{s=1}^{n}\sum_{j=1}^{m}w_{sj} \tag{22}$$

(3) Invulnerability of TKC network

The invulnerability of network is directly related to the security and reliability of network [18]. For the task t_i, the invulnerability of TKC network refers to the minimum number of lost customers that caused a certain proportion of knowledge loss.

Let r' denote the proportion of knowledge loss, q' represent the minimum number of customers that are needed to remove. The remove method is like the selectivity attacks of complex networks. Customers who own more knowledge are removed firstly. At the same time, remove the corresponding knowledge from $K-K$ network. The total knowledge that removed from $K-K$ network account for the set of knowledge K (i.e. r') reflects the sensitivity of knowledge loss to customers drain.

(4) Invulnerability of core knowledge in the TKC network

As discussed above, φ_{ij} denotes the effect of knowledge point k_j to the completion of task t_i. The larger φ_{ij} is, the more critical of knowledge point k_j. Different knowledge have different value of φ_{ij}. This study defines the knowledge that is critical for tasks as core knowledge. It is important for the firm to prevent the core knowledge lossing.

For the task t_i, invulnerability of core knowledge in the TKC network refers to the minimum number of customers drain that caused a certain proportion of core knowledge loss. Let r'' denote the proportion of core knowledge loss, q'' represents the minimum number of customers are needed to remove. The remove method is also selectivity removes. r'' and q'' reflect the sensitivity of core knowledge loss to customers drain.

For other tasks in the process of product development, it's useful to use the three indicators to measure the robustness of network. The results of above analysis of the robustness of network can be used to help firms analyze the unique knowledge, judge the important customers, manage knowledge, and prevent important customers and their knowledge from losing.

4. Case Study

This section presents a mobile phone design case to verify the proposed method in this paper. A firm wants to develop a new mobile phone mainly for the mid-and-low-end customers in China. In order to develop this product more effectively and improve customer's satisfaction, fifteen customers forming a group are invited to collaborate. Moreover, they are communicating and sharing their knowledge and ideas.

(1) Tasks of mobile phone design

For simplicity, take mobile phone interface design as an example to illustrate the process of tasks decomposition. The tasks of mobile phone interface design mainly include icon elements design, text elements design, color elements design, and interface format design. Then these four tasks are decomposed as shown in Figure 4.

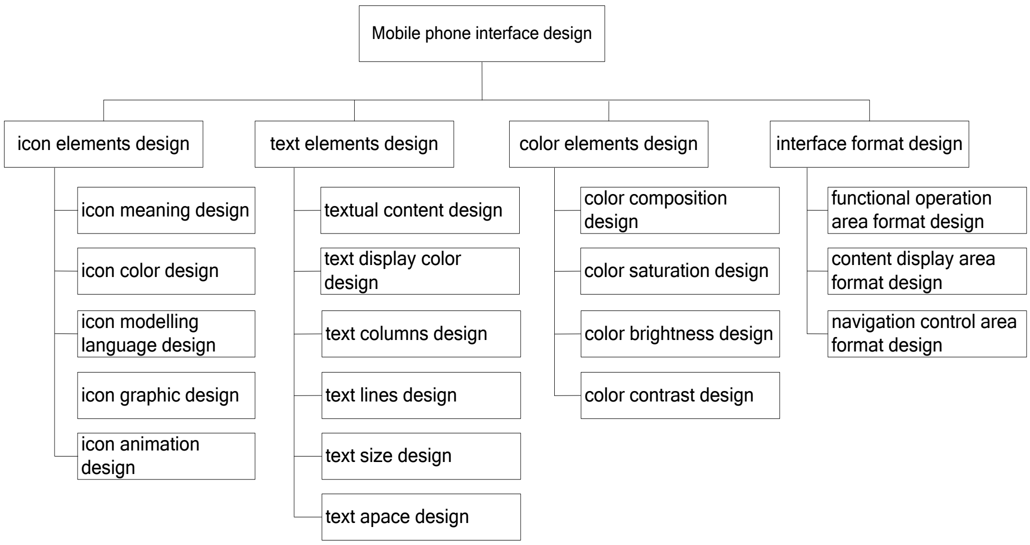

Figure 4. Task Decomposition of Mobile Phone Interface Design

(2) Customer's knowledge acquisition

The experts and firm personnel collect customers' knowledge that are related to mobile phone interface design, and form a sheet. An example is shown in Table 1.

Table 1. The Sheet of Customer's Knowledge

Customer ID	XXX		**Customer type**	Lead user	
Biography	Education background	Work experience	Specialty	Interests	…
Knowledge domain	Basic knowledge	Requirement information	Creative knowledge	Perceptual knowledge	…
Description	This refers to description of customer's knowledge by using text language.				
Application scope	This refers to the functions of customer's knowledge to the mobile phone interface design.				
The degree of mastery	Very good	Good	Not good	Bad	Very bad

(3) Establishment of $C-C$ network

In the $C-C$ network, customers act as nodes, the relationship among customers act as edges (figure 5). The relationship mainly refers to knowledge exchanging and sharing.

(4) Establishment of $K-K$ network and TKC network

For the collected customers' knowledge, it needs to analyze and merge these customers' knowledge points. According to the method in the literature[19], the ontology tree of customers' knowledge is constructed (Figure 6). Then customers' knowledge points act as nodes, the affiliation between knowledge points act as edges, and the $K-K$ network is formed as shown in Figure 7.

Based on this, the network consisting of customers and their knowledge is built. The figure 8 is for the task of icon animation design.

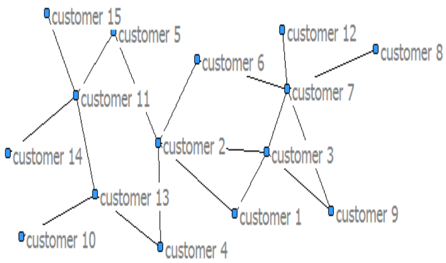

Figure 5. $C-C$ Network, Drawn by Ucinet 6[20]

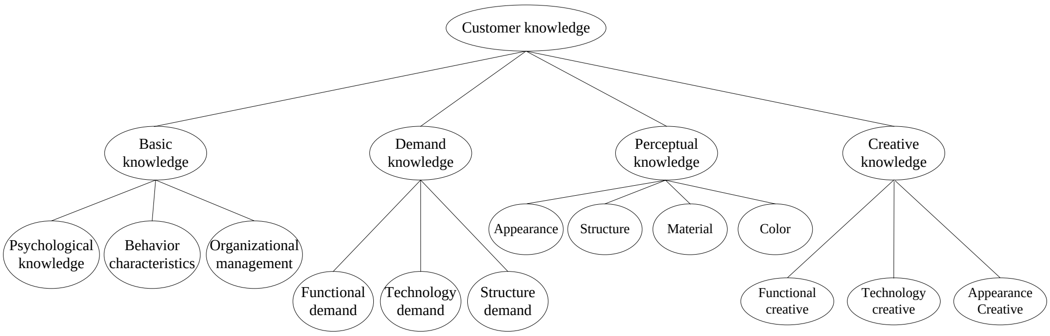

Figure 6. Part of Ontology Tree of Customer's Knowledge

Figure 7. $K-K$ **Network**

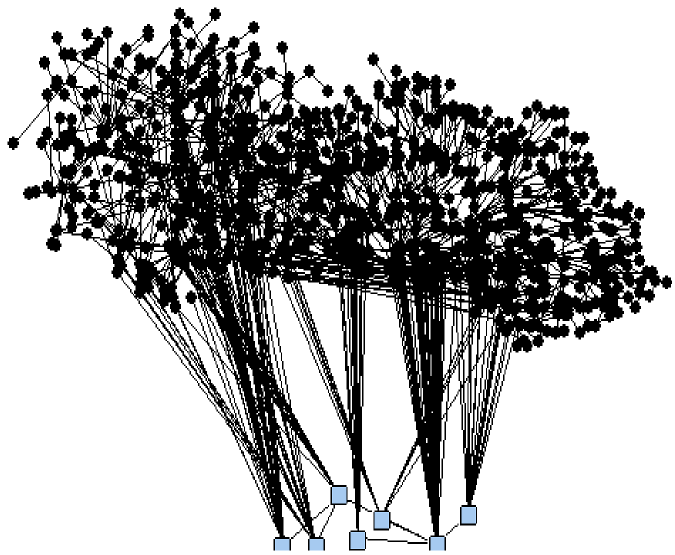

Figure 8. The Super-Network of Part of Customers and their Knowledge

(5) The robustness analysis of network

For the task of icon animation design, the unique knowledge and the proportion of unique knowledge are analyzed based on above analysis. The results are as below:

Table 2. The Results of Unique Knowledge and the Proportion of It

The total knowledge points	Unique knowledge	The proportion of unique knowledge
1032	689	66.76%

According to equation (3-9), the importance of these fifteen customers and the proportion of their unique knowledge and core knowledge are analyzed. The importance of these fifteen customers is ranked based on the proportion of their core knowledge. The results are as below:

Table 3. The Results of the Proportion of Customers' Unique Knowledge and Core Knowledge

Customers	the proportion of unique knowledge	The proportion of core knowledge	Order of importance
C_1	6.21%	8.31%	5
C_2	9.21%	8.38%	4
C_3	12.36%	11.16%	2
C_4	6.98%	2.36%	14
C_5	5.78%	5.62%	8
C_6	5.31%	7.25%	7
C_7	14.04%	17.81%	1
C_8	7.12%	7.63%	6
C_9	6.42%	4.56%	10
C_{10}	1.19%	2.42%	13
C_{11}	9.63%	10.28%	3
C_{12}	7.27%	5.46%	9
C_{13}	4.14%	3.29%	12
C_{14}	3.26%	1.12%	15
C_{15}	5.08%	4.35%	11

Experts and product developers evaluate the core knowledge of customers, which is critical to complete the tasks.

For the invulnerability of network, the customer with the highest proportion of unique knowledge is removed from $C-C$ network firstly. Then the loss of knowledge is analyzed. Then, the secondary customer is removed, and the total loss of knowledge is analyzed, and so on. For the core knowledge in the network, the same method is used to analyze its invulnerability. Therefore the relationship between r' and q', r'' and q'' can be illustrated as shown in Figure 9. Considering that the number of customers is small, only seven customers are removed.

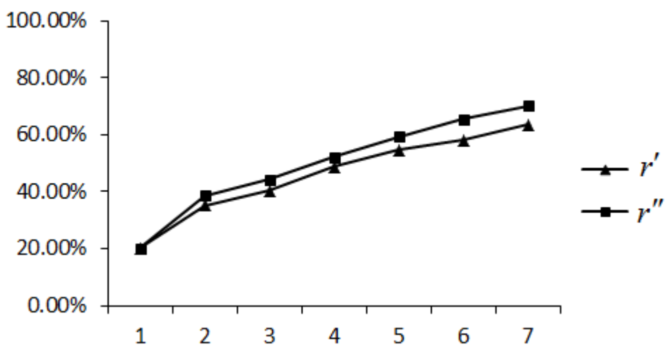

Figure 9. The Invulnerability of Network and Core Knowledge

5. Conclusions

With the increasing competition in markets, firms which are subject to rapid changes of external environment need to develop new products better and faster than their competitors. These demands make the external resource, especially customers and their knowledge, so important. It has been recognized widely that collaboration is of great importance in the development of products.

In summary, the main contribution of this paper is to analyze the characteristics of product development tasks, customers and their knowledge, and shed light on the relationships among them by using super network approach. In addition, a method of associated node removal was proposed to analyze the robustness of network. Moreover, four indexes were put forward to measure the robustness of this network. They were unique knowledge, the proportion of unique knowledge, invulnerability of network and core knowledge.

The results of our research may provide useful managerial implications. Different customers and their knowledge have different importance in the development of new product. The firm in resource-limited condition should let these limited resources play an important role in the product development process. In this paper, we analyzed the unique knowledge and its proportion of each customer. Managers can be aware of the importance of different customers and their knowledge, and take some actions to prevent customers and their knowledge from draining. The actions include the priority of resources usage for important customers, encouraging communication and sharing between customers and firm personnel, recording these unique knowledge, learning and translating into the own assets of the firm, etc. In addition, the analysis of invulnerability of network and core knowledge can help the firm to realize the importance of the safety of customer's knowledge and improving its ability to adapt quickly changes and protecting these knowledge that is easy to lose.

This work is not free from limitations. The increase of the number of customers, analysis of their knowledge and robustness of network should adopt the method of intelligent systems. Future studies may extend the development of intelligent systems to store and analyze customers' knowledge and measure the robustness of network.

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