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Computers in Industry 59 (2008) 242–253

COMPUTERS IN INDUSTRY

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Developing new products with knowledge management methods and process development management in a network

Hsing Hung Chen [a], He-Yau Kang [b], Xiaoqiang Xing [a], Amy H.I. Lee [c,*], Yunhuan Tong [a]

[a] College of Economics and Management, Tsinghua University, Department of Technology Economics Management, Beijing, China
[b] Department of Industrial Engineering and Management, National Chin-Yi University of Technology, 35, Lane 215, Sec. 1, Chung San Rd., Taiping, Taichung 411, Taiwan
[c] Department of Industrial Engineering and System Management, Chung Hua University, No. 707, Sec. 2, Wu Fu Rd., Hsinchu 300, Taiwan

Available online 16 August 2007

Abstract

When managing the problem of new product development (NPD), a firm needs to cooperate with or compete with its strategic partners in a network to survive in the industry. This paper first discusses the critical success factors (CSF) of NPD in a network, and then simplifies 37 CSFs into 10 items within 3 groups by factor analysis and Delphi method. While analytic hierarchy process (AHP) is capable of dealing with the NPD managerial problems by generalizing subjective judgment of experts, it cannot deal with the inter-relationship among factors or the usually imprecise and vague human judgment. To compensate this deficiency, analytic network process (ANP) incorporated with sensitivity analysis, instead of the popular fuzzy AHP model, is proposed, and a firm can make a decisive evaluation by applying the model. However, developing new products with strategic partners in a network is positively associated with efficiency and effectiveness and negatively with innovation. In order to lead a firm to operate efficiently, effectively and innovatively, the product lifecycle management (PLM) including suitable knowledge management (KM) and process development management is advised for the execution of the selected NPD mix. Balanced scorecard (BSC) using ANP with sensitivity analysis is then suggested to demonstrate the effectiveness of the proposed procedure and models.

Keywords: New product development (NPD); Analytic network process (ANP); Product lifecycle management (PLM); Knowledge management (KM)

1. Introduction

A survey done by Product Development and Management Association (PDMA) reveals that more than 50% of the sales in successful companies were coming from new products and that the percentage was even over 60% in the most successful overall company [1]. As a result, the advanced-technology product development and introduction process need to be improved to enhance a company's competitive advantage. Product lifecycle management (PLM) is a strategic business approach that consistently manages all lifecycle stages of a product, commencing from market requirements through the disposal and the recycling [2,3]. However, successful execution of new product development (NPD) must be implemented in most stages of PLM including market requirement, product concept, detailed design, process plan, production and so on. How to keep operating innovatively, effectively and efficiently is important, but the issue has never been simultaneously discussed before, especially in the perspective of supplier–buyer collaboration.

To survive in a highly competitive industry, strategies to collaborate with or compete with suitable firms within a network should be considered in the NPD process. The findings suggest that buyer–supplier collaboration is positively associated with efficiency and negatively with innovation [4]. Precisely speaking, as buyer–supplier collaboration leads to variance reduction and control, they may create incremental, exploitative innovation at the expense of radical, exploratory innovation [5]. As some authors correctly point out, the positive effects of buyer–supplier involvement happened at the strategic evaluation are not easily achieved in NPD processes [6], and the management of buyer–supplier involvement in innovation processes appears to be a critical factor [7]. Therefore, how to create radical, exploratory innovation is crucial in buyer–supplier collaboration. In order to

* Corresponding author. Tel.: +886 3 5186582.
E-mail address: amylee@chu.edu.tw (A.H.I. Lee).

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doi:10.1016/j.compind.2007.06.020

encourage knowledge creation in NPD process, a suitable knowledge management (KM) method needs to be selected based on the purpose for which knowledge is being managed during each stage of PLM [8]. In addition, a suitable process development management for the improvement of effectiveness and efficiency needs to be adopted at each of the PLM stages.

In this research, a model that adopts analytic network process (ANP) with sensitivity analysis is proposed to solve the NPD mix selection problem first. Then, with the strategic NPD mix selection result, PLM including suitable KM methods and process development management are integrated to keep a firm operating efficiently, effectively and innovatively in a network. The performances of NPD mix before and after PLM are analyzed last by a balanced scorecard (BSC) with ANP approach. This paper is organized as follows. In section two, the characteristics of NPD mix selection in a network and KM methods are introduced. Critical success factors (CSFs) and portfolio management of NPD is examined in Section 3. The ANP model with sensitivity analysis for evaluation and selection of NPD projects is constructed in Section 4, and a real case is examined in Section 5. In Section 6, the adoption of KM methods and process management are discussed, and the performance improvement after the adoption is presented. Some conclusion remarks and discussions are provided in the last section.

2. The characteristics of NPD mix selection in a network and KM methods

In industries with fierce competition, each company usually focuses on a certain part of the production process, such as design, components production, assembly, testing, transportation and distribution, marketing and so on, and then vertically or horizontally collaborate with each other, even to the extent of supporting competitors, to meet customer demand. Since the maximum profit of the network can be obtained by sharing the risk and the benefit with participants, it is important for corporations to collaborate in networks in order to develop capacity, capability and competence to perform new product development and become suppliers of complete systems. The early involvement of strategic suppliers and partners in a NPD has been shown to have a positive effect on the fundamental business drivers, time, cost and functionality of a product [9,10]. With the advantages of knowledge accumulation, powerful competency, resources utilization, core technologies, organizational learning, social capitals inside a network [11–13] and the requirement of an innovative environment for NPD [14,15], developing new products in a network dominates main trend in the industry [16].

The skills of management leading to innovation and efficiency/effectiveness are different and contradictory [17]. Efficiency requires coordination and cooperation and results in the improvement of development schedule and development cost; effectiveness requires standardization, control and conformity to procedures and results in the improvement of product cost and product quality [18]; and innovation needs flexibility, breaking existing rules, autonomy, risk taking and tolerance for mistakes in the pursuit of new knowledge [19]. As buyer–supplier collaboration focuses on rationalizing, coordinating, reducing variance and repetitive processes, incremental, exploitative innovation can be created at the expense of radical, exploratory innovation. A firm has a strategic dilemma between the exploitation of new opportunities and the exploration of old opportunities [20]. From clear controversy between these two strategies, a firm with limited budget and focused technology can be cast in light of the trade-off strategy between exploitation and exploration [5]. Nevertheless, a different approach that asserts both strategies can exist at the same time has been proposed [21–23]. Brown and Eisenhardt [22] proposed balancing the budgets and schedules with a flexibility of ensuring proper surroundings for innovation. Argote [21] and Mirone et al. [23] acknowledged the existing conflict between heterogeneity and standardization, but pointed out that some organizations managed to balance both. It is no doubt that these approaches still emphasize compromised and balanced strategies with some specific limitation. Our research proposes that both exploratory innovation and exploitative innovation can be independently developed as long as a critical factor, ‘‘the knowledge under specific environment is being managed’’, can be analyzed and understood in advance and then suitable PLM including KM methods and process development management for the development of new products can be adopted at specific time and places. Although knowledge capture and sharing stresses on the exploitation of existing knowledge or the distribution of new knowledge, the most beneficial for innovation and NPD is the creation of new knowledge [24]. In order to encourage knowledge creation in NPD process, suitable KM methods should be applied regarding to the knowledge creation modes and mature level of the selected NPD item. Four knowledge creation modes, including socialization (tacit to tacit knowledge), externalization (tacit to explicit knowledge), combination (explicit to explicit knowledge) and internalization (explicit to tacit knowledge), spirally and sequentially induce existing tacit and explicit knowledge into new knowledge and lead to a successful NPD project [25,26]. The KM methods such as informal event are for the knowledge creation of socialization, experience workshop and expert interviews are for the knowledge creation of externalization, project briefing and best practice cases are for the knowledge creation of combination, and research services are for the knowledge creation of internalization [8]. The process development management of NPD project based on knowledge creation mode and mature level also can be divided into four sequential PLM steps as shown in Table 1: (1) test sample (TS), (2) engineering sample (ES), (3) customer sample (CS) and (4) mass sample (MS). Steps 1 and 2 focus on creating exploratory innovation using KM methods alone, and Steps 3 and 4 stress on creating effectiveness in product quality and product cost, efficiency in development schedule and development cost, and exploitative innovation using KM methods and process development management.

A full understanding of KM methods, process development management and their utilization at a specific situation is necessary; otherwise negative and chaotic effect may be resulted.

Table 1
The sequential procedures of NPD project with respect to PLM

NPD sequence	Test sample (TS)	Engineering sample (ES)	Customer sample (CS)	Mass sample (MS)
KCM[a]	Internalization	Socialization	Externalization	Combination
Innovation	Exploratory	Exploratory	Exploitative	Exploitative
Technology resources	New technologies	New technologies	Existing technologies	Existing technologies
Process development management	N/A	N/A	Development time and development cost	
			Product cost	Prototype test
			Product quality	Prototype verification
Starting stage	Product C	Product B	Product D	Product A
	Next to ES	Next to CS	Next to MS	Next to TS

Note: New products are sequentially developed according to KCM and mature level.
[a] KCM means knowledge creation mode.

3. Portfolio management and critical success factors of NPD

Portfolio management is a dynamic decision process, whereby a list of new projects is constantly updated and revised [27,28]. New projects are selected and prioritized; existing projects may be accelerated, killed or de-prioritized; and resources are allocated and re-allocated to the active projects during each stage. Uncertainty and obscure information, unknown risks or opportunities, multiple targets, strategic selection, interdependence among different projects, multiple decision-makers and dynamic locations characterize the portfolio decision. Portfolio decisions are challenging because of the difficulty of allocating a scarce budget over multiple periods, because of multi-period consequences, and because of uncertain and often interdependent products that compete for a common pool of resources [29]. However, to increase the likelihood of having some successful products, multiple NPD are selected.

A wide range of criteria, such as strategic target, competitors, technical feasibility, manufacturing capability, financing, risks, organizational culture, market potentials and project schedule, are used for analysis [30]. Considerable effort has been made in the past several years to help organizations make better decisions in NPD project selection [31,32]. These studies attempted to identify the factors that were necessary for the success of NPD. Different methodologies were used, and similar, inconsistent or even contradictory results were found [33].

Various CSFs need to be simultaneously considered when selecting NPD projects; however, the problem becomes very complex since there are simply too many factors related to the final results. In order to simplify the problem for ANP analysis, we should try to have a number of suitable groups and put each CSF into one of the suitable groups by scientific methodology. With the analysis of potential risk and consequence analysis on the design/process failure mode and effect analysis (FMEA) [34], effective measures and actions can be taken to reconsider the projects with high risk, and the risk and loss in efficiency and scrap afterwards can be reduced as a result. Accordingly, 100 technology companies in China were investigated by design/process FMEA questionnaires with 37 possible CSFs. The collected data are analyzed by factor analysis, and the factors with initial eigenvalues over one are selected as a common CSF group. A total of 10 groups are selected. Rotated method, varimax with Kaiser Normalization, is adopted next, and the factors with a loading greater than 0.5 are selected. The groups that represent the characteristics of aggregate sets of CSFs are named and shown in Table 2.

From factor analysis, we obtain 10 groups and 37 sub-groups. However, the ANP manipulation with such a situation is simply too complex and cumbersome. Since the relationship between 10 groups and 3 upper-level major factors (*organization and market capability*, *manufacturing capabilities* and *technology capability*) is rather intuitive, Delphi method is applied to subjectively find their hierarchical relationship. In order to simplify the calculation and to utilize scientific results, we propose that the criteria in the first layer (the three upper-level major factors) are decided by decision makers accompanying with sensitivity analysis, and the results from factor analysis are used as sub-criteria (the 10 groups) and their detailed judgment factors (the 37 sub-groups). By this way, we only need to execute sensitivity analysis at the first layer which is decided by subjective opinions and is the most important layer, and the ANP calculation becomes simple. The results of the selected CSFs shown in Table 2 and Fig. 1 are used in Section 5.

4. A simplified ANP model with sensitivity analysis

The analytic hierarchy process (AHP) is a simple mathematically based multi-criteria decision-making tool to deal with complex, unstructured and multi-attribute problems. Whereas AHP represents a framework with a uni-directional hierarchical relationship, ANP allows for more complex interrelationships among decision levels and attributes. The ANP feedback approach replaces hierarchies with networks to solve problems in which the relationships between levels are not easily represented as higher or lower, dominated or being dominated, directly or indirectly [35]. For instance, not only does the importance of the criteria determine the importance of the alternatives as in a hierarchy, but also the importance of the alternatives may have impact on the importance of the criteria [36]. Therefore, a hierarchical structure with a linear form is not

Table 2
Summary of CSFs used in the paper

Goal	Item (3 criteria)	Group (10 sub-criteria)	Sub-group (37 detailed criteria)
Performance	Organization and market	(a) Quality of human capitals	The mechanism of motivation, organization structure and characteristics of management personnel
		(b) Market potential of products	The size of the market and the potential growth of the market
		(c) Entrance ability of products into the market	The design of sales channel, the openness of the market, and the visible demand of the market
		(d) Positive net present value of income	The expected NPV generated from the addition of the selected feature under limited budgets
	Manufacturing capability	(e) Capability of survival of products	The possibility of product substitutes, reliable quality and low cost production
		(f) Related equipment and assets	The existence and/or easy acquisition of necessary equipment for manufacturing the selected product mix
		(g) Competitors and production experience	The existence of major competitors and the firm's previous production experiences
	Technology and engineering	(h) Technological characteristics of products	Technological capability of being imitated, complex technologies, substitutes of technology and low start-up cost
		(i) Competitive advantage of products	The number of competitors, excellence in functions, capability of continuous R&D, competitive advantage, core technology, new or radical technologies, flexible production processes, reasonable income and piloting advantages
		(j) Technology possessed in the trade	The reputation of the inventor, sufficiency of resources and previous technology experiences

applicable for a complex system like NPD selection, which can be better represented by a network and solved by ANP.

An assumption of AHP and ANP is consistency, or transitivity of preference; however, this may not always be true in real life [37,38]. In such a case, the use of fuzzy numbers and linguistic terms may be more suitable. The application of fuzzy AHP has become popular in recent years [39–41]. However, fuzzy AHP/ANP is very complicated. Since the criteria weights are critical determinants of the final ranking of research alternatives, the stability of the rank order under different weighting schemes from vagueness and ambiguity of decision makers can be tested by a sensitivity analysis [42]. Accordingly, we propose using an ANP methodology with sensitivity analysis, which is an excellent tool and has the

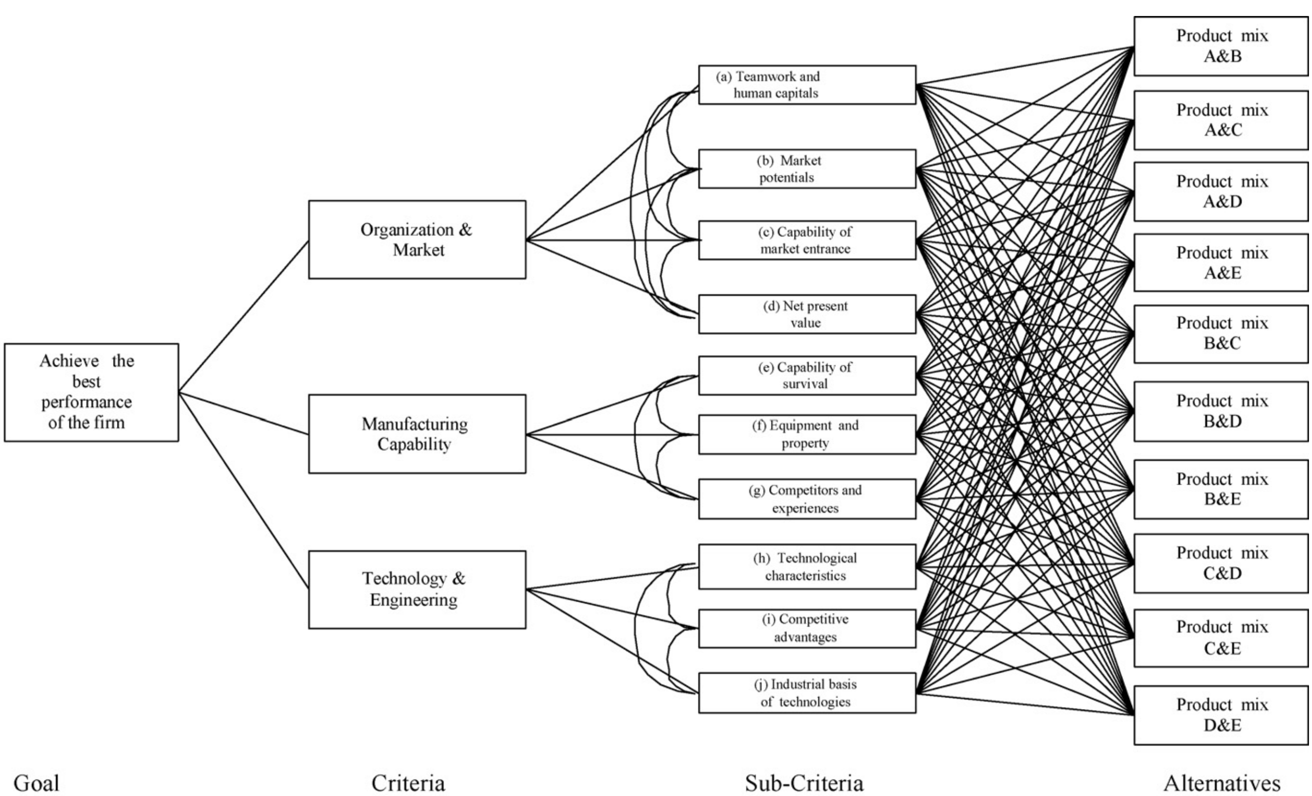

Fig. 1. The network of the new product mix problem.

advantages of considering experts' opinions, having a logical calculation, handling both quantitative and qualitative data, and examining the sensitivity of the solution. When a network is not too complicated, a simplified matrix manipulation approach may be employed [43,44]. With the combination of sensitivity analysis, the procedures are as follows:

1. Determine the importance of each criterion with respect to achieving the overall objective. Criteria are compared pairwisely, and relative ratings are assigned. A paired comparison matrix is formed after each criterion has been compared. For example, m criteria, denoted by $X_1, X_2, X_3, \ldots, X_m$, are compared in pairs according to their relative weights, denoted by $w_1, w_2, w_3, \ldots, w_m$, respectively. A matrix, $\mathbf{W}_1$, can be formed to represent the pairwise comparisons [45,46].

$$\mathbf{W}_1 = \begin{matrix} & C_1 & C_2 & \cdots & C_m \\ C_1 & \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_m} \\ C_2 & \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_m & \frac{w_m}{w_1} & \frac{w_m}{w_2} & \cdots & \frac{w_m}{w_m} \end{matrix} = \begin{matrix} & C_1 & C_2 & \cdots & C_m \\ C_1 & c_{11} & c_{12} & \cdots & c_{1m} \\ C_2 & c_{21} & c_{22} & \cdots & c_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_m & c_{m1} & c_{m2} & \cdots & c_{mm} \end{matrix} \quad (1)$$

Obtain the maximum eigenvalue and eigenvector (w_1) with the following formula:

$$\mathbf{W}_1 \cdot w_1 = \lambda_{\max} \cdot w_1 \quad (2)$$

where w_1 is the eigenvector, the weight vector, of $\mathbf{W}_1$, $\lambda_{\max}$ is the largest eigenvalue of $\mathbf{W}_1$ and m is the number of criteria. The consistency index (CI) and consistency ratio (CR) need to be checked [46].

2. Assume that there is no dependence among sub-criteria, determine the importance of each sub-criterion with respect to its upper-level criterion. After the check of consistency property, the matrix and the eigenvector with respect to an upper-level criterion (m) are as follows:

$$\mathbf{W}_{2m} = \begin{matrix} & D_{1(m)} & D_{2(m)} & \cdots & D_{n(m)} \\ D_{1(m)} & d_{11(m)} & d_{12(m)} & \cdots & d_{1n(m)} \\ D_{2(m)} & d_{21(m)} & d_{22(m)} & \cdots & d_{2n(m)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ D_{n(m)} & d_{n1(m)} & d_{n2(m)} & \cdots & d_{nn(m)} \end{matrix}, \quad \text{for each } m \quad (3)$$

and

$$w_{2m} = \begin{matrix} D_{1(m)} \\ D_{2(m)} \\ \vdots \\ D_{n(m)} \end{matrix} \begin{bmatrix} d_{1(m)} \\ d_{2(m)} \\ \vdots \\ d_{n(m)} \end{bmatrix}, \quad \text{for each } m \quad (4)$$

where $n(m)$ is the number of sub-criteria respective to an upper-level m, and the total number of sub-criteria n is equal to the sum of all $n(m)$, that is, $n = n(1) + n(2) + \cdots + n(m)$.

3. Obtain the priorities of alternatives with respect to each of the sub-criterion. The general form of matrix and eigenvector are as follows:

$$\mathbf{W}_{en} = \begin{matrix} & E_{1(n)} & E_{2(n)} & \cdots & E_{p(n)} \\ E_{1(n)} & e_{11(n)} & e_{12(n)} & \cdots & e_{1p(n)} \\ E_{2(n)} & e_{21(n)} & e_{22(n)} & \cdots & e_{2p(n)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ E_{p(n)} & e_{p1(n)} & e_{p2(n)} & \cdots & e_{pp(n)} \end{matrix}, \quad \text{for each } n \quad (5)$$

and

$$w_{en} = \begin{matrix} E_{1(n)} \\ E_{2(n)} \\ \vdots \\ E_{p(n)} \end{matrix} \begin{bmatrix} e_{1(n)} \\ e_{2(n)} \\ \vdots \\ e_{p(n)} \end{bmatrix}, \quad \text{for each } n \quad (6)$$

where p is the number of alternatives. Combine the above eigenvectors with respect to criterion m and obtain the following matrix:

$$\mathbf{W}_{3m} = \begin{matrix} & D_{1(m)} & D_{2(m)} & \cdots & D_{n(m)} \\ E_1 & e_{1(1)} & e_{1(2)} & \cdots & e_{1(n)} \\ E_2 & e_{2(1)} & e_{2(2)} & \cdots & e_{2(n)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ E_p & e_{p(1)} & e_{p(2)} & \cdots & e_{p(n)} \end{matrix}, \quad \text{for each } m. \quad (7)$$

4. Determine the interdependence among sub-criteria. The inner dependence among sub-criteria under the same criterion is calculated through analyzing the impact of each sub-criterion on other sub-criteria with the same upper-level criterion. The interdependence weight matrix of sub-criteria with the same upper-level criterion is:

$$\mathbf{W}_{4m} = \begin{matrix} & D_{1(m)} & D_{2(m)} & \cdots & D_{n(m)} \\ D_{1(m)} & k_{11(m)} & k_{12(m)} & \cdots & k_{1n(m)} \\ D_{2(m)} & k_{21(m)} & k_{22(m)} & \cdots & k_{2n(m)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ D_{n(m)} & k_{n1(m)} & k_{n2(m)} & \cdots & k_{nn(m)} \end{matrix}, \quad (8)$$

for each m.

5. Obtain the interdependence priorities, $w_{DC(m)}$, of the sub-criteria by synthesizing the results from Steps 2 and 4.

$$w_{DC(m)} = \mathbf{W}_{4m} \times w_{2m}, \quad \text{for each } m. \quad (9)$$

6. Determine the priorities of alternatives, $w_{21(m)}$, with respect to each criterion by synthesizing the results from Steps 3 and 5 as follows:

$$w_{21(m)} = \mathbf{W}_{3m} \times w_{DC(m)}, \quad \text{for each } m. \quad (10)$$

The matrix $\mathbf{W}_{21}$ groups together the columns of $w_{21(m)}$ for all m's:

$$\mathbf{W}_{21} = (w_{21(1)}, w_{21(2)}, \ldots, w_{21(m)}) \tag{11}$$

7. The overall priorities for the alternatives are obtained by synthesizing the results from Steps 1 and 6; that is, multiplying $\mathbf{W}_{21}$ by w_1.

$$w = \mathbf{W}_{21} \times w_1 \tag{12}$$

8. Sensitivity analysis is performed to test the stability of the priority ranking. The weights of criteria are separately altered, simulating weights between closest left limit and closest right limit. This means that if the relative weight of an important criterion is 5, then a simulated weight between 4 and 6 (optimistic view) or between 3 and 7 (conservative view) can be separately considered. The vibration of relative weights of an important criterion may come from imprecise and vague expression of decision makers, system risk of market and technology, and collected data. Then, a new eigenvector, w_1, obtained by Eq. (2), is applied to Eq. (12) again to check the new priority ranking. The decision makers need to carefully check the suitability about the weights of the criteria if the priority ranking changes. Steps 1 and 7 need to be executed again until sensitivity analysis is completed.

5. New product mix selection model

In order to propose a model of NPD mix selection with a suitable PLM, an anonymous manufacturer of small-sized home appliances in China is used as an example. To simplify the complexity of the environment for our analysis, this paper is based on the following assumptions. The firm tries to select two products for development from a list of five candidate new products, A, B, C, D and E, and the development activities of these products are categorized in Table 3. Product A is a very different product from what the firm is producing now, and it can be a product such as home-scaled robots or home automation. The product will be developed outside the network and have a promising market potential in the future. Producing such a product mainly focuses on a socialization activity since the external and internal knowledge including the related technological experience, practical manufacturing and marketing experience are not standardized and documentary. Product B is an upgrade of current products with a different price. These current products occupy 20% of the firm's sales volume and have reached the mature stage in their product lifecycle. Product B can be developed from the current products with the firms within the networks, and the target of developing Product B is to differentiate and to modularize with the existed products. For example, the price of a series of products, such as coffee makers, can range from less than US $100 for a conventional coffee maker to hundreds of US dollars for a one-touch coffee maker. As a result, the development of Product B mainly focuses on a combination activity since the external and internal knowledge including the related technological experience, practical manufacturing and marketing experience are standardized and documentary. Product C is a core component of an appliance from plastic injection plants or stamping factories and can be exploited with the participants in the network to reduce cost and simultaneously meet better quality requirement. This development mainly focuses on an externalization activity because the tacit existing knowledge about the integrated products ignited by the explicit external knowledge like quality control techniques, production management skills, or codified knowledge of core components can be transferred into new knowledge. Product D can be a product with fuzzy automation, nano-technology or anion (HO) porcelain materials and can be explored with the competitive firms in the network to develop incompatible technology, and the development mainly focuses on an internalization activity since new knowledge is induced when the codified existing experiences about the home appliances are impacted by the tacit external knowledge about the new technology. New technology will replace existed technology with better performance if it is developed successfully. Finally, the firm can independently develop new Product E to substitute up-streamed core components offered by sub-suppliers. The cost of products can be abruptly reduced, and the firm will be able to dominate the market in the future. However, the production and development of the major parts need to integrate a lot of technologies with huge capital investment.

Table 3
The relationship between NPD and knowledge creation methods

Explicit to implicit Internalization Product C Test Sample Stage	Implicit to implicit Socialization Product B Engineering Sample Stage
Explicit to explicit Combination Product A Mass Sample Stage	Implicit to explicit Externalization Product D Customer Sample Stage

Because of limited internal resources, only two products can be selected in this stage. In addition, any two products selected for development can have a certain degree of inter-relationship that has to be considered at the same time. Therefore, each alternative under evaluation is a combination of two products, such as products mix A&B, products mix A&C, etc. With 5 products under consideration, a total of 10 kinds of product mixes must be evaluated.

Senior managers, including technology development managers, research managers, manufacturing managers, marketing managers and controllers, contributed their professional experience and use the results from the factor analysis stated in Section 3 to verify the criteria, sub-criteria and their detailed criteria that influence the decision. The network form of determining the firm's overall performance is shown in Fig. 1 and Table 2. Under criterion *organization and market*, there are sub-criteria of groups (a–d). Under criterion *manufacturing capability*, there are groups (e–g). Groups (h–j) are the sub-criteria of criterion *technology and engineering*. Note that there is interrelationship among sub-criteria that have the same

Table 4
Pairwise comparison for strategic NPD mix selection

	Absolute		Very strong		Strong		Weak		Equal	Weak		Strong		Very strong		Absolute		
	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	
In order to achieve the firm's best performance, which criteria should be emphasized more?																		
Organization and market							X											Manufacturing capability
Organization and market											X							Technology and engineering
Manufacturing capability														X				Technology and engineering

upper-level criterion (i.e., *organization and market*, *manufacturing capability* and *technology and engineering*).

A simplified ANP approach with sensitivity analysis, which is introduced in Section 4, is adopted to solve the problem. The procedures are as follows. In the first level of the network, the question, "which criterion should be emphasized more in determining the firm's performance, and how much more?" is asked. A part of the questionnaire is shown in Table 4, and a nine-point scale is used to do the pairwise comparison. The Delphi method is performed to obtain a consensus among the people who are involved [47]. The comparison matrix for comparing the criteria in level 2 in terms of their contribution to achieving the overall objective is obtained by Eq. (1) and shown in Table 5. The eigenvector, w_1, is obtained by Eq. (2), and it shows the priority of the three criteria. In addition, CI and CR are checked to examine the consistency of the matrix. In the opinion of the managers, *technology and engineering*, with a weight of 0.655, is the major factor in determining the overall performance of the firm. The reason is that technology and engineering is the key to a firm's survival in the competitive market. *Organization and market* and *manufacturing capability* rank the second and the third with weights of 0.250 and 0.095.

Assume there is no interdependence among sub-criteria, the comparison matrices of sub-criteria in accordance to their respective upper-level criteria (*organization and market*, *manufacturing capability*, *technology and engineering*), are again generated through Delphi method, their eigenvectors and consistent ratios are obtained by Eqs. (3) and (4). Eigenvectors for *organization and market*, *manufacturing capability* and *technology and engineering* are w_{2O}, w_{2M} and w_{2T}, respectively.

Evaluation results of alternatives are rated by managers. Since there is no interdependence among alternatives, they are compared with respect to each sub-criterion yielding the column eigenvectors regarding each sub-criterion. Managers are asked to give a rating of each NPD mix in terms of each sub-criterion in a range of 0–100, and arithmetic average of all managers' ratings for each NPD mix on each sub-criterion is calculated. The NPD mix evaluation results are transformed into utility indices to show the relative performance of NPD mixes under each sub-criterion. By dividing each utility index to the total value of the column, the utility indices are next transformed into weights so that each column can sum to one. The results that have the same upper-level criterion are grouped together to be w_{3O}, w_{3M} and w_{3T}.

Table 5
Comparison matrix for the criteria

w_1[a]	Organization and market (OM)	Manufacturing capability (MC)	Technology and engineering (TE)
Organization and market (OM)	1	3[b]	1/3[b]
Manufacturing capability (MC)	1/3	1	1/6[b]
Technology and engineering (TE)	3	6	1

[a] After calculation of {3, 1/3, 1/6} using Eq. (2), eigenvector $w_1 = (0.250, 0.095, 0.655)$.
[b] {3, 1/3, 1/6} represents the relative weights of {OM with MC, OM with TE, MC with TE}.

Table 6
Pairwise comparison of interdependence for NPD selection

	Absolute		Very strong		Strong		Weak		Equal	Weak		Strong		Very strong		Absolute		
	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	
What is the relative importance of one detailed criterion when compared to another criterion on controlling (a)?																		
(a)							X											(b)
(a)								X										(c)
(a)							X											(d)
(b)							X											(c)
(b)										X								(d)
(c)										X								(d)

The interdependence among the criteria is determined through analyzing the impact of each sub-criterion on other sub-criteria with the same upper criterion by using pairwise comparisons. An excerpt of the questionnaire is in Table 6. We ask questions such as "What is the relative importance of (b) when compared to (c) on controlling (a)? The interdependence matrices for *organization and market*, *manufacturing capability* and *technology and engineering* are w_{4O}, w_{4M} and w_{4T}, respectively. Zeros are assigned to the eigenvector weights of criteria that are independent.

The interdependence priorities of the sub-criteria and the priorities of alternatives with respect to each of the three criteria are synthesized by Steps 5 and 6 detailed in Section 4, and the matrix $\mathbf{W}_{21}$ is formed.

Finally, the overall priorities for the alternatives (NPD mixes) are calculated by multiplying $\mathbf{W}_{21}$ by w_1.

$$w = \mathbf{W}_{21} \times w_1$$

$$= \begin{array}{c} \\ \text{A\&B} \\ \text{A\&C} \\ \text{A\&D} \\ \text{A\&E} \\ \text{A\&C} \\ \text{B\&D} \\ \text{B\&E} \\ \text{C\&D} \\ \text{C\&E} \\ \text{D\&E} \end{array} \begin{array}{c} \begin{array}{ccc} \text{O} & \text{M} & \text{T} \end{array} \\ \begin{bmatrix} 0.126 & 0.097 & 0.102 \\ 0.082 & 0.132 & 0.119 \\ 0.085 & 0.084 & 0.102 \\ 0.117 & 0.064 & 0.096 \\ 0.106 & 0.157 & 0.097 \\ 0.083 & 0.133 & 0.125 \\ 0.112 & 0.077 & 0.080 \\ 0.092 & 0.099 & 0.089 \\ 0.099 & 0.079 & 0.072 \\ 0.098 & 0.071 & 0.120 \end{bmatrix} \end{array} \times \begin{array}{c} \text{O} \\ \text{M} \\ \text{T} \end{array} \begin{bmatrix} 0.250 \\ 0.095 \\ 0.655 \end{bmatrix}$$

$$= \begin{array}{c} \text{A\&B} \\ \text{A\&C} \\ \text{A\&D} \\ \text{A\&E} \\ \text{B\&C} \\ \text{B\&D} \\ \text{B\&E} \\ \text{C\&D} \\ \text{C\&E} \\ \text{D\&E} \end{array} \begin{bmatrix} 0.107 \\ 0.111 \\ 0.096 \\ 0.098 \\ 0.105 \\ 0.115 \\ 0.088 \\ 0.091 \\ 0.078 \\ 0.109 \end{bmatrix}$$

The ANP analysis results indicate that the most operational excellent mix is new product mix B&D, with a relative importance value of 0.115, which is relatively more important than product mix A&C, with a value of 0.111.

The final stage is sensitivity analysis. The priority ranking remains the same when simulated weights under six better cases shown in Table 7 are applied. Under this simulation, the relative weight only shifts left or right one point based on Satty's nine-point scale. However, if the relative weight shifts 2 points left or right shown in Table 7, the priority ranking is all the same except for a set with eigenvector $w_1 = (0.397, 0.106, 0.497)$. The new ranking is A&B (0.1109), B&D (0.1092) and A&C (0.1061). Then, the decision makers need to make a decision whether (1) the sensitivity analysis is relatively robust or (2) going back Steps 1 and 7 and reconsidering the input.

From the result of the sensitivity analysis, the priority ranking is relatively robust. There is only one critical point happened at an extremely bad situation when the relative weight of "organization and market" with "technology and engineering" is changed from 1/3 to 1. The change in relative weights of the two criteria is not just with a huge magnitude, but also with a different sign (from lower to equal). As a result, this special situation can be neglected. Accordingly, selecting new product mix B&D or A&C is likely to lead to the best performance for the anonymous firm.

6. The adoption of KM methods and process management

After selecting NPD mix B&D at the strategy-leveled project, suitable KM methods and process development management need to be adopted in order to ensure the successful execution of product development process at the project level (Tables 1 and 3). The KM methods such as informal events are good for socialization activity (at the beginning stage of Product B) while experience workshops, expert interviews and experience reports are good for externalization activity (at the beginning stage of Product D). Product B will start from ES without process development management and Product D will begin from CS with process development management stressing on the improvement of product cost/quality and development time/cost. Following the development of the project, each project will move toward arrowed direction, shown in Table 3, associated

Table 7
Simulating weights of important criteria are listed below

	Organization and market vs. manufacturing capability	Organization and market vs. technology and engineering	Manufacturing capability vs. technology and engineering
Relative importance	3	1/3	1/6
w_1		(0.250, 0.095, 0.655)	
Better case	2[a]–4[b] (0.220, 0.112, 0.668), (0.270, 0.084, 0.646)	1/2–1/4 (0.300, 0.100, 0.600), (0.217, 0.090, 0.693)	1/5–1/7 (0.254, 0.103, 0.643), (0.241, 0.085, 0.674)
Worse case	1–5[c] (0.175, 0.139, 0.686), (0.286, 0.077, 0.637)	1–1/5[c] (0.397, 0.106, 0.497), (0.194, 0.087, 0.719)	1/4[c]–1/8 (0.265, 0.118, 0.617), (0.236, 0.082, 0.682)

[a] {2, 1/3, 1/6} represents the simulated weights of left limit {3, 1/3, 1/6} under a better case. $w_1 = (0.220, 0.112, 0.668)$ by Eq. (2).
[b] {4, 1/3, 1/6} represents the simulated weights of right limit {3, 1/3, 1/6} under a better case. $w_1 = (0.270, 0.084, 0.646)$ by Eq. (2).
[c] Although consistency ratio (CR) is over 0.05, those points are simulated too.

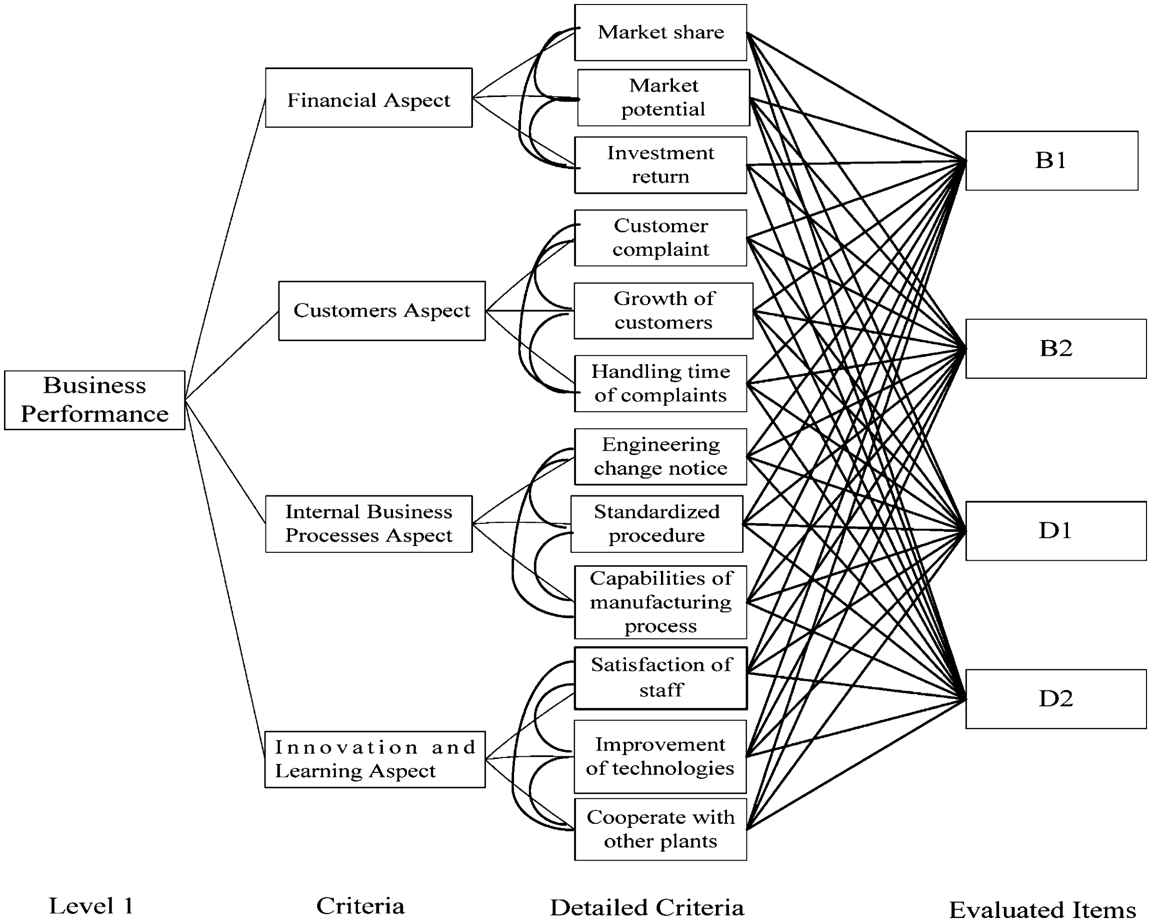

Fig. 2. A standard hierarchy for BSC with ANP.

with suitable KM methods and process development management in Table 1.

A BSC with simplified ANP approach is applied to compare the original results (Products B1 and D1) with the results after PLM (Products B2 and D2). The structure for determining the project's overall performance is shown in Fig. 2.

Under criterion *financial aspect* (C_1), there are sub-criteria of market share (C_{11}), market potential (C_{12}) and investment return (C_{13}). Under criterion *customer aspect* (C_2), there are number of customer complaints (C_{21}), growth of sales volume from new customers (C_{22}) and handling time for each complaint (C_{23}). Number of engineering change notice (C_{31}), extent of standardized procedure (C_{32}) and capabilities of manufacturing process (C_{33}) are the sub-criteria of criterion *internal business processes aspect* (C_3). Satisfaction of the involved staff (C_{41}), improvement of the technologies (C_{42}) and opportunities to cooperate with other plants (C_{43}) are sub-criteria of criterion *innovation and learning aspect* (C_4). Experts' opinions are obtained through pairwise comparisons, and a portion of the questionnaire, pairwise comparison of detailed criteria with the same upper-level criterion, is shown in Table 8.

By Steps 1–6 described in Section 4, the performances of the two products before and after the adoption PLM including KM methods and process development management are obtained and shown by $\mathbf{W}_{21}$ (Eq. (11)).

$$\mathbf{W}_{21} = \begin{matrix} \\ \text{B1} \\ \text{B2} \\ \text{D1} \\ \text{D2} \end{matrix} \begin{matrix} \begin{matrix} C_1 & C_2 & C_3 & C_4 \end{matrix} \\ \begin{bmatrix} 0.316 & 0.258 & 0.101 & 0.267 \\ 0.427 & 0.323 & 0.193 & 0.394 \\ 0.112 & 0.183 & 0.275 & 0.125 \\ 0.145 & 0.236 & 0.431 & 0.125 \end{bmatrix} \end{matrix}$$

Use NPD B1 (before PLM) as an example, the performance scores under *financial aspect* (C_1), *customer aspect* (C_2), *internal business process aspect* (C_3) and *innovation and learning aspect* (C_4) are 0.316, 0.258, 0.101 and 0.267, respectively. The result of the performances of product development before and after applying suitable KM methods and process development management are as follows. For the *learning and growth aspect* (C_4), the score increases abruptly from 0.267 to 0.394 for Product B and from 0.125 to 0.214 for Product D. For the *internal business process aspect* (C_3), the score improves from 0.101 to 0.193 for Product B and from 0.275 to 0.431 for Product D. For the *customer aspect* (C_2), the score increases from 0.258 to 0.323 for Product B and 0.183 to 0.236 for Product D. For the *financial aspect* (C_1), the score improves from 0.316 to 0.427 for Product B and 0.112 to 0.145

Table 8
Pairwise comparison for BSC performance evaluation

	Absolute		Very strong		Strong		Weak		Equal	Weak		Strong		Very strong		Absolute		
	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	
In order to achieve the best performance in *financial aspect* (C_1), which factor should be emphasized more?																		
(C_{11})											X							(C_{12})
(C_{11})														X				(C_{13})
(C_{12})											X							(C_{13})
In order to achieve the best performance in the *customer aspect* (C_2), which factor should be emphasized more?																		
(C_{21})							X											(C_{22})
(C_{21})											X							(C_{23})
(C_{22})														X				(C_{23})
In order to achieve the best performance in *internal process aspect* (C_3), which factor should be emphasized more?																		
(C_{31})											X							(C_{32})
(C_{31})							X											(C_{33})
(C_{32})			X															(C_{33})
In order to achieve the best performance learning and innovation aspect (C_4), which factor should be emphasized more?																		
(C_{41})											X							(C_{42})
(C_{41})							X											(C_{43})
(C_{42})			X															(C_{43})

for Product D. Accordingly, we conclude that the proposed PLM can keep a firm operating efficiently, effectively and innovatively, and can lead to a more satisfactory performance.

7. Discussion and conclusion

With the needs to respond quickly to dynamic customer needs, increased complexity of product design and rapidly changing technologies, the selection of the right set of NPD is critical to a company's long-term success. In this research, an ANP model with sensitivity analysis is first constructed to prioritize the relative importance of multiple criteria and the preferences of new product mixes by generalizing experts' opinions. After selecting NPD mix strategically, product lifecycle management, with suitable KM methods and process development management, needs to be adopted in order to ensure the successful execution of product development process. With ANP and sensitivity analysis, balanced scorecard is constructed to examine the outcomes of the proposed product lifecycle management.

For the case study, selecting new product mix B&D, following by A&C, will have the best performance for the enterprise. From the sensitivity analysis, the performance results of NPD mixes are relatively robust since there is only one critical point happened at an extreme situation when priority of the new product mixes does change. Overall, the most recommended options are a family product plan (Product B) with the replacement of core sub-systems (Product D) or multi-product plan (Product A) with the upgrade of core sub-systems (Product C). The outcomes are reasonable since the plans of the replacement of the core sub-systems and multi-product are radical innovation with high risk, while the activities of the upgrade of core sub-systems and family product belong to incremental innovation with low risk. NPD is vital as described before and needs to be developed both innovatively and steadily. There is no surprise that NPD sets of A&C and B&D have the best expected performance. The firm may take most advantage if it develops Product E successfully and independently to substitute up-streamed core components. However, it is risky from the point of view of the firm, and it is a repetitive investment from the point of view of the network. After analyzing the characteristics of strategic NPD mix including knowledge creation mode, mature level of new products, and technology resources, and then adopting PLM including suitable KM methods and process development management at the right place and time, a firm can operate innovatively, effectively and efficiently at the NPD project processes. Finally, the performances of the investigated firm before and after using PLM are compared to demonstrate the effectiveness of the models. The proposed models are recommended to practitioners in selecting and developing NPD projects.

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Hsing Hung Chen received the master degree in the Department of Electrical Engineering from the University of Missouri, USA, 1990. He was ever a division head of new product development at a TFT-LCD company. Right now, he is a PhD candidate at the College of Economics and Management, Tsinghua University, China.

Dr. He-Yau Kang is associate professor of the Department of Industrial Engineering and Management, National Chin-Yi University of Technology, Taiwan, ROC. He received his PhD degree in industrial engineering and management from National Chiao-Tung University. His research interests include production planning, fuzzy logic, performance evaluation, and their applications in electronic business and IC manufacturing.

Xiaoqiang Xing received the master degree in the Department of Engineering Economics from the Tianjin University, China, 2003. He is now a PhD candidate at the College of Economics and Management, Tsinghua University, China.

Amy Hsin-I. Lee received the MBA degree from the University of British Columbia, Canada, in 1993 and PhD degree in industrial engineering and management from the National Chiao Tung University, Taiwan in 2004. She is an associate professor in the Department of Industrial Engineering and System Management at Chung Hua University, Taiwan. Her research interests include performance evaluation, scheduling and production management.

Yunhuan Tong is an associate dean and a professor in the College of Economics and Management, Tsinghua University, China. His research interests include management of technology innovation, project management, knowledge management, technology assessment, theory and methods of evaluation/assessment, pricing of new technology, evaluation methods for commercial application of new technology, etc.