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A model to analyze strategic products for photovoltaic silicon thin-film solar cell power industry

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ABSTRACT

With natural resource scarcity and environmental protection, the use of renewable energy has become a promise for offering clean and plentiful energy. Photovoltaic (PV) solar cell is one of the emerging renewable energy applications; however, it suffers a large difficulty in high production cost with low conversion efficiency currently. Hence, an urgent pressure to upgrade technology and to formulate product strategy is evident in the solar cell power industry. In order to prosper PV silicone solar cell power industry, the paper develops a conceptual model, which is composed of a fuzzy analytic network process with interpretive structural modeling and benefits, opportunities, costs and risks, to help analyze suitable strategic products. The empirical study shows that the conceptual model can effectively and precisely handle such a complicated problem and can lead to an outstanding performance result.

Contents

1. Introduction

Photovoltaic (PV) solar cells are semiconductor devices that transfer sunlight directly into electricity by converting the energy of the light to electrons in the atoms of the cell. The converting process is called the PV effect, and it is done without the use of either chemical reactions or moving parts [1]. With the policies of many countries in promoting the PV solar cell industry, the industry has grown tremendously, and the global production capacity of silicon solar cell increased from 52 MWp in 2000 to 4.60 GWp, 6.3 GWp, 9.1 GWp, and 12.0 GWp in 2005, 2006, 2007 and 2008, respectively [2,3]. Even though PV systems can offer cleaner and plentiful energy, the major obstacle they face is that their energy cost is still too high [4]. The most commonly used solar cell today is made from crystalline silicon, but the main trend of solar cell industry is toward the PV silicon thin-film solar cell because of its potential reduction of production costs, low material consumption, lower energy consumption and a shorter energy payback time [5]. The crystalline silicon material and energy consumption for making a PV silicon thin-film solar cell is only 1/10 of that for a traditional solar cell. However, solar radiation conversion efficiency (currently less than 12%), product stability (different absorption rates for lights with different wavelengths), and lifetime (deformation after extensive sun exposure) for PV silicon thin-film solar cells all need to be enhanced [6–8]. In addition, thin-film technologies also face a wide range of problems from the lack of knowledge of basic material properties, the availability issues of production technologies

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to the legal concerns about patent infringements and the possible market perspectives. Compared with Japan, US or Europe, Taiwan government has an urgent pressure to formulate product strategies because its technologies are still behind those countries and its initial investment costs are very high. However, Taiwan has a great potential since its production capacity in semiconductor, flat panel display (FPD), and conventional PV solar cell industries, which are highly related to this emergent market, all have large shares in the world's markets. Accordingly, a plan to design product strategy for PV silicone thin-film solar cell power industry in Taiwan is necessary. In addition, firms within a manufacturing network are forced to integrate and collaborate with each other in order to develop new strategies, capacities and capabilities in a global competitive environment [9]. Thus, in this study, the product strategy will be considered from the perspective of a PV silicone thin-film solar cell power industry.

Product strategy involves decisions about target market, product mix, project prioritization, resource allocation and technology selection. With a tremendous degree of complexity and uncertainty, multiple strategic products are usually selected to increase the possibility of having a few successful projects [10]. In essence, it is a set of strategic decisions to ensure that the right markets and products are pursued [11]. To facilitate the prosperousness of the PV silicone solar cell power industry, this paper develops a conceptual model, using fuzzy analytic network process (FANP) with interpretive structural modeling (ISM) and benefits, opportunities, costs and risks (BOCR), to help analyze suitable strategic products for the thin-film solar cell power manufacturing network.

In this paper, the characteristic analysis of PV silicone thin-film solar cell power industry is considered in Section 2. A conceptual model to help devise appropriate product strategies from the perspectives of a large firm in the manufacturing network is introduced in Section 3. In order to incorporate the opinions and the expertise of decision makers, a FANP with ISM and BOCR for product strategy analysis is constructed in Section 4. A practical investigation of a large firm in the solar cell power industry is examined in Section 5. Some conclusion remarks and discussions are provided in the last sections.

2. Characteristic analysis of PV silicone thin-film solar cell industry

Solar cells can be categorized into two main groups: wafer-type (single crystalline or multi-crystalline) and thin film (a-Si, Cd-Te and CIGS). The former are made from wafers cut from a silicon ingot, and the latter are made by depositing silicon directly onto a substrate such as glass or steel. Wafer-type solar cells dominated 95% of commercial PV market while the remaining 5% were mainly PV silicon thin-film solar cells in 2007 [3]. Because the lack supply of crystalline silicone limits the application of conventional silicone solar cells, three major PV silicon thin-film materials, including amorphous silicon (a-Si), polycrystalline (Cd–Te), and polycrystalline CuIn(Ga)Se_2 (CIGS), are emerging as significant players [12]. The potential reduction of manufacturing costs, low material consumption, and lower energy consumption accelerate the development of PV silicon thin-film solar cell [13].

The single junction cell structure is prepared by plasma-enhanced chemical vapor deposition (PECVD), VHF PECVD or short-pulsed VHF PECVD, and the cell structure contains a-Si/uc-Si Tandem or a-Si/a-SiGe Tandem [8]. Other thin-film technologies, based on copper/indium/gallium/diselenide (CIGS) or cadmium telluride (Cd–Te), have reached sufficient maturity to be industrialized into production. Advanced production technologies consisting of system engineering and integration, manufacturing automation (such as glass cleaning and transmission systems), and process equipment (such as CAT–CVD or sputtering) will help save production cost, improve product reliability, and increase yield rate [8,14]. In addition, advanced solar cell technologies including new materials introduction (such as nano and microcrystalline silicon thin-film solar cell), advanced devices (such as laser scriber), and new methods (such as extremely thin absorber and multiple excitation generation) will also help increase solar conversion efficiency, reduce production costs, and extend life-cycle period [6,14]. With the rapid development of thin-film solar cell industry, the demand of glass substrate will increase substantially since it is a critical material for producing thin-film solar cells and modules. Therefore, PV glass will be the next industrial focus [14,15]. Technologies of PV glass, including extra-clear float glass, extra-reflective patterned coatings, anti-reflective coatings, conductive coatings and low emissive coatings, will promote the development of PV silicone thin-film solar cell industry [14]. On the other hand, a critical problem that must be tackled by the crystalline silicon thin-film solar cell power manufacturers is the future supply of silane, which is the material for making crystalline silicon [8].

The PV module is the main component of a PV solar energy system and usually consists of a number of solar cells [16]. Costs of a PV system consist of module costs and peripheral costs including electrical installation, inverters, support structure and building integration. All thin-film technologies share a common issue of relatively high initial investment costs. Capital costs could reach to prohibitive levels if production cannot be run at full capacity, production yields are lower than expected, and downtimes related to maintenance or product development cycles lead to lower production volumes. Sales and marketing of products could cause further problems due to disorganized distribution channels or lack of consumer demand, and this would then add to negative price pressures of products in the market. Finally, both the chip and FPD industries depend on highly automated, high-volume manufacturing technologies, several of which are immediately applicable to making solar cells in volume production. These technologies, including deposition, etching and others, are provided by companies with deep engineering expertise in materials, chemistry and process technology. Because of its technology and capital-intensiveness, the industry has a relatively high entry barrier.

The PV thin-film market may be divided into four major segments: end customers, remote industrial applications, developing countries/rural electrification, and on-grid systems. The expected market demand of the four segments in 2030 is 20 GMp, 60 GMp, 70 GMp and 120 GMp, respectively [4]. Prices of solar modules declined from approximately \$6/Watt to \$2.70/Watt between 1996 and 2005. An industry goal is to further cut this price to \$1.0/Watt before 2020 [17]. Revenues from the solar energy industry grew from US\$14.5 billion in 2006 to US\$18.6 billion in 2007. Based on this brisk annual growth rate, it is highly possible that its revenue will achieve US\$36.4 billion in 2010 and reach over US\$100 billion in 2020 [18]. Especially, since many nations have a stated goal of internalizing the external costs of energy attributable to environmental damage, PV will gain an advantage because low environmental damage is one of the main justifications for promoting solar energy [19–21]. In addition, according to German Feed-in Law EEG, PV solar electricity fed into the public grid by owners of installations has to be purchased by the utility companies at an enhanced price. From national stimulation programs in Japan, US, China, and Germany, this driving force expands the PV marketing potentials [4,22,23].

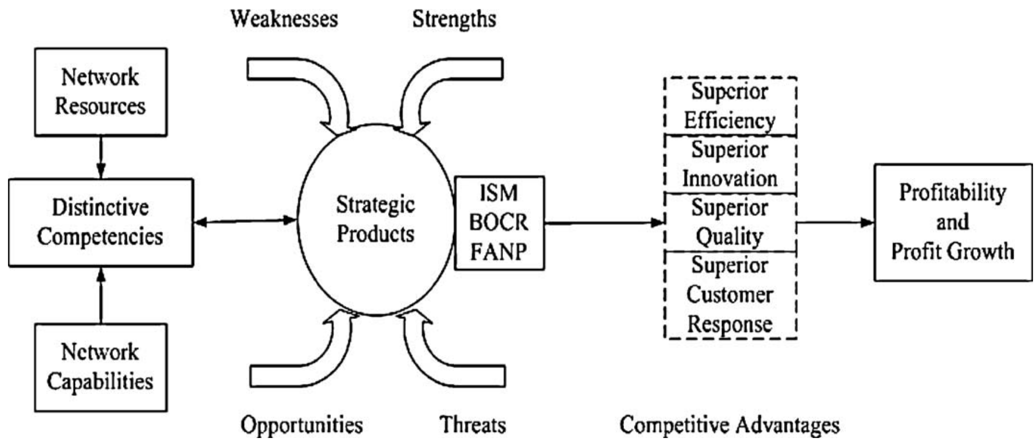


Fig. 1. Strategic products leading to competitive advantages.

3. A conceptual model for selecting suitable strategic products

Because of fierce competition and limited resources, most companies today can only focus on a certain part of the production process, such as research and design, components production, assembly production, packing and testing, transportation and distribution, marketing and sales. With the industrial value chain being divided into tiny segments, each company can only concentrate on its specialized field and needs to share its capabilities to solve problems with partners or competitors to obtain the maximum benefits of the production network [24]. In addition, a major process accompanying the inter-firm activities is the significant knowledge flow that takes place among the firms, and it is regarded as an important engine for innovation [25]. Firms within the manufacturing network share a particular body of compound core capabilities, complementary assets and capability to learn [26]. The core competitiveness of the firms is not just the advantages in capital, capacity and capability [9,27], but also in innovation and inspiration [28]. Accordingly, the product strategy for PV silicone thin-film solar cell power industry should be considered from the perspective of the manufacturing network.

Network resources contain both tangible properties such as financial capitals, core equipments, complementary technologies, and human resources, and intangible properties like patents, trademarks, and brand loyalty. Mutual trust, inter-organizational structure, working processes, and specific control systems are network capabilities. Distinctive competencies are the capabilities to integrate and coordinate network resources to produce superior performances [29–31]. Distinctive competencies allow a firm in a manufacturing network to differentiate its product offerings and lower its cost structure, and then result in superior efficiency, quality, innovation, and responsiveness to customers [32,33]. Thus, a participant in a manufacturing network achieves competitive advantages, and in turn results in superior profit and profit growth [34]. However, based on distinctive competencies and dynamic environments, a company in the manufacturing network needs to select a set of product strategies to achieve competitive advantages [32,33]. Distinctive competencies contain two constructs: network resources and network capabilities. Dynamic environments can be analyzed from four constructs: internal strengths and weaknesses, and external opportunities and threats. In order to help select a suitable product strategy, a conceptual model is built up and is as shown in Fig. 1.

There are various resources and capabilities in the manufacturing network, and they change when external and internal environment change [24,35–37]. After an extensive interview and literature review, distinctive characteristics for a firm in the manufacturing network, specifically in PV solar cell, FPD, and semiconductor industries, are collected under the benefits, opportunities, costs and risks aspects. Under the *Benefits*, the criteria are: (b1) relational alignment including compatible cultures, mutual trust, and compromise, (b2) technological alignment including technology complementarities, overlapping knowledge bases, and product improvement, (b3) strategic alignment containing motivation correspondence, goals, and long-term orientation, (b4) resources alignment such as closeness, resources complementarities, and market experience and (b5) marketing alignment containing market penetration, and complementary market. The criteria under the *Opportunities* are: (o1) R&D advantage consisting of conversion efficiency, and support in product simplification, (o2) market potential including market share, and product price, (o3) product proliferation including a full series of product lines, (o4) speed of R&D including learning organizations, and innovative environments, and (o5) speed of new product containing commercialization capabilities, and engineering capabilities. The criteria under *Costs* are: (c1) production costs containing equipment costs, materials costs, and labor costs, (c2) inventory level including raw materials, work-in-process products, and final products, (c3) product quality including product consistency, product reliability, and product stability, (c4) distribution cost contains transportation cost, channel management cost, and channel inventory level, (c5) facility usage rate including maintenance, flexibility, and production activity control, (c6) switching opportunity costs among enterprises, customers, and suppliers. The criteria under the *Risks* are: (r1) legal uncertainty consisting of environmental justifications, feeding into law, and tariff reduction law, (r2) technological uncertainty including conversion efficiency ratio, durability, and product reliability, (r3) financial uncertainty including capital loan, and sales income, and (r4) uncertainty of customer needs including product price, and product function. These selected distinctive characteristics will be applied in Section 5.

4. A FANP model with ISM and BOCR for evaluating strategic products

A systematic FANP model incorporated with ISM and BOCR is proposed to help analyze the suitable strategic products from the perspectives of a large firm in a PV silicone solar cell power manufacturing network. The model is comprised of five phrases, as shown in Fig. 2, and the respective steps are described here.

Phase I: Construction of a PV silicone solar cell product strategy evaluation network.

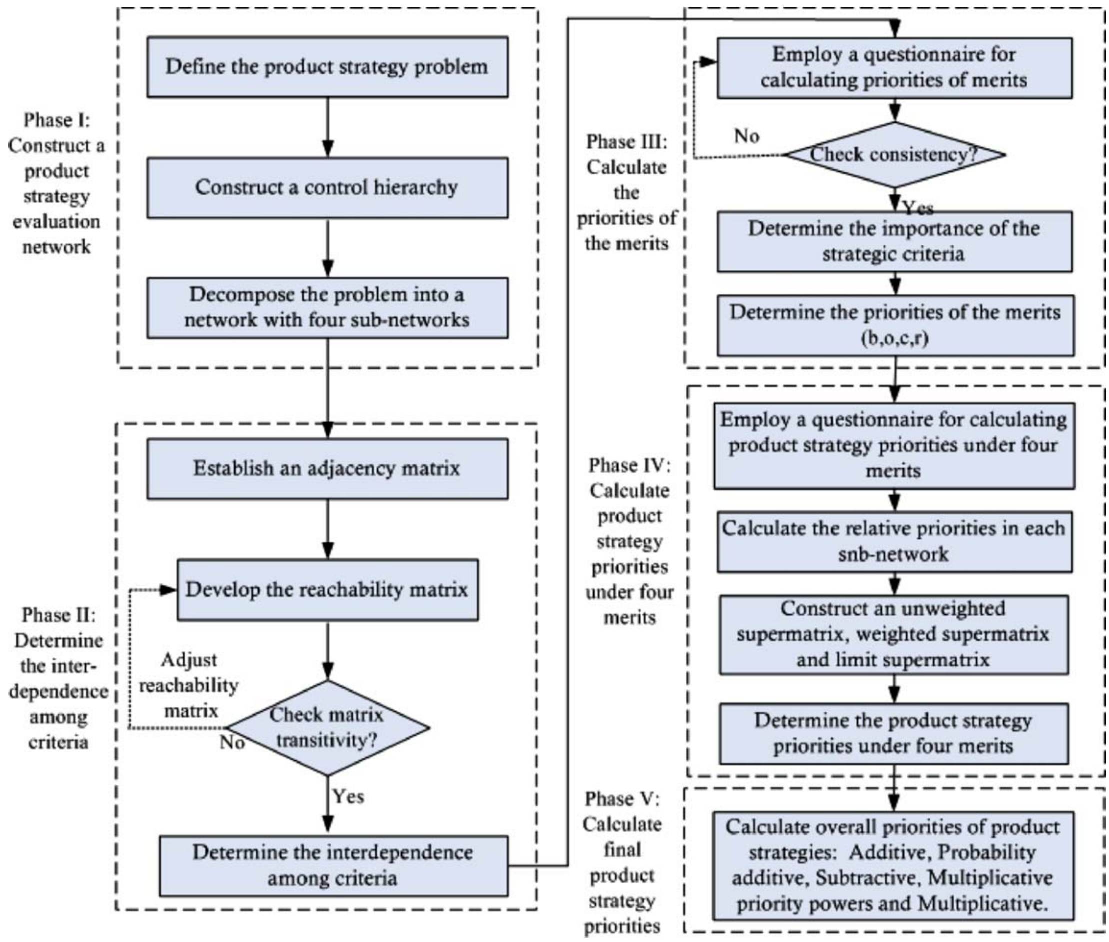


Fig. 2. Flowchart of the proposed model.

Step 1. Form a committee of experts in the PV silicone solar cell industry and define the problem for selecting suitable strategic products.

Step 2. Construct a control hierarchy for the strategic product evaluation problem. A control hierarchy contains strategic criteria, the very basic criteria used to assess the problem, and the four merits, benefits, opportunities, costs and risks. The control hierarchy is used to calculate the priorities of the four merits.

Step 3. Decompose the strategic product evaluation problem into a network with four sub-networks. Based on literature review and experts' opinions, a network is constructed. Four merits must be considered in achieving the overall goal, and a sub-network is formed for each of the merits. For instance, for the sub-network for opportunities (O) merit, there are criteria for achieving the opportunities of the ultimate goal, and the lowest level are the strategic products under evaluation.

Phase II: Determination of the interdependence among criteria.

Step 4. Establish an adjacency matrix which shows the contextual relationship among the criteria under each merit. In Phase II, ISM is adopted to determine the interdependence among the criteria. Questionnaire is prepared first to identify the contextual relationship between any two criteria, and the associated direction of the relation. Let x_i^m and x_j^m be respectively the ith and the jth criterion of merit m, and π_{ij}^m be the relation between ith and jth criteria of merit m. If x_i^m influences x_j^m, then $\pi_{ij}^m = 1$; otherwise, $\pi_{ij}^m = 0$. If x_j^m influences x_i^m, then $\pi_{ji}^m = 1$; otherwise, $\pi_{ji}^m = 0$. The geometric mean of experts' opinions on the relationship between each pair of criteria is calculated. A threshold value of 0.5 is used to determine whether the criteria are dependent or not [38]. That is, if the mean value is less than 0.5, then we set π_{ij}^m be 0; if the mean value is greater than or equal to 0.5, then we set π_{ij}^m be 1. The adjacency matrix $\mathbf{D}_m$ is presented as follows:

$$\mathbf{D}_m = \begin{matrix} & \begin{matrix} x_1^m & x_2^m & \cdots & x_n^m \end{matrix} \\ \begin{matrix} x_1^m \\ x_2^m \\ \vdots \\ x_n^m \end{matrix} & \begin{bmatrix} 0 & \pi_{12}^m & \cdots & \pi_{1n}^m \\ \pi_{21}^m & 0 & \cdots & \pi_{2n}^m \\ \vdots & \vdots & 0 & \vdots \\ \pi_{n1}^m & \pi_{n2}^m & \cdots & 0 \end{bmatrix} \end{matrix} \tag{1}$$

Step 5. Develop the reachability matrix and check for transitivity. The initial reachability matrix $\mathbf{H}_m$ is calculated by adding $\mathbf{D}_m$ from step 4 with the unit matrix I:

$$\mathbf{H}_m = \mathbf{D}_m + I \tag{2}$$

The transitivity of the contextual relation means that if criterion x_i^m is related to x_j^m and x_j^m is related to x_p^m, then x_i^m is necessarily related to x_p^m. The final reachability matrix $\mathbf{H}_m^*$ is under the operators of the Boolean multiplication and addition (i.e., $1 \times 0 = 0 \times 1 = 0$, $1 + 0 = 0 + 1 = 1$), and a convergence can be met:

$$\mathbf{H}_m^* = \mathbf{H}_m^b = \mathbf{H}_m^{b+1}, \quad b > 1 \tag{3}$$

Step 6. Determine the interdependence among criteria under each merit. Based on $\mathbf{H}_m^*$, the interdependence among criteria under merit m can be depicted.

Phase III: Calculation of priorities of the merits.

Step 7. Employ a questionnaire to collect experts' opinions on the importance of strategic criteria and the importance of merits to strategic criteria. Experts are asked to pairwise compare the strate-

Table 1
Triangular fuzzy numbers.

Linguistic variables	Positive triangular fuzzy numbers	Positive reciprocal triangular fuzzy numbers
Equally important	(1, 1, 1)	(1, 1, 1)
Weakly important	(1, 1, 3)	(1/3, 1, 1)
Moderately important	(1, 3, 5)	(1/5, 1/3, 1)
Important	(3, 5, 7)	(1/7, 1/5, 1/3)
Very important	(5, 7, 9)	(1/9, 1/7, 1/5)
Extremely important	(7, 9, 9)	(1/9, 1/9, 1/7)

Table 2
Linguistic value table.

Fuzzy language	Quantitative value
Very high (good)	(7, 9, 9)
High (good)	(5, 7, 9)
Fair	(3, 5, 7)
Low (poor)	(1, 3, 5)
Very low (poor)	(1, 1, 3)

gic criteria in a questionnaire using six different linguistic terms shown in Table 1. Experts are also asked to rate the importance of each merit to each strategic criterion using five linguistic levels, as shown in Table 2.

Step 8. Determine the priorities of the strategic criteria. For each expert's questionnaire results on the importance of strategic criteria, the linguistic variables of pairwise comparison from each expert are transformed into triangular fuzzy numbers using Table 1. A pairwise comparison matrix with triangular fuzzy numbers is formed. The centroid method is applied to defuzzify the triangular fuzzy numbers and to form a pairwise comparison matrix with crisp values. Examine the consistency property of the matrix. If an inconsistency is found, the expert is asked to revise the questionnaire, and the calculation is done again. After the consistency tests are passed for all the experts, use the geometric mean method to form an aggregate fuzzy pairwise comparison matrix for all the experts. The centroid method is applied next to form an aggregate pairwise comparison matrix with crisp values, and the synthesized priorities of the strategic criteria are calculated.

Step 9. Determine the importance of each merit to each strategic criterion. For each expert's questionnaire result on the importance of each merit to each strategic criterion, the linguistic variable is transformed into a triangular fuzzy number using Table 2. The geometric mean method is applied to aggregate the experts' opinions, and the centroid method is applied to obtain the crisp value of the importance of each merit to each strategic criterion.

Step 10. Determine the priorities of the merits. Calculate the priority of a merit by multiplying the value of a merit on each strategic criterion from Step 9 with the priority of the respective strategic criterion from Step 8 and summing up the calculated values for the merit. After normalization, the priorities of benefits, opportunities, costs and risks, that is, *b*, *o*, *c* and *r*, can be determined.

Phase IV: Calculation of product strategy priorities under the four merits.

Step 11. Employ a questionnaire to collect experts' opinions on the importance of criteria, the interdependence among criteria and the expected performance of product strategies. Experts are asked to pairwise compare the criteria using six different linguistic terms as shown in Table 1, so is the interdependence among criteria with the same upper-level merit. Experts are also asked to rate the expected performance of product strategies using five linguistic levels listed in Table 2.

Step 12. Calculate the relative priorities in each sub-network. The relative importance weights of criteria with respect to the same upper-level merit and the interdependence priorities among the criteria that have the same upper-level merit are calculated using a similar procedure as in Step 8. The performance priority of each product strategy with respect to each criterion is evaluated singly using a rating method as in Step 9.

Step 13. Form an unweighted supermatrix for each merit sub-network. Based on the procedure of ANP proposed by Saaty [39]), the priorities obtained from Step 12 are used to form an unweighted supermatrix for merit *m*:

$$\mathbf{M}_m = \begin{array}{r} \\ \text{Merit } m \\ \text{Criteria} \\ \text{Product strategies} \end{array} \begin{array}{c} \begin{array}{ccc} \text{Merit } m & \text{Criteria} & \text{Product strategies} \end{array} \\ \begin{bmatrix} 0 & 0 & 0 \\ w_{CM} & \mathbf{W}_{CC} & 0 \\ 0 & \mathbf{W}_{PC} & \mathbf{I} \end{bmatrix} \end{array} \quad (4)$$

where w_{CM} is a vector that represents the impact of the merit on the criteria, $\mathbf{W}_{CC}$ indicates the interdependency of the criteria, $\mathbf{W}_{PC}$ is a matrix that represents the impact of criteria on each product strategy, **I** is the identity matrix, and entries of zeros correspond to those elements that have no influence.

Step 14. Calculate weighted supermatrix for each merit sub-network. To make the supermatrix stochastic, an unweighted supermatrix needs to be transformed into a weighted supermatrix for each merit sub-network.

Step 15. Calculate the limit supermatrix and obtain the priorities of product strategies under each merit sub-network. By raising the weighted supermatrix to powers, the limit supermatrix can be obtained. The priorities of the product strategies under each merit are obtained by checking the product strategy-to-merit column of the limit supermatrix of the merit.

Phase V: Calculation of final priorities of the product strategies.

Step 16. Calculate overall priorities of the product strategies by synthesizing priorities of each product strategy under each merit from Step 15 with the corresponding normalized weights *b*, *o*, *c* and *r* from Step 10. There are five ways to combine the scores of each product strategy under *B*, *O*, *C* and *R* [40,41].

Additive:

$$P_i = bB_i + oO_i + c\left(\frac{1}{C_i}\right)_{\text{Normalized}} + r\left(\frac{1}{R_i}\right)_{\text{Normalized}} \quad (5)$$

where B_i, O_i, C_i and R_i represent the synthesized results of product strategy *i* under merit *B*, *O*, *C* and *R*, respectively, and *b*, *o*, *c* and *r* are normalized weights of merit *B*, *O*, *C* and *R*, respectively.

Probabilistic additive

$$P_i = bB_i + oO_i + c(1 - C_i) + r(1 - R_i) \quad (6)$$

Subtractive

$$P_i = bB_i + oO_i - cC_i - rR_i \quad (7)$$

Multiplicative priority powers

$$P_i = B_i^b Oi^o \left[\left(\frac{1}{C_i}\right)_{\text{Normalized}}\right]^c \left[\left(\frac{1}{R_i}\right)_{\text{Normalized}}\right]^r \quad (8)$$

Multiplicative

$$P_i = \frac{B_i O_i}{C_i R_i} \quad (9)$$

A case study of product strategy evaluation in PV silicone thin-film solar cell industry will be presented to examine the practicality of the proposed conceptual model described in Section 3 and the FANP-ISM-BOCR model described in Section 4. The results shall provide a comprehensive framework and guidance to PV silicone thin-film solar cell manufacturers in evaluating product strategies.

5. A practical investigation for strategic products in industry

Taiwan has a strong background and foundation for developing the PV solar cell power industry because it requires very analogous technology and less complex process than semiconductor and

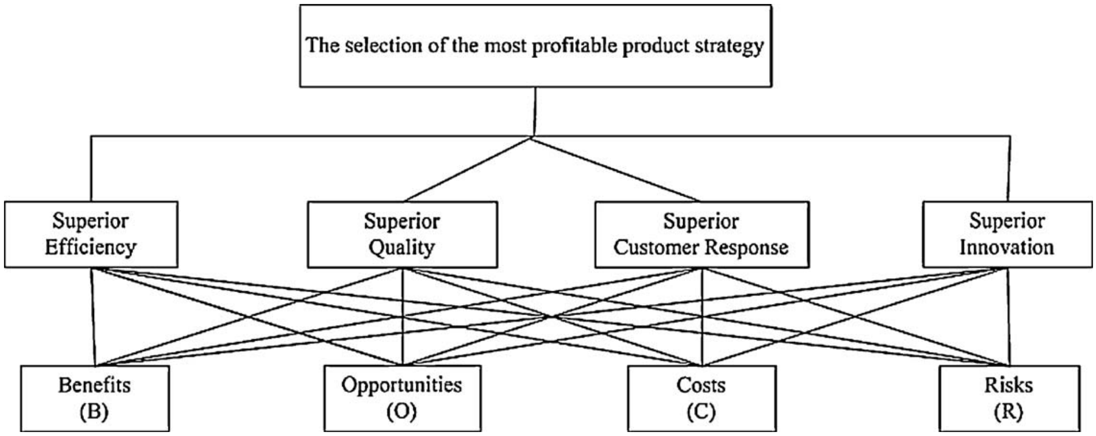


Fig. 3. Control hierarchy.

FPD manufacturing industries, two of the most brilliant industries in Taiwan. The PV solar cell power industry is transitioning from production in relatively small factories with production capacities of 10–100 MW per year to much larger ones producing up to 1 GW or more per year [42]. Such manufacturing transition is analogous to the early years of semiconductor industry and recent FPD industry, both of which depend on highly automated, high-volume manufacturing technologies [42]. Some technologies from the two industries are immediately applicable to making solar cells in volume production, including deposition, etching and others. With the high global demand from renewable energy and the technical advantages obtained from the semiconductor and FPD industries, Taiwan's PV solar cell power industry has a high potential in achieving a strong position in the global market.

In order to examine the practicality of the proposed conceptual model, the PV silicon thin-film solar cell power industry in Taiwan is used as an example. Because Taiwan's semiconductor, FPD, and conventional PV solar cells production have large global market shares, many firms in Taiwan are participating or planning to enter the emergent PV silicon thin-film solar cell market. An anonymous enterprise, which has business in TFT-LCD manufacturing and has just setup a subsidiary firm in developing PV solar cells, is under study. In the first step, the firm's position is located by Porter's analysis. Companies producing components like PV glass, crystalline silicon, PECVD, and silane are its up-streamed suppliers. Firms producing PV solar cell modules and PV solar cell systems for on-grid systems, transportation systems and building systems are its down-streamed customers. Companies with technologies like dye-sensitized solar cell (DSSC), crystalline silicon solar cell, and inorganic PV cells fabricate potential substitutes of the current products. Companies that expect to enter this field like CGS Solar Glass and Scheuten Solar are new entrance. Firms like Sharp, Kaneka, Mitsubishi, SolarGlas AG are its potential competitors. In order to devise a product strategy with the most appropriate product portfolio in the PV silicone thin-film solar cells industry in Taiwan, the firm must consider patterns and activities like exploitation, exploration [43,44], market, technologies, social and environmental impacts [45,46].

To simplify the complexity of the environment for our analysis, this paper is based on the following assumptions. Through the analysis of the firm's current position in the market, the firm currently may have the capability and gain relevant resources to develop and produce five kinds of products, A, B, C, D and E. A brief description of the five kinds of products is given below. Product A, such as DSSC and inorganic PV cells, which is very different from what the firm is producing now, can be developed with new cooperated firms within the manufacturing network and has a promising market potential in the future. However, the firm only has related technological experience and does not have practical manufacturing and marketing experience. Product B is a PV solar cell system suitable for different radiation, humidity, and temperature from what the firm is producing now, and it is an upgrade of a current existing product. Product B can be upgraded from a current product with the existing cooperated firms, and the target of developing product B is to differentiate and to modularize with the existing products. Product C is a major equipment or method for mass production, such as laser scriber, glass cleaning automation, and extremely thin absorber and multiple excitation generation. It can be exploited with the firm's existing cooperative firms within the manufacturing network to reduce production costs and simultaneously improve production yield rate. Product D, such as nano silicon thin-film solar cell and microcrystalline silicon thin-film solar cell, can be explored with the existing cooperated firms within the network to develop incompatible products. Finally, the firm can independently develop product E, such as PV glass, or silane, to substitute up-streamed core components. The cost of the new product can be abruptly reduced, and the firm will be able to dominate the market in the future. However, the development of these major components needs to integrate many advanced technologies with huge capital investment. Because of limited internal resources, only two strategic products can be selected in the program. In addition, any two products selected for development have a certain degree of inter-relationship that has to be considered at the same time. Therefore, each alternative under judgment is a combination of two products, such as strategic product mix A&B, strategic product mix C&D, etc. With five strategic products under consideration, a total of 10 strategic product mixes must be evaluated.

Phase I: Construction of a PV silicone solar cell product strategy evaluation network.

In order to evaluate the final performance of different product strategies, 10 experts, including technology R&D managers, entrepreneurs, official policy planners and industry analysts, are invited to form the evaluation committee. Their first task was to verify the distinctive competencies introduced in Section 3. Then, the structure for determining the project's overall performance can be divided into two parts: the control hierarchy (Fig. 3) and the BOCR network (Fig. 4). As shown in Fig. 3, the first level of the control hierarchy contains the goal, the selection of the most profitable product strategy. In the second level, four strategic criteria are considered, namely, *superior efficiency*, *superior quality*, *superior customer response*, and *superior innovation*. *Superior efficiency* helps a company attain a competitive advantage through a lower cost structure. *Superior quality* considers customer perception of greater value in a product's attributes form, features, performance, durability, reliability, style, and design. *Superior customer response* differentiates a company's products and services

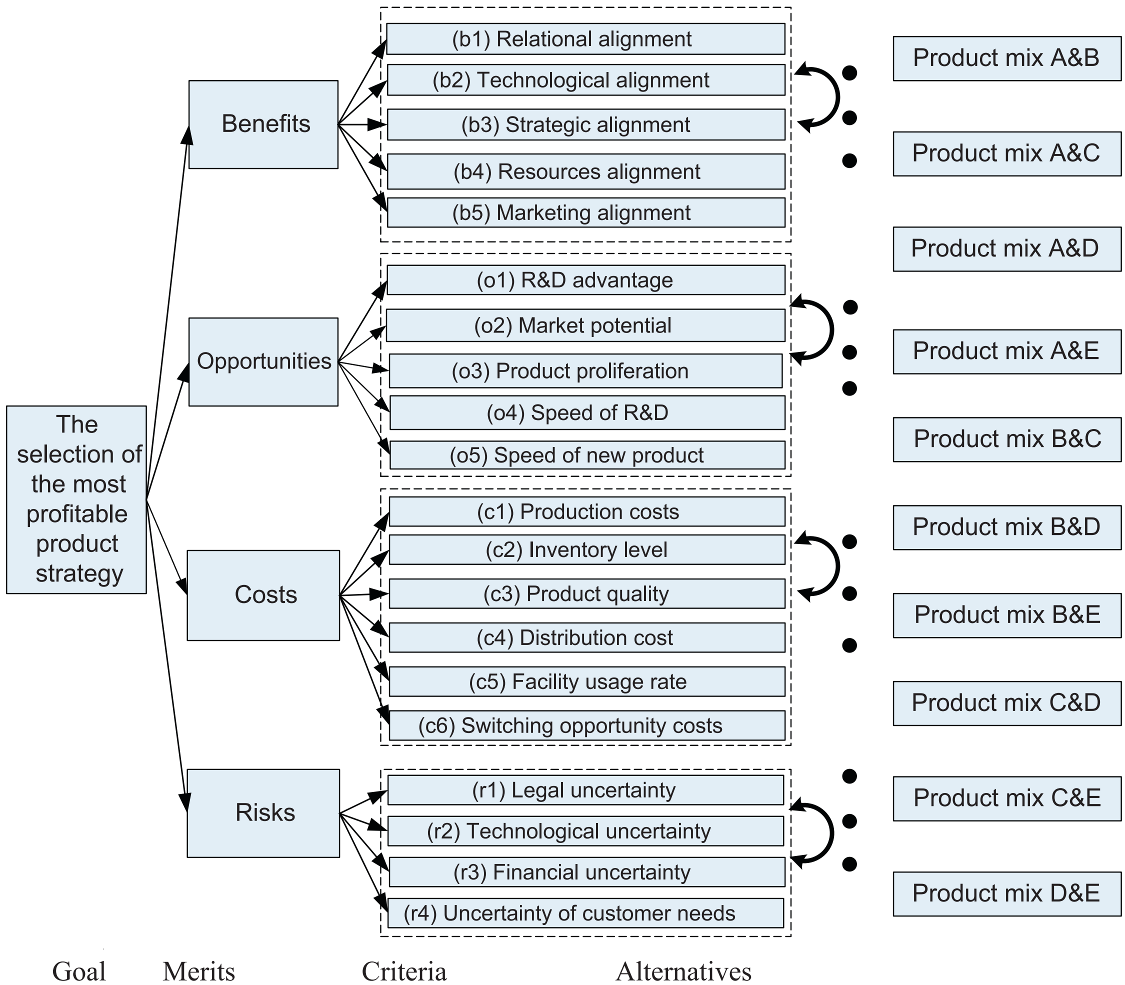


Fig. 4. The BOCR network.

from the competitors' and leads to brand loyalty and premium pricing. *Superior innovation* can be a major source of competitive advantage by giving a company something unique, something competitors lack. In the third level, there are four merits: benefits (*B*), opportunities (*O*), costs (*C*), and risks (*R*). The purpose of the control hierarchy is to calculate the priorities, *b*, *o*, *c* and *r*, of the four merits.

The BOCR network, as shown in Fig. 4, has the same goal as the control hierarchy does, and the purpose of this network is to calculate the priorities of the product strategies. The BOCR network can be further divided into four sub-networks: *benefits* sub-network, *opportunities* sub-network, *costs* sub-network, and *risks* sub-network. In the third level of the network, twenty criteria described in Section 3 are applied here to evaluate the performance of each project. Under *benefits* merit, there are five criteria, group factors (b1) through (b5). Under *opportunities* merit, there are five criteria, group factor (o1) and (o5). Group factors (c1) through (c6) are the criteria of *costs* merit, and group factors (r1) through (r4) are the criteria of *risks* merit. Ten different product mixes under evaluation are in the last level of the network.

Phase II: Determination of the interdependence among criteria.

A questionnaire is prepared to ask the relationship of one criterion to another. The geometric mean method is applied to aggregate the experts' opinions. That is, an adjacency matrix is prepared for each expert first, and a mean adjacency matrix is calculated using the geometric mean method to combine adjacency matrices from all experts. A threshold value of 0.5 is used to determine the relationship between each pair of criteria. The integrated adjacency matrix between the criteria under the *benefits* merit is obtained as shown in Table 3.

The initial reachability matrix $\mathbf{H}_b$ for criteria under the *benefits* merit is calculated:

$$\mathbf{H}_b=\mathbf{D}_b+\mathbf{I}=\begin{bmatrix}0&1&1&0&1\\0&0&1&1&1\\0&0&0&1&1\\0&1&0&0&1\\0&1&1&0&0\end{bmatrix}+\begin{bmatrix}1&0&0&0&0\\0&1&0&0&0\\0&0&1&0&0\\0&0&0&1&0\\0&0&0&0&1\end{bmatrix}=\begin{bmatrix}1&1&1&0&1\\0&1&1&1&1\\0&0&1&1&1\\0&1&0&1&1\\0&1&1&0&1\end{bmatrix}$$

The final reachability matrix $\mathbf{H}^{b^*}$ for criteria under the *benefits* merit is:

$$\mathbf{H}_b^*=\mathbf{H}^2=\mathbf{H}^3=\begin{bmatrix}1&1&1&1&1\\0&1&1&1&1\\0&1&1&1&1\\0&1&1&1&1\\0&1&1&1&1\end{bmatrix}$$

Table 3
Adjacency matrix between criteria under *benefits* merit.

$\mathbf{D_b}$	(b1)	(b2)	(b3)	(b4)	(b5)
(b1)	0	1	1	0	1
(b2)	0	0	1	1	1
(b3)	0	0	0	1	1
(b4)	0	1	0	0	1
(b5)	0	1	1	0	0

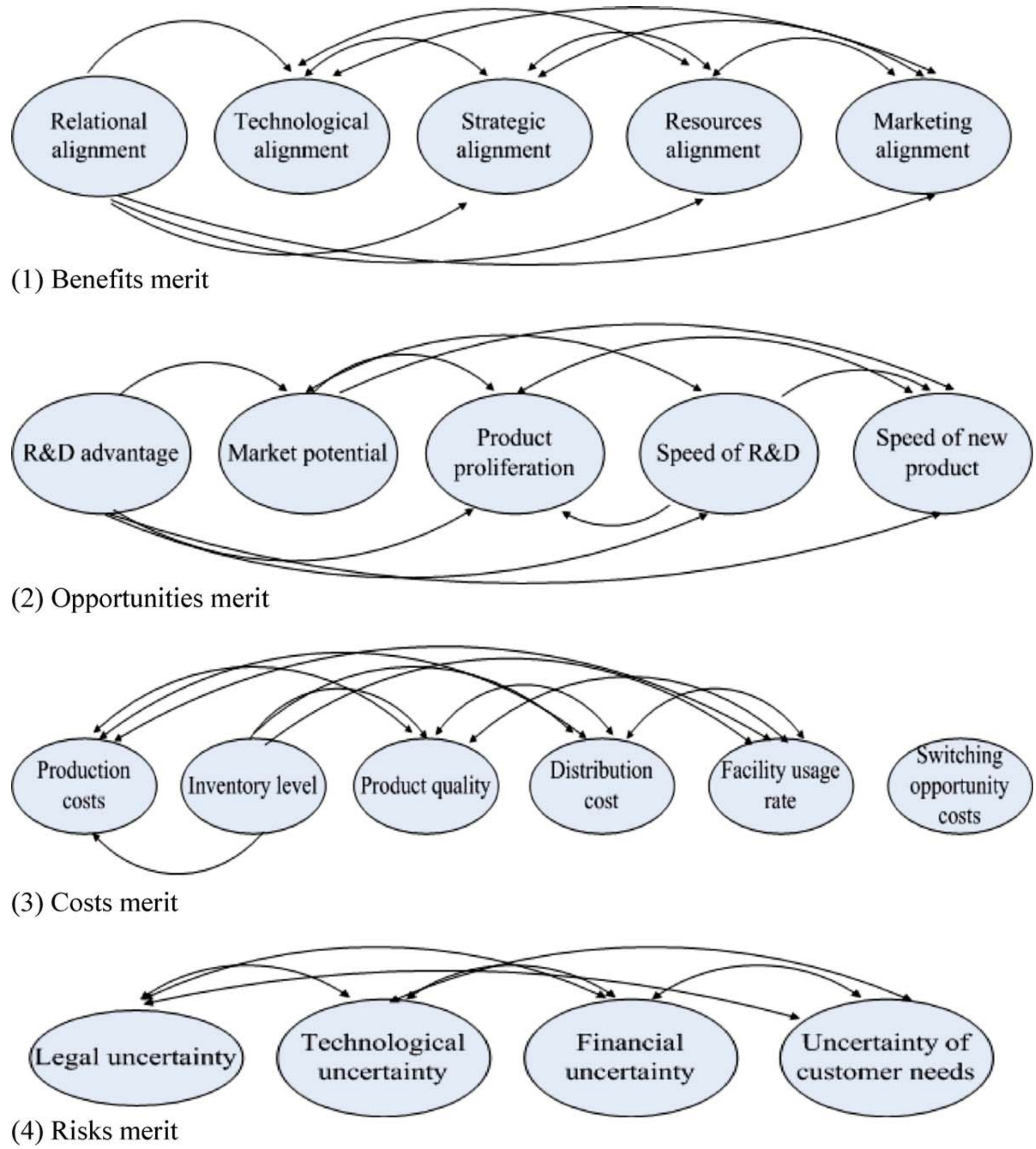


Fig. 5. The interrelationship among criteria under each merit.

Based on $\mathbf{H}^{b^*}$, the interrelationship among the five criteria can be depicted as in Fig. 5. According to the experts' opinions through ISM analysis, b2, b3, b4 and b5 are mutually interrelated. This can be seen from the double-sided arrows among the four criteria in Fig. 5(1). Note that relational alignment (b1) affects the other four criteria; however, it is not affected by the other criteria. The interrelationships among criteria under the opportunities, costs, and risks merits are also shown in Fig. 5.

Phase III: Calculation of priorities of the merits.

A set of questionnaire is completed by the experts to generate the priorities of the four merits. After Step 8 calculations, the crisp-valued aggregate positive reciprocal matrix is obtained, as shown in Table 4. With a CR value of 0.094, a value less than the threshold of 0.1, the consistency test is passed. The synthesized priorities are 0.575, 0.116, 0.056 and 0.253 for *superior efficiency*, *superior quality, superior customer response*, and *superior innovation*, respectively. The results respond to the different emphasis on the stages of product life cycle from innovation, efficiency, quality, to customer response. Since PV silicone thin-film solar cell is an emerging market, innovation and efficiency should be paid more attention.

The importance of each merit to each strategic criterion is determined next by Step 9. Geometric mean method is applied to aggregate experts' opinions, and the centroid method is used to defuzzify the fuzzy numbers. For instance, the 10 experts' ratings of benefits on *superior efficiency* are “$\tilde{7}$”, “$\tilde{7}$”, “$\tilde{9}$”, “$\tilde{7}$”, “$\tilde{5}$” “$\tilde{7}$”, “$\tilde{9}$”, “$\tilde{7}$”, “$\tilde{5}$” and “$\tilde{7}$”. The fuzzy numbers are (5, 7, 9), (5, 7, 9), (7, 9, 9), (5, 7, 9), (3, 5, 7), (5, 7, 9), (7, 9, 9), (5, 7, 9), (3, 5, 7) and (5, 7, 9). The aggregated triangular fuzzy number is $(4.83, 6.88, 8.56) = ((5\times5\times7\times5\times3\times5\times7\times5\times3\times5)^{1/9}, (7\times7\times9\times7\times5\times7\times9\times7\times5\times7)^{1/9}, (9\times9\times9\times9\times7\times9\times9\times9\times7\times9)^{1/9})$, and the crisp value is 6.756 using the centroid method. Table 5 shows the calculated weights and the normalized weights of the four merits on strategic criteria.

Table 4
Comparison matrix for the strategic criteria.

	Superior efficiency	Superior quality	Superior customer response	Superior innovation	Priorities of strategic criteria
Superior efficiency	1	4.938	8.034	3.305	0.575
Superior quality	0.203	1	2.914	0.274	0.116
Superior customer response	0.124	0.343	1	0.247	0.056
Superior innovation	0.303	3.651	4.043	1	0.253
			$\lambda_{max} = 4.254$	CI = 0.085	CR = 0.094

Table 5
Weights of the four merits.

	Superior efficiency (0.575)		Superior quality (0.116)		Superior customer response (0.056)		Superior innovation (0.253)	
	Crisp weights	Normalized weights	Crisp weights	Normalized weights	Crisp weights	Normalized weights	Crisp weights	Normalized weights
Benefits (*B*)	6.756	0.265	7.487	0.318	6.756	0.286	6.987	0.265
Opportunities (*O*)	7.753	0.305	6.987	0.296	7.487	0.317	7.753	0.294
Costs (*C*)	8.034	0.316	6.523	0.277	5.714	0.242	5.897	0.224
Risks (*R*)	2.914	0.114	2.582	0.110	3.651	0.155	5.714	0.217

Using the priorities of strategic criteria from Table 4 and the normalized weights of the four merits from Table 5, the overall priorities of the four merits are calculated as follows:

$b = 0.575 \times 0.265 + 0.116 \times 0.318 + 0.056 \times 0.286 + 0.253 \times 0.265 = 0.273$

$o = 0.575 \times 0.305 + 0.116 \times 0.296 + 0.056 \times 0.317 + 0.253 \times 0.294 = 0.302$

$c = 0.575 \times 0.316 + 0.116 \times 0.277 + 0.056 \times 0.242 + 0.253 \times 0.224 = 0.284$

$r = 0.575 \times 0.114 + 0.116 \times 0.110 + 0.056 \times 0.155 + 0.253 \times 0.217 = 0.142$

Phase IV: Calculation of product strategy priorities under the four merits.

A questionnaire is employed to collect experts' opinions on the importance of criteria, the interdependence among criteria and the expected performance of product strategies. The strategic product mix evaluation results under criteria (o2), (c1), (c4), and (c6) are quantitative. The quantitative data of market potential (o2) are obtained based on market share and product price, while the data of production costs (c1) are acquired from equipment cost, materials costs and labor hour expense. In addition, the quantitative data of distribution cost (c4) are coming from transportation cost, channel management cost, and channel inventory level while the data of switching costs (c6) are obtained from any opportunity cost occurred among enterprises, suppliers, and customers. Because the unit of measure of quantitative data can range differently, the data is transformed into values between zero and one. The concept of membership function, by assigning values of zero and one to the worst and the best outcomes, is used to obtain a performance index of different product mixes.

Whereas quantitative results can be used to estimate the firm's performance, data of many factors are very hard to be quantified. Therefore, criteria, other than (o2), (c1), (c4) and (c6), are evaluated by the experts qualitatively. Five different levels of evaluation shown in Table 2 are used here.

After the calculations, the relative priorities in each merit sub-network are calculated. An unweighted supermatrix for each sub-network can be formed by entering the priorities in the appropriate columns. Use the *benefits* merit as an example. Table 6 shows the unweighted supermatrix for the *benefits* sub-network. The unweighted supermatrix is transformed into a weighted supermatrix, and a limit supermatrix is calculated last. The priorities of the 10 product mixes under the benefits sub-networks are shown in the alternatives-to-benefits column of the limit supermatrix. The procedure is repeated for the other three merits.

The relative performance of alternatives under each merit is shown in Table 7. Under the benefits merit, product mix B&D performs the best with a priority of 0.139, followed by product mix A&C with 0.13792. Under the opportunities merit, product mix B&D performs the best with a priority of 0.12126, followed by product mix A&C with 0.1172. Under the costs merit, product mix A&C is least costly with a normalized reciprocal priority of 0.21328, fol-

Table 6
Unweighted supermatrix for *benefits* sub-network.

	Benefits (B)	(a)	(b)	(c)	(d)	(e)	A&B	A&C	A&D	A&E	B&C	B&D	B&E	C&D	C&E	D&E
Benefits (B)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
(a)	0.47904	1.00000	0.45411	0.49852	0.25219	0.44611	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
(b)	0.02813	0.00000	0.10047	0.06395	0.07595	0.04541	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
(c)	0.14465	0.00000	0.10771	0.23154	0.49051	0.09327	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
(d)	0.26354	0.00000	0.05074	0.03925	0.14115	0.32193	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
(e)	0.08465	0.00000	0.28697	0.16675	0.04020	0.32193	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A&B	0.00000	0.04225	0.04000	0.03636	0.01613	0.03390	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A&C	0.00000	0.07042	0.08000	0.07273	0.03226	0.06779	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A&D	0.00000	0.09859	0.12000	0.07273	0.06452	0.06779	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A&E	0.00000	0.12676	0.13333	0.10909	0.06452	0.06779	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
B&C	0.00000	0.14085	0.05333	0.09091	0.09677	0.10169	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
B&D	0.00000	0.04225	0.08000	0.12728	0.11290	0.11865	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
B&E	0.00000	0.07042	0.10667	0.14545	0.14516	0.15255	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
C&D	0.00000	0.14085	0.12000	0.10909	0.16129	0.13559	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
C&E	0.00000	0.14085	0.13333	0.10909	0.14516	0.15255	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
D&E	0.00000	0.12676	0.13333	0.12728	0.16129	0.10169	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

Table 7
Priorities of product mixes under four merits.

Alternatives	Merits			
	Benefits (0.27255)		Opportunities (0.30168)	
	Normalized	Rank	Normalized	Rank
Product mix A&B	0.03682	10	0.11455	3
Product mix A&C	0.13792	2	0.11720	2
Product mix A&D	0.07019	8	0.09681	6
Product mix A&E	0.09802	6	0.08465	9
Product mix B&C	0.13082	3	0.07867	10
Product mix B&D	0.13900	1	0.12126	1
Product mix B&E	0.06485	9	0.09209	7
Product mix C&D	0.11120	5	0.09208	8
Product mix C&E	0.12264	4	0.09884	5
Product mix D&E	0.08854	7	0.10385	4

Alternatives	Merits							
	Costs (0.28374)				Risks (0.14204)			
	Normalized	Reciprocal	Normalized Reciprocal	Rank	Normalized	Reciprocal	Normalized Reciprocal	Rank
Product mix A&B	0.17368	5.75772	0.04681	10	0.12666	7.89515	0.07058	10
Product mix A&C	0.03812	26.23295	0.21328	1	0.06695	14.93652	0.13353	2
Product mix A&D	0.10659	9.38174	0.07628	7	0.11505	8.69187	0.07770	6
Product mix A&E	0.10638	9.40026	0.07643	6	0.11010	9.08265	0.08119	4
Product mix B&C	0.05750	17.39130	0.14139	3	0.06695	14.93652	0.13353	2
Product mix B&D	0.04973	20.10859	0.16349	2	0.04512	22.16312	0.19813	1
Product mix B&E	0.12047	8.30082	0.06749	8	0.11804	8.47170	0.07573	7
Product mix C&D	0.10435	9.58313	0.07791	5	0.11804	8.47170	0.07573	7
Product mix C&E	0.14016	7.13470	0.05801	9	0.11010	9.08265	0.08119	4
Product mix D&E	0.10302	9.70685	0.07892	4	0.12299	8.13074	0.07269	9

lowed by product mix B&D with 0.16349. Under the risks merit, the least risky alternative is product mix B&D with a normalized reciprocal priority of 0.19813, followed by product mix B&C with 0.13353.

Phase V: Calculation of final priorities of the product strategies.

The final ranking of the product mixes is calculated by the five methods, additive, probabilistic additive, subtractive, multiplicative priority powers and multiplicative, to aggregate the scores of each alternative under *B*, *O*, *C* and *R*. The results are as shown in Table 8.

Under all the five methods of synthesizing the scores of alternatives, the top two alternatives are product mix B&D and A&C, and the ranking depends on the synthesizing methods. Product mix B&D ranks the first under the probabilistic additive method, subtractive method and multiplicative method, while product mix A&C ranks the first under the additive method and multiplicative priority powers method. Product mix B&C ranks the third under all five methods. The reasons for the high ranking of product mix B&D are the relatively high benefits and excellent potentials and relatively low costs and risks expected from the products. The reasons for the good ranking of product mix A&C are because it has the lowest costs and ranks the second under the benefits, opportunities and risks merits.

To examine the robustness of the outcomes under the five methods, a sensitivity analysis is carried out next by changing the priorities of the merits. The results of the sensitivity analysis are shown in Table 9. Use costs merit as an example. The original priority of costs (c) is 0.28374, and a trial and error method is applied to calculate how much priority c needs to increase or decrease to make the best product mix change to another product mix. When c decreases from 0.28374 to 0.26584, the best product mix changes from product mix A&C to product mix B&D under the additive method. When c decreases to 0.2644, the best product mix changes from product mix A&C to product mix B&D under the multiplicative priority powers method. On the other hand, the best alternative becomes product mix A&C when c increases to 0.35715 under both the probabilistic additive and subtractive methods. Therefore, depending on the likelihood of c to decrease or increase substantially, the best product mix may be changed as a result. Note that the best alternative does not change under the multiplicative method since the priorities of merits are not included in the calculation. The sensitivity analysis can also be carried out using the software Super Decisions (Saaty, 2003). The results from the additive method are as shown in Fig. 6. Fig. 6(1)–(4) shows the sensitivity analysis graph when the priority of benefits, opportunities, costs and risks changes, respectively.

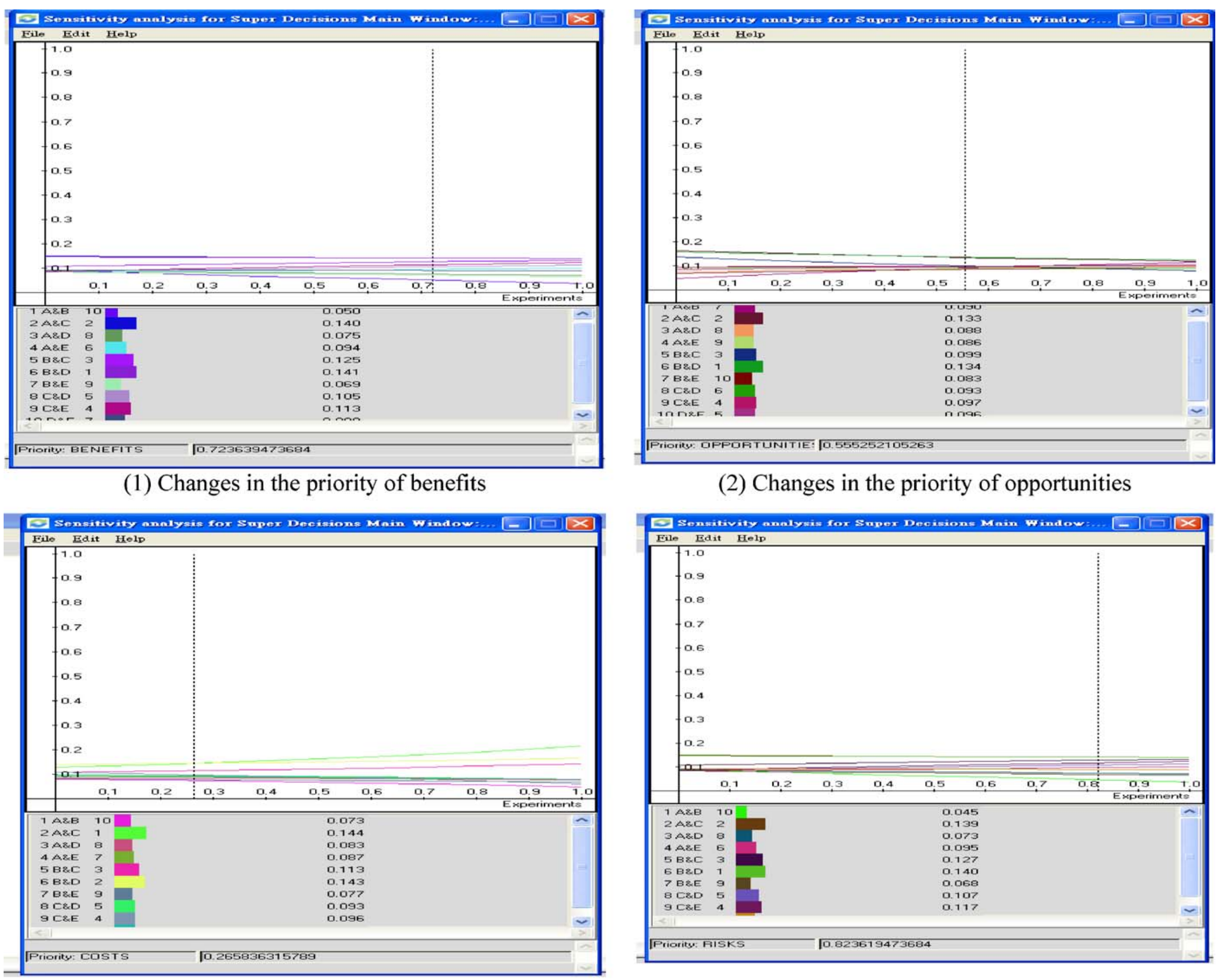
Table 8
Final priorities of product mixes.

	Additive	Rank	Probabilistic additive	Rank	Subtractive	Rank	Multiplicative priority powers	Rank	Multiplicative	Rank
Product mix A&B	0.06790	10	0.40310	10	-0.02268	10	0.06088	10	0.19173	10
Product mix A&C	0.15243	1	0.47840	2	0.05262	2	0.14792	1	6.33361	2
Product mix A&D	0.08101	8	0.42753	8	0.00175	8	0.08034	8	0.55411	8
Product mix A&E	0.08547	7	0.43221	7	0.00643	7	0.08508	7	0.70843	7
Product mix B&C	0.11847	3	0.45934	3	0.03356	3	0.11505	3	2.67341	3
Product mix B&D	0.14899	2	0.47972	1	0.05395	1	0.14689	2	7.51181	1
Product mix B&E	0.07536	9	0.42028	9	-0.00549	9	0.07453	9	0.41997	9
Product mix C&D	0.09095	4	0.43749	4	0.01171	4	0.08992	4	0.83128	4
Product mix C&E	0.09123	5	0.43361	6	0.00784	6	0.08763	5	0.78551	5
Product mix D&E	0.08818	6	0.43454	5	0.00876	5	0.08744	6	0.72570	6

Table 9
Sensitivity analysis under different priorities of merits.

Merits	Benefits (0.27255)				Opportunities (0.30168)			
Merit weight changes	*b* decreases		*b* increases		*o* decreases		*o* increases	
Synthesizing method	*b*	Best alternative	*b*	Best alternative	*o*	Best alternative	*o*	Best alternative
Additive	N/A	A&C	0.72364	B&D	N/A	A&C	0.55525	B&D
Probabilistic additive	N/A	B&D	N/A	B&D	N/A	B&D	N/A	B&D
Subtractive	N/A	B&D	N/A	B&D	N/A	B&D	N/A	B&D
Multiplicative priority powers	N/A	A&C	0.61627	B&D	N/A	A&C	0.42056	B&D
Multiplicative	N/A	B&D	N/A	B&D	N/A	B&D	N/A	B&D

Merits	Costs (0.28374)				Risks (0.14204)			
Merit weight changes	*c* decreases		*c* increases		*r* decreases		*r* increases	
Synthesizing method	*c*	Best alternative	*c*	Best alternative	*r*	Best alternative	*r*	Best alternative
Additive	0.26584	B&D	N/A	A&C	N/A	A&C	0.82362	B&D
Probabilistic additive	N/A	B&D	0.35715	A&C	0.08656	A&C	N/A	B&D
Subtractive	N/A	B&D	0.35715	A&C	0.08656	A&C	N/A	B&D
Multiplicative priority powers	0.2644	B&D	N/A	A&C	N/A	A&C	0.15697	B&D
Multiplicative	N/A	B&D	N/A	B&D	N/A	B&D	N/A	B&D



(1) Changes in the priority of benefits

(2) Changes in the priority of opportunities

(3) Changes in the priority of costs

(4) Changes in the priority of risks

Fig. 6. The sensitivity analysis under the additive method.

To summarize, based on the experts' judgment on the priorities of the merits and the different kinds of synthesizing methods, the best product mix may change from product mix A&C to product mix B&D, or vice versa. Nevertheless, under normal situations, product mix A&C and B&D are the most appropriate alternatives for the firm, and one of them should be chosen for developing.

6. Discussion

Due to keen challenges of quick response to dynamic customer needs and increasing complexity of product design along with rapidly changing technologies, the selection of the right set of new products to develop is critical for a long-term success. From above analysis, the paper finds that either a series of family products (Product B) with emerging new parts (Product D) or a multi-product (Product A) with upgrading existing equipment (Product C) should be the best option. The results are reasonable since the strategic products of both emerging new parts and multi-products are exploratory innovation with high risk; while the strategic products of both family products and upgrading existing equipment belong to exploitative innovation with low risk. Various studies have argued that organizations need to become ambidextrous [47] and develop exploratory and exploitative innovation simultaneously in order to reach sustainable competitive advantages [48]. Units that engage in exploratory innovation pursue new knowledge and develop new products and services for emerging customers or markets. Units pursuing exploitative innovation build on existing knowledge and extend existing products and services for existing customers. In addition, the firm may take most advantage if it develops product E successfully and independently. However, it is risky from the point view of the firm, and it is a repetitive investment from the point view of the network. In order to attain the maximum profit of the network while satisfying individual customer needs and sharing risks and benefits with participants, a firm should decide not to develop product E.

7. Conclusion

From empirical demonstration, the conceptual model with a fuzzy analytic network process (FANP), interpretive structural modeling (ISM) and benefits, opportunities, costs and risks (BOCR) can effectively and precisely handle the complicated product strategy problem and lead to an outstanding result. From the practical view of the manufacturing industry, the outcome of strategic products analysis is the instrument for receiving supports from central authorities. In addition, official policy planners not only represent central authorities to show their points of views, but also utilize the model to design their development plan. Fortunately, our results from the view of the industry are very similar to the future structure plan of PV solar cell power stipulated by the central government. It means that the proposed strategic products will be supported with slight amendment by central authorities. In addition, public policies have an important role in providing future directions and triggering necessary changes to achieve expected goals. These polices should ultimately lead to a market transformation from less acceptable or undesirable solutions to more ideal ones. Simultaneously, the public sector is confronting pressure to reduce its expenditures and to provide products and services more competitive. Therefore, the firms will put more emphasis on impact-driven policies for effective resource uses.

In the case study, two product mixes have rather outstanding performances, and which one out of the two alternatives should be chosen can be our future research direction. Methodologies such as multiple goal programming can be incorporated into the model to consider the limitations of resources in time and cost, and the most suitable product mix can be selected as a result.

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