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Combined DEMATEL techniques with novel MCDM for the organic light emitting diode technology selection

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ABSTRACT

This research aims to propose a hybrid process concerning the economic and industrial prospects along with critical technology streams toward a more effective selection on new technology. The integration of fuzzy Delphi method, the Decision Making Trial and Evaluation Laboratory (DEMATEL) technique, and the analytic network process (ANP) is employed to construct a technology selection model regarding the economic and industrial prospects. On the other hand, the patent co-citation approach (PCA) is applied to objectively draw key technology fields as technology alternatives for the technology selection model from patent data. The emerging organic light emitting diode (OLED) display technology is used as a case in order to verify the applicability of proposed a novel hybrid MCDM method for the best technology selection. The result of this hybrid process can help top managers of technology-based companies or policy makers of governments to more objectively and effectively determine future research and development direction.

1. Introduction

Technology selection is one of the most challenging decision-making areas that the management of a company encounters (Torkkeli & Tuominen, 2002). A company has to select and invest in a technology field with comparative advantage from various technology-alternatives under multiple criteria and within a complicated environment (Yu, Hsu, & Chen, 1998). Technology-based enterprises rely on the renewal of existing technological resources and exploitation of new technologies to remain competitive and to sustain growth (McNamara & Baden-Fuller, 1999). This type of firm needs expert technological planning and strategizing to maintain its competitive advantages or to grasp new opportunities. Selection of key technologies helps these firms and countries to establish their advantage in a competitive environment (Clark, 1989; Lee & Song, 2007; Morone, 1989; Torkkeli & Tuominen, 2002). At the national level, selecting and supporting key emerging technologies help countries to establish their strategic advantage in the international market (Khalil, 2000).

However, technology selection is a multiple criteria decision making (MCDM) challenge (Lamb & Gregory, 1997). It is necessary for decision makers to completely consider various aspects of criteria such as potential benefit, risk, and cost, in order to determine the most suitable technologies. Furthermore, interdependent relations may exist among such criteria in real world. To address this challenging decision-making issue, this study aims to propose a hybrid technology selection process integrating the fuzzy Delphi method, the Decision Making Trial and Evaluation Laboratory (DEMATEL) technique, and the analytic network process (ANP) with novel MCDM method for the best OLED (organic light emitting diode) technology selection.

The fuzzy Delphi method is applied to gather information and identify critical evaluation criteria for technology selection. The DEMATEL is used to detect and build the complex network relationship map (NRM) among dimensions/criteria. The ANP is employed to conduct the dependence and feedback among criteria and to decide the relative weights of the criteria by super-matrix. The combination of fuzzy Delphi method, DEMATEL technique, and ANP with novel MCDM method is used to perform for constructing a technology selection structure.

In addition, the increasing complexity of the relations between technologies and economic problems combined with the occurrence of national or organizational budget resource restrictions imply new challenges for science and technology (Ronde, 2003). Hence, it is necessary to carefully identify key technologies which have the greatest impact on economic and industrial competitiveness. Patent data provides an effective way to learn R&D information of a specific technology and is useful for conducting an

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analysis on technology trend (Abraham & Morita, 2001; Liu & Shyu, 1997). Researchers can learn the R&D status of a specific industry using patent analysis and then employ this information for research planning and technology forecasting (Daim, Reuda, Martin, & Gerdsri, 2006; Lai & Wu, 2005). In order to generate valuable information from patent data for research planning or strategy making, the first step of patent management is to classify patents based on the need of a specific industry. Lai and Wu (2005) develop the patent co-citation approach (PCA) based on the co-citation analysis of the bibliometrics to provide an overall picture of the industrial technology information via patents and to generate technology categories with more valuable information. The PCA is used to extract key technology fields as the alternatives in the technology selection structure constructed by the combination of fuzzy Delphi method, DEMATEL technique, and ANP with novel MCDM method.

The remainder of this study is organized as follows: Section 2 reviews related technology selection literature. Section 3 describes the proposed technology selection process integrating the fuzzy Delphi method, the DEMATEL, the ANP, and the PCA. In Section 4, the organic light emitting diode (OLED) technology is adopted as a case to verify the proposed novel MCDM method for technology selection process. Finally, Section 5 provides concluding remarks.

2. Technology selection

Technology as a major source of competitive advantage for manufacturing industries is widely accepted by practitioners, governments and academics. An enterprise can waste its competitive advantages by investing in wrong alternatives at the wrong time or by investing too much in the right ones (Torkkeli & Tuominen, 2002). A country can obtain its competitive advantages by investing in emerging technologies with comparative advantages (Lee & Song, 2007; Yu et al., 1998). In order to realize this competitive advantage, it is vital to understand both the specific technologies, and the ways in which organizations can best manage technology (Phaal, Farrukh, & Probert, 2001). Gregory (1995) has proposed that management of technology is comprised of five generic processes: identification, selection, acquisition, exploitation, and protection. Among these processes, technology selection is defined as involving the choice of technologies that should be supported and promoted (Gregory, 1995). In the phase of technology selection, decision makers have to gather information from various sources about the alternatives, and evaluate these alternatives against each other or some set of criteria (Lamb & Gregory, 1997). Accordingly, Gregory (1995) separates the "identification" and "selection" phases where the former is concerned with gathering alternatives and the latter is concerned with the action to decide on an alternative. In contrast, Dussauge, Hart, and Ramanatsoa (1992) defines the technology selection process as identification and selection of new or additional technologies which the firm seeks to master. In sum, a key theme in these definitions is that technology selection is a "process" that is closely linked to organizational objectives and is associated with the broader technological and market environment (Shehabuddeen, Probert, & Phaal, 2006; Stacey & Ashton, 1990).

However, it is becoming more difficult to identify the right technologies because the number of technologies is increasing and the technologies are becoming more and more complex (Torkkeli & Tuominen, 2002). Additionally, decision makers need to face other challenges such the rising cost of technological development, abundance of technological options, and rapid diffusion of technologies (Berry & Taggart, 1994; Lei, 2000; Steensma & Fairbank, 1999). For example, technology accounts on average for more than one-third of all business capital spending (Bakos, 1998). The abundance and complexity of technological options makes the task of accessing suitable technologies and selection of the most suitable option more difficult (Cantwell, 1992). Ronde (2001) selects 98 specific technologies of future possibilities in the field of biotechnology in France. Using the same foresight technique, Ronde (2003) respectively introduces 40, 51, 39 and 50 potential areas in the fields of elementary particles, energy, natural resources and environment for Germany and France. Lee and Song (2007) also provide 56 research areas in nano-technology field for South Korea.

Besides the increasing cost of technological development and the abundance of technology options, many studies have shown that companies fail to assess new technologies. Hackett (1990) and Greenberg and Canzoneri (1995) point out that projects to incorporate new technology in a majority of companies are failing or are not fulfilling expectations. Huang and Mak (1999) argue that the failure of a chosen technology often results from poor management and assessment. Some of the causes have been attributed to the inability to consider the wider relationship of technology to the industrial context and the technology investments (Schroder & Sohal, 1999). These studies demonstrate the necessity for a careful assessment to overcome the difficulties of technology selection before introducing a new technology (Efstathiades, Tassou, Oxinos, & Antoniou, 2000).

3. Building a novel hybrid MCDM model for OLED technology selection

A novel hybrid MCDM model (combined many methods/techniques) is used to deal with complex evaluation problems for the best OLCD technology selection. Methods/techniques of novel hybrid MCDM model are included as follows: (1) the fuzzy Delphi method integrates experts' opinions without modifying their original idea, processes the fuzziness within their thoughts and, moreover, reduces survey costs; the DEMATEL technique helps to determine relationships and construct NRM among these criteria; then (3) the ANP-based on NRM forces experts to consider the decision-making problems systematically and conducts the interdependence among these evaluation criteria to build supper-matrix for finding preference weightings; finally (4) evaluation model is used to improve and select the best OLED technology. In evaluation model the PCA provides the performance information for research planning by generating the technology fields based on a classification system of the industry's basic patents by experts. Therefore this study proposes a technology selection process integrating the four aforementioned methodologies in order to extract their advantages to conduct technology selection. The process through fuzzy Delphi method, the DEMATEL technique, and the ANP involves the assessment of economic or industrial consideration toward a more efficient evaluation of new technologies. On the other hand, the PCA focuses on the identification of key technology fields associated with a major R&D trend of specific technology. This technology selection process includes eight steps, described in detail below and in Fig. 1:

The first step of this process is to define the technology selection problem. Researchers need to identify the scope for a technology which is desired to be analyzed.

The step 2 through step 4 aims to construct a technology selection model. The technology selection criteria regarding economic or industrial prospect are explored by performing literature review. Moreover, the fuzzy Delphi method is adopted to widely gather information and experts' judgments to determine the importance of criteria. Then, construct the relation structure among the dimensions of technology selection by applying the DEMATEL and obtain the weights of these criteria affiliated in each

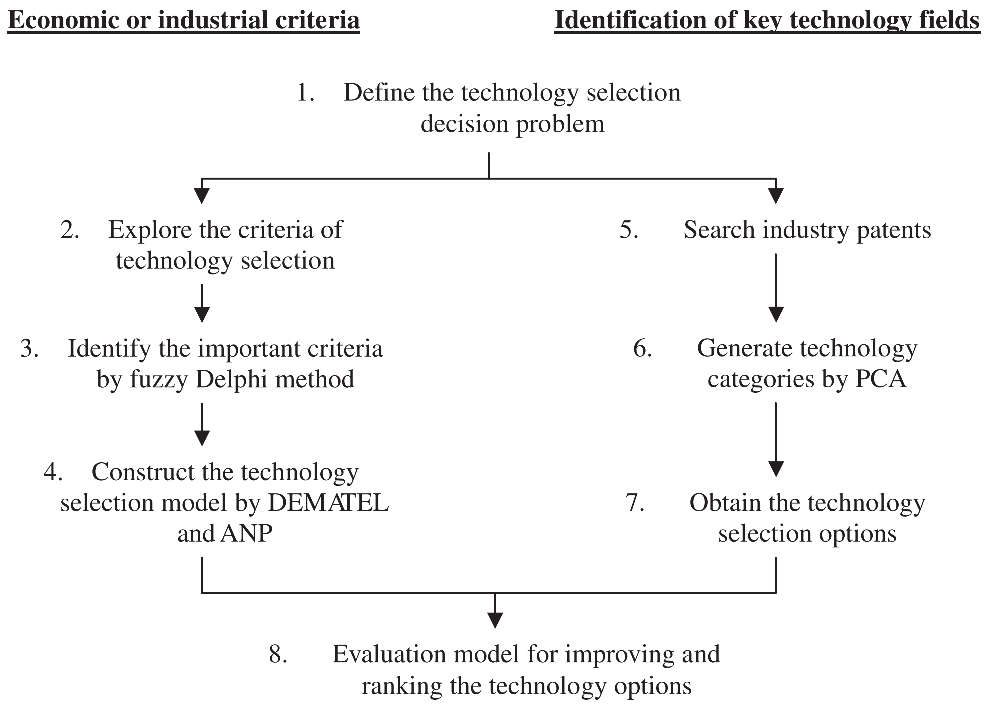

Fig. 1. The technology selection process.

dimension by the ANP to create a technology selection model for a certain technology. The experts who are familiar with the R&D and the industry of a specific technology are invited to filter the important criteria and to determine the weights of criteria by the ANP.

Next, the step 5 through 7 is the identification of significant technology fields. Researchers have to determine the proper database, technology keywords, assignee, application date, and issue date to search patents of a specific technology. The results of patent search are classified into several significant technology fields by applying PCA. Subsequently, the technology categories are named by technology experts to be the technology alternatives for the technology selection model constructed in the previous steps.

Finally, the R&D experts are invited to evaluate each technology alternative based on the technology selection model.

The four methods/techniques applied in this technology selection process are briefly described as follows.

3.1. Fuzzy Delphi method

Many published studies on technology selection have developed a wide variety of models related to experts' judgments (Baker, 1974; Liberatore & Titus, 1983; Schmidt & Freeland, 1992). In order to integrate experts' opinions and identify a critical set of criteria for technology selection, the Delphi method developed by Rand Corporation is a widely used technique (Bañuls & Salmeron, 2007; Bañuls & Salmeron, 2008; Chen, Kang, Xing, Lee, & Tong, 2008; Dalkey & Helmer, 1963; Lee & Kim, 2001). The Delphi method aims to improve group decision making by seeking opinions without face-to-face interaction and is commonly defined as "a method of systematic solicitation and collection of judgments on a particular topic through a set of carefully designed sequential questionnaires, interspersed with summarized information and feedback of opinions derived from earlier responses" (Delbecq, Van de Ven, & Gustafson, 1975; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003). Several features characterize the Delphi method and distinguish it from face-to-face group interrogative method, including anonymity, iteration, controlled feedback, statistical group response, and stability in responses among the experts on a specific issue (Cochran, 1983; Cyphert & Grant, 1971; Dailey & Holmberg, 1990; Uhl, 1983; van Zolingen & Klaassen, 2003; Whitman, 1990). Compared to the traditional face-to-face group decision technique, the Delphi method has four principal advantages thought to be important in gaining the considered opinions of experts:

(1) It uses group decision-making techniques, involving experts in the field, which have greater validity than those made by an individual (Brooks, 1979);
(2) The anonymity of participants and the use of questionnaires avoid the problems commonly associated with group interviews, for example, specious persuasion or "deference to authority, impact of oral facility, reluctance to modify publicized opinions and bandwagon effects" (Martorella, 1991);
(3) Consensus reached by the group reflects reasoned opinions because the Delphi process forces group members to consider logically the problem under study and to provide written responses (Murry & Hammons, 1995);
(4) Opinions using the Delphi method can be received from a group of experts who may be geographically separated from one another (Murry & Hammons, 1995).

Although the Delphi method provides a chance to completely integrate diverse experts' opinions, it is time-consuming, costly, and has a lower questionnaire return rate because it tries to obtain converged results through repetitive surveys. In addition, the problems of ambiguity and uncertainty still exist in experts' responses (Chang, Huang, & Lin, 2000; Hwang & Lin, 1987). Ishikawa et al. (1993) introduce fuzzy Delphi method to avoid the above defects using fuzzy logic. The fuzzy Delphi method can converge the experts' responses with fewer survey rounds and effectively conduct their ambiguity and uncertainty (Klir & Folger, 1988). Furthermore, recent studies have widely adopted fuzzy Delphi method together with ANP to conduct decision making at a different stage, such as e-marketplace (Lee & Li, 2006), urban renewal project selection (Wey & Wu, 2008), and product design (Wei & Chang, 2008). This study employs fuzzy Delphi method to integrate experts' opinions toward technology selection criteria.

The process of the fuzzy Delphi method is briefly explained as follows: The experts' opinions in the technology selection criteria collected by the questionnaires are identified by the triangular fuzzy number as follow:

$$\tilde{w}_k = (a_k, b_k, c_k) \tag{1}$$

where $\tilde{w}_k$ is the fuzzy number of the criterion k, a_k is the minimum of the experts' evaluation, b_k denotes the average of the experts' evaluation, and c_k denotes the maximum of the experts' evaluation.

The center-of-gravity method is in common use (Klir & Folger, 1988), where S_k denotes the clear value as follow:

$$S_k = \frac{a_k + b_k + c_k}{3} \tag{2}$$

Finally, researchers select the proper criteria according to the needs of the study. The principles are as follows:

(1) If $S_k \geqslant \lambda$ then accept criterion k;
(2) If $S_k < \lambda$ then omit criterion k.

3.2. DEMATEL method

In a totally interdependent system, all criteria of the system are mutually related, directly or indirectly; thus, any interference with one of the criteria affects all the others, so it is difficult to find priorities for decision-making (Tzeng, Chiang, & Li, 2007). The DEMATEL, originated from the Geneva Research Centre of the Battelle Memorial Institute (Fontela & Gabus, 1976; Gabus & Fontela, 1973), aims to convert the relationship between the causes and effects of criteria into an intelligible structural model of the system (Huang, Shyu, & Tzeng, 2007; Lee, Kim, Cho, & Park, 2009; Lin & Tzeng, 2009; Liou, Yen, & Tzeng, 2008; Ou Yang, Leu, & Tzeng, 2009; Tzeng et al., 2007), The DEMATEL method is briefly described as follows:

Step 1: Calculate the initial direct-relation matrix.
Experts are asked to indicate the direct influence degree between criterion i and criterion j, as indicated by z_{ij}, using a pairwise comparison scale designated five levels, where the scores ranging from 0 to 4 represent "no influence" to "very high influence", respectively. The initial direct-relation matrix $\boldsymbol{Z} = [z_{ij}]_{l\times l}$ is obtained by pairwise comparisons in terms of influences and directions between criteria, in which l denotes the number of criteria.

Step 2: Normalize the direct-relation matrix.
The normalized direct-relation matrix $\boldsymbol{X}$ is obtained through Eqs. (3) and (4), in which all principal diagonal elements are equal to zero.

$$\boldsymbol{X} = y \cdot \boldsymbol{Z} \tag{3}$$

$$y = \min_{i,j}\left[\frac{1}{\max_{1\leqslant i\leqslant l}\sum_{j=1}^{l} z_{ij}}, \frac{1}{\max_{1\leqslant j\leqslant l}\sum_{i=1}^{l} z_{ij}}\right] \tag{4}$$

Step 3: Calculate the total-relation matrix
Once the normalized direct-relation matrix $\boldsymbol{X}$ has been obtained, the total-relation matrix $\boldsymbol{T}$ is acquired by Eq. (5):

$$\boldsymbol{T} = \boldsymbol{X}(\boldsymbol{I} - \boldsymbol{X})^{-1} \tag{5}$$

where $\boldsymbol{I}$ is the identity matrix.

Step 4: Obtain the inner dependence matrix
In this step, the sum of each row in total-relation matrix is equal to 1 by normalization method, and then the inner dependence matrix can be acquired for ANP super-matrix in diagonal matrix (Wu, 2008).

3.3. The ANP

The ANP is a generalization of AHP (Saaty, 1996) to overcome the problem of interdependence and feedback between criteria (Lee, Tzeng, Guan, Chien, & Huang, 2009). The AHP, one of the most widely used multiple criteria decision making (MCDM) methods, decomposes a problem into several levels that make up a hierarchy in which each decision element is supposed to be independent. The ANP extends the AHP to problems with dependence and feedback. It allows for more complex interrelationship among decision elements by replacing a hierarchy in the AHP with a network (Meade & Sarkis, 1999). Several studies have adopted the ANP to conduct the problem of technology selection (Erdoğmuş, Kapanoglu, & Koç, 2005; Erdoğmuş, Aras, & Koç, 2006; Kengpol & Tuominen, 2006; Lee et al., 2009).

However, the difficulty of ANP is to determine the dependence and feedback among dimensions/criteria. In order to overcome this problem we use the DEMATEL technique to build the network relationship map (NRM) for objectively constructing super-matrix in ANP. Therefore the ANP conducts dependence and feedback within a cluster (inner dependence) and among different clusters (outer dependence) based on NRM. The first step of the ANP is to compare the criteria in the entire system to form a super-matrix through pairwise comparisons. A nine-point scale recommended by Saaty (1980) is adopted to obtain experts' opinions—with preferences between alternatives given as equally, moderately, strongly, very strongly, or extremely preferred (with pairwise weight of 1, 3, 5, 7, and 9, respectively)—and values of 2, 4, 6, and 8 as the intermediate values for the preference scale. The general form of the super-matrix is shown as Eq. (6):

$$\boldsymbol{A} = \begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & & C_s \\ e_{11}\cdots e_{1t_1} & e_{21}\cdots e_{2t_2} & & e_{s1}\cdots e_{st_s} \end{array} \\ \begin{array}{cc} C_1 & \begin{array}{c} e_{11} \\ e_{12} \\ \vdots \\ e_{1t_1} \end{array} \\ C_2 & \begin{array}{c} e_{21} \\ \vdots \\ e_{2t_2} \end{array} \\ \vdots & \vdots \\ C_s & \begin{array}{c} e_{s1} \\ \vdots \\ e_{st_s} \end{array} \end{array} & \begin{bmatrix} \boldsymbol{A}_{11} & \boldsymbol{A}_{12} & \cdots & \boldsymbol{A}_{1m} \\ \boldsymbol{A}_{21} & \boldsymbol{A}_{22} & \cdots & \boldsymbol{A}_{2m} \\ \vdots & \ddots & \vdots & \\ \boldsymbol{A}_{s1} & \boldsymbol{A}_{s2} & \cdots & \boldsymbol{A}_{ss} \end{bmatrix} \end{array} \tag{6}$$

within clusters, C_s, which is known as inner dependence, and between clusters, which is known as outer dependence, where C_s denotes the sth cluster, e_{st} denotes the tth element in the sth cluster, and matrix $\boldsymbol{A}_{ss'}$ is the principal eigenvector of the influence of the criteria compared in the sth cluster to the s'th cluster. The super-matrix represents the impact of all model elements relative to the complete element set. The actual elements that make up the columns ($\boldsymbol{A}_{ss'}$) of the super-matrix are the eigenvector solutions within the components. Since there usually is interdependence among clusters, the columns of a super-matrix usually sum to more than one. The super-matrix must be normalized to make it stochastic, that is, each column of the matrix sums to unity. The final priority weights, which account for element interactions, are derived by multiplying the super-matrix by itself until the columns stabilize (Niemira & Saaty, 2004).

3.4. The PCA

One of the biggest problems in technology selection is how to derive promising technology alternatives from blurred and various development directions of an emerging technology. Researchers utilize two different methodologies to overcome this problem. One is to perform cluster analysis using survey data with questionnaires; the other is to perform bibliometrics, such as citation analysis and patent mapping (Lee & Song, 2007). Cluster analysis needs to conduct a large-scale survey which is time-consuming and costly. Otherwise, the technology estimate will not be precise and discerning (Lee & Song, 2007). Instead, past studies adopting bibliometrics have proved that patent data can provide researchers an overall picture of a specific technology development status and effectively helps to learn the major technology streams via patent information (Jaffe & Trajtenberg, 2002; Jaffe, 1986; Kostoff & Scaller, 2001; Porter & Detampel, 1995; Verspagen, 1997). In order for the patents to yield valuable information for research planning or strategy making, recent studies have applied the co-citation analysis of bibliometrics to provide an overall picture of the industrial technology information via patents (Chang, Lai, & Chang, 2009; Oda, Gemba, & Matsushima, 2008). Therefore, this study applies the patent co-citation approach proposed by Lai and Wu (2005) to generate a classification system for OLED technology with more valuable information.

A patent specification is required to identify its cited documents. According to the view of bibliometrics, a patent specification can be identified with a citing document, and its prior arts can be defined as cited documents (Lai & Wu, 2005). In bibliometrics, Small (1973) proposed the co-citation approach to assess the documents' similarities. The focus of the co-citation analysis is on computing the frequency of Documents A and B co-cited by specific documents. However, the number of A and B being co-cited is not subject to limitation because there may be other new document citing A and B simultaneously. Therefore, using the co-cited frequency of documents can effectively assess the similarities and identify the category of the scientific literature and its evolution (Sharabchiev, 1989).

The purpose of the assessment of document similarities is to classify documents. Lai and Wu (2005) proposed the patent co-citation approach to create a patent classification system based on the concept of co-citation analysis. The patent classification system created by the PCA classifies an industry's basic patents. After the patent classification system is built, target patents are classified by comparing them with basic patents. In the PCA, target patents are patents to be classified, and basic patents are patents to be repeatedly cited by the target patents (Lai & Wu, 2005). The concept of the PCA is shown in Fig. 2.

Q_1–Q_7 are target patents that cite the basic patents P_1–P_5. The lines between target patents and basic patents represent the relationships between the two groups of patents. Based on the similarities of basic patents, technology categories F_1 and F_2 are identified. The technology categories F_1 and F_2 also represent the major technology streams or fields in a specific technology domain (Lai & Wu, 2005).

The PCA is divided into three phases to complete this classification system. Phase I selects the proper patent database to search target patents and specify basic patents. Phase II applies the co-cited frequency of the basic patent pairs to assess the patent similarities. Phase III uses factor analysis to group basic patents into a smaller set of factors.

3.4.1. Phase I: Searching for patents and defining industry basic patents

In Phase I, a proper patent database will be selected with which to conduct the patent search. As a result, industry basic patents will be defined from the search results.

Step 1: Patent search.

In accordance with the purpose of study, the researchers may search specific patent databases based on the criteria of technology keywords, inventors, patent application date, and the patent issue date. The selected patents from this step will be divided into two groups: target patents and candidate of basic patents. Where Q_p is denoted as the target patent p, and CP_q is denoted as a candidate for basic patent q. Target patents are citing patents that will be classified. Candidates for basic patents are the patents cited by target patents. The referential relationship between target patents and candidates for basic patents are represented in the matrix shown in Eq. (7):

$$[\alpha_{pq}]_{M\times N},\quad \text{where } \alpha_{pq} = \begin{cases} 1 & Q_p \text{ cites } CP_q \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

where M is the number of target patents, and N is the number of candidates of basic patents.

Step 2: The selection of basic patents.

The PCA defines technology categories by industry basic patents. The more often a specific early patent is cited by later patents, the more likely it is to be the foundation of these later patents (Mogee, 1997); thus, a so-called basic patent is a patent repeatedly cited by later patents (Lai & Wu, 2005). The frequency of CP_q being cited is shown in Eq. (8):

$$CS_q = \sum_{p=1}^{M} \alpha_{pq} \tag{8}$$

CP_q becomes a basic patent if CS_q is greater than or equal to the threshold c for selecting basic patents. The threshold c depends on the cited frequency of the candidates for basic patents.

After identifying basic patents, a matrix will be created from the relationship between the basic patents and the target patents shown in Eq. (9):

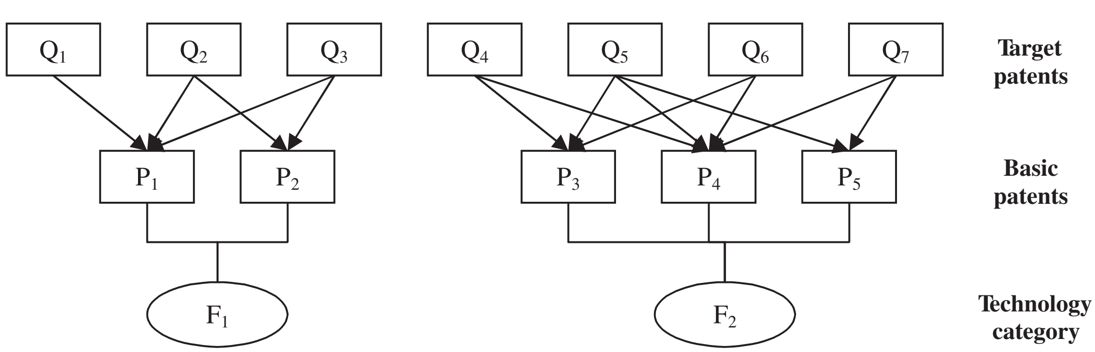

Fig. 2. The concept of the PCA.

$$[\varepsilon_{pq}]_{m\times n}, \quad \text{where } \varepsilon_{pq} = \begin{cases} 1 & Q_p \text{ cites } P_q \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

where P_q is a basic patent q, m is the number of target patents that can be classified by the basic patents, and n is the number of basic patents.

3.4.2. Phase II: Assessment of the similarities in basic patent pairs

The PCA adopts the Pearson correlation coefficient to assess the similarity for a basic patent pair. There are three steps required to obtain the similarities in the basic patent pairs.

Step 1: Calculating the co-cited frequency of each basic patent pair.

The co-cited frequency of the given basic patent q and q' is shown in Eq. (10):

$$\omega_{qq'} = \begin{cases} \sum_{p=1}^{m} \varepsilon_{pq}\varepsilon_{pq'} & \text{if } q \neq q', \\ 0 & \text{if } q = q', \end{cases} \quad 1 \leqslant q \leqslant n, \ 1 \leqslant q' \leqslant n \tag{10}$$

where ε_{pq} and $\varepsilon_{pq'}$ are citing relationships as defined in Eq. (9); and a symmetric matrix $\omega_{qq'}$ can be obtained after computing all of the co-cited frequencies of n basic patents.

Step 2: Calculate the linkage strength of each basic patent pair.

The linkage strength of a basic patent pair is calculated as Eq. (11):

$$\pi_{qq'} = \begin{cases} \frac{\omega_{qq'}}{S_q + S_{q'} - \omega_{qq'}} & \text{if } q \neq q', \\ 0 & \text{if } q = q', \end{cases} \quad 1 \leqslant q \leqslant n, \ 1 \leqslant q' \leqslant n \tag{11}$$

where $\omega_{qq'}$ is the co-cited frequency calculated in the previous steps. $S_q = \sum_{p=1}^{m} \varepsilon_{pq}$ is the cited frequency of a basic patent q.

Step 3: Calculating the Pearson correlation coefficient of each basic patent pair.

Before calculating the Pearson correlation coefficient of the given basic patents q and q', the linkage strengths of these basic patent pairs are divided into two groups. The first group is $\Pi_q = \{\pi_{rq}, r \neq q, q'\}$, and the second group is $\Pi_q = \{\pi_{rq'}, \ r \neq q, \ q'\}$.

Next, calculating the Pearson correlation coefficient of basic patent pairs using Eq. (12):

$$r_{qq'} = \begin{cases} \frac{(n-2)\sum_{r=1}^{n} \pi_{rq}\pi_{rq'} - \sum_{r=1}^{n} \pi_{rq} \sum_{r=1}^{n} \pi_{rq'}}{\sqrt{(n-2)\left(\sum_{r=1}^{n} \pi_{rq}^2\right) - \left(\sum_{r=1}^{n} \pi_{rq}\right)^2} \sqrt{(n-2)\left(\sum_{r=1}^{n} \pi_{rq'}^2\right) - \left(\sum_{r=1}^{n} \pi_{rq'}\right)^2}} \\ \quad \text{if } q \neq q' \\ 1 \\ \quad \text{if } q = q' \end{cases} \tag{12}$$

where $\pi_{rq} \in \Pi_q$ is the linkage strength between basic patents r and q, and $\pi_{rq'} \in \Pi_{q'}$ is the linkage strength between basic patents r and q'.

3.4.3. Phase III: Creation of a patent classification system

The bibliometrics generally employs factor analysis, cluster analysis, or multi-dimensional scaling to classify documents, journals, and authors. The PCA employs factor analysis to classify patents based on two considerations. First, the loading of patents on the technology category indicates the degree of importance for the basic patents to the technology. Second, factor analysis can be repeated to create a hierarchical classification system, if necessary (Lai & Wu, 2005).

The inputs for the factor analysis are the Pearson correlation coefficients calculated by the third step in Phase II.

4. The case of OLED display technology selection

OLED display has more advantages than numerous other display technologies. The features of the OLED display are: (1) self-illuminating (that is, it needs no backlight); (2) wide viewing angle; (3) fast response (about 1 μs); (4) highly energy efficient; (5) low drive-voltage (3–10 V); (6) slim profile (smaller than 2 mm); (7) easy to use for a large area; (8) flexible; and (9) has a simple manufacturing process (Chen & Huang, 2005). These features meet the needs of both multimedia displays and portable communications products with a display component. The OLED display has the potential to become the next mainstream display technology. In 2006's International Meeting of Information Display, the CEO of Samsung SDI, Soon-Taek Kim claimed that OLED is the ultimate display of the future (Chen & Huang, 2007). However, the driving, coloring, and manufacturing process of OLED are still diversified without dominant design. Every manufacturer has its own know-how, techniques, and equipment (Chen & Huang, 2005). Since the original OLED patent launched by Kodak has matured in 2005, the OLED display technology has been considered as a great opportunity for Taiwanese flat display industry to overcome the industry stereotype of original equipment manufacturing. It is necessary for Taiwan to invest in the key technology fields associated with economic and technological competitiveness. Therefore, this study takes OLED display technology as a case and to verify the feasibility of the proposed technology selection process.

4.1. Construct the technology selection model

In order to construct the technology selection model regarding economic or industrial prospects, the literature related to technology selection is reviewed first.

The selection model developed by Arbel and Shapira (1999) focuses on benefit and cost. Piipo and Tuominen (1990) emphasize the matching of alternatives to the capabilities and strategies of companies and risks as major factors in the selection, in addition to the benefits and costs. Yap and Souder (1993) emphasize the uncertainties of commercial and technical success, the funding history of technologies, the resource requirements to develop technologies, the degree to which the technologies contribute to established missions, and the current life-cycle stage of the technologies. Yu et al. (1998) focus on the strategic importance, business effect, business opportunity, risk, present technology position, and the cost to obtain the technology to evaluate feasibility. Coldrick, Longhurst, Ivey, and Hannis (2005) consider the technical, corporate and strategic factors; as well as the regulatory, market, financial, and application factors of the R&D project selection. Huang, Chu, and Chiang (2008) emphasize the scientific and technological merit, potential benefits, project execution, and the project risk for the government-sponsored R&D project selection. Shehabuddeen et al. (2006) propose a technology selection process that consists of requirement filters, adoption filters, internal factors, and external factors.

This study concludes the technology selection criteria for OLED from the above-mentioned studies (Arbel & Shapira, 1999; Coldrick et al., 2005; Huang et al., 2008; Piipo & Tuominen, 1990; Shehabuddeen et al., 2006; Yap & Souder, 1993; Yu et al., 1998) to four scales: technological merit, business effect, technology development potential, and risk with 18 criteria. These criteria are presented in Table 1 with a short description.

Next, the fuzzy Delphi method is used to filter the important criteria. This study applies snowball sampling by inviting six technology experts and five industry research experts to evaluate the importance of the criteria explored in the previous step. The importance of the criteria is measured using the linguistic scales and their corresponding fuzzy numbers: (0.7,0.9,0.9) – extremely important, (0.5,0.7,0.9) – important, (0.3,0.5,0.7) – normal, (0.1,0.3,0.5) – unimportant, (0.1,0.1,0.3) – extremely unimportant.

The important criteria are sifted from the evaluation result by employing the fuzzy Delphi method. The sifting threshold value will affect the number of criteria. If the threshold value is higher, there will be fewer remaining criteria so that the following research may be affected. Therefore, this study adopts 0.6 as the threshold value because it is the mean of the minimum value of "important" (0.5) and the maximum value of "normal" (0.7). The result is shown in Table 2:

According to the results of the criterion sifting, the five criteria—potential return on investment, technical resource availability, equipment support, opportunity of technical success, and technical difficulties—are canceled. In addition, financial risk (i_{14}) and technical personnel support (D_4/i_{15}) are suggested in the in-depth interviews with experts.

After verifying the importance of criteria by fuzzy Delphi method, the OLED display technology selection model is constructed by adopting DEMATEL and ANP. To detect the relationship among the dimensions of technological merit (D_1), business effect (D_2), risk (D_3), and technical personnel support (D_4), the total-relation matrix $\boldsymbol{T}$ among the four dimensions is derived by from Eqs. (3)–(5). Determined by experts, the result shown as Table 3 demonstrates the outer dependence existing among these four dimensions. According to this total-relation matrix, the network relationship map can be constructed as a map shown in Fig. 3.

Next, the DEMATEL method is also used to determine the relationship among criteria within the four dimensions. Through Eqs. (3)–(5), the total-relation matrices of technological merit (D_1), business effect (D_2), and risk (D_3) are shown as Tables 4–6.

As Tables 4–6, the interdependence exists among criteria within the three dimensions. The inner dependence matrices, hence, can be obtained by normalizing the three total-relation matrices. The outer dependence among different dimensions is based on the network structure expressed in Fig. 3. The unweighted super-matrix, which is shown as Table 7, is then multiplied by the priority weights from

Table 2
The sifting result of important OLED technology selection criteria.

Scale	Criteria	S	Result
Technological merit (D_1)	Advancement of technology (i_1)	0.76061	
	Innovation of technology (i_2)	0.66364	
	Key of technology (i_3)	0.66970	
	Proprietary technology (i_4)	0.76061	
	Generics of technology (i_5)	0.63333	
	Technological connections (i_6)	0.65152	
	Technological extendibility (i_7)	0.66364	
Business effect (D_2)	Potential return on investment	0.54242	Cancel
	Effect on existing market share (i_8)	0.67576	
	New market potential (i_9)	0.68182	
	The potential size of market (i_{10})	0.66970	
	Timing for technology (i_{11})	0.65758	
Technology development potential	Technical resource available	0.56061	Cancel
	Equipment support	0.57879	Cancel
	Opportunity of technical success	0.53030	Cancel
Risk (D_3)	Commercial risk (i_{12})	0.74849	
	Technical risk (i_{13})	0.74242	
	Technical difficulties	0.58485	Cancel

Table 3
The total-relation matrix $\boldsymbol{T}$.

	D_1	D_2	D_3	D_4
D_1	2.05	2.28	1.51	2.22
D_2	2.16	1.88	1.34	2.09
D_3	2.14	2.10	1.24	2.10
D_4	2.50	2.47	1.60	2.15

Table 1
Description of OLED technology selection criteria.

Criteria	Descriptions
1. Technological merit	
Advancement of technology	Level of advancement of the proposed technology compared with existing technology
Innovation of technology	Innovation level of the proposed technology
Key of technology	Whether the proposed technology is critical for product or industry development
Proprietary technology	Whether the technology project will generate a proprietary technology position through the intellectual property rights
Generics of technology	Whether the proposed technology is a generic technology to industry
Technological connections	Whether the proposed technology is applicable for many products; the more technological applications, the higher technological connections
Technological extendibility	The extent to which the proposed technology has the potential for further technology development
2. Business effect	
Potential return on investment	The potential return on investment in the technology
Effect on existing market share	Whether the technology can enlarge the existing market share
New market potential	Whether the technology has the potential to create a new market
Potential size of market	The potential size of the market in which the products apply the technology
Timing for technology	Whether this is the right time to develop the technology
3. Technology development potential	
Technical resources availability	Access to which the technology can obtain technical resources
Equipment support	Extents to technology that can be supported by necessary facilities
Opportunity for technical success	Opportunity of success for proposed technology and whether there is any similar successful technology
4. Risk	
Commercial risk	Potential commercial risk of the applications
Technical risk	Potential technical risk of the technology development
Technical difficulties	Whether the applications can be mass produced

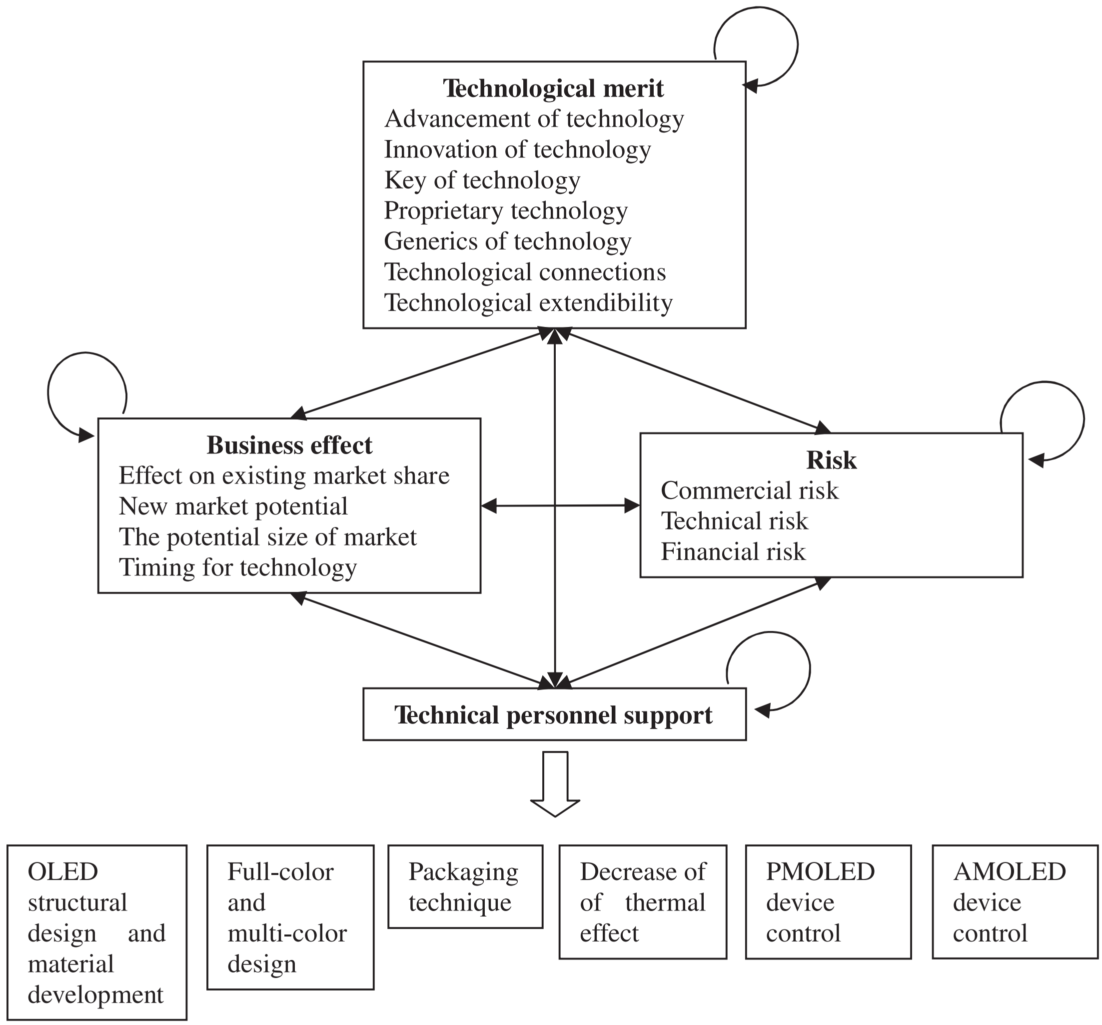

Fig. 3. The OLED technology selection model.

the dimensions, which yields the weighted super-matrix. Finally, the system solution is derived by multiplying the weighted super-matrix by itself until the system's row values converge to the same value for each column of the matrix. This process generates the limiting super-matrix shown as Table 8 which provides the relative importance weights for every criterion in the model

According to the results, technical personnel support (i_{15} = 0.26935), timing of technology (i_{11} = 0.09504), and financial risk (i_{14} = 0.08967) rank first, second, and third in all criteria, respectively.

Table 4
The total-relation matrix ***T*** of technological merit (D_1).

	i_1	i_2	i_3	i_4	i_5	i_6	i_7
i_1	0.50	0.71	0.81	0.80	0.58	0.77	0.77
i_2	0.50	0.44	0.63	0.66	0.52	0.59	0.59
i_3	0.67	0.73	0.70	0.86	0.67	0.84	0.84
i_4	0.49	0.53	0.64	0.51	0.53	0.65	0.65
i_5	0.38	0.41	0.52	0.46	0.33	0.51	0.51
i_6	0.59	0.64	0.78	0.72	0.63	0.61	0.77
i_7	0.59	0.67	0.78	0.72	0.61	0.77	0.62

Table 5
The total-relation matrix ***T*** of business effect (D_2).

	i_8	i_9	i_{10}	i_{11}
i_8	0.89	1.03	1.11	0.89
i_9	1.16	0.89	1.16	0.94
i_{10}	1.16	1.11	0.94	0.94
i_{11}	1.40	1.34	1.40	0.92

4.2. Identify the key technology fields

In this section, the key technology fields are identified by performing PCA to understand the important technology trends. In order to cover as many OLED patents as possible, the keywords used to search are acquired through interviews with technology experts. Based on the result of these interviews, this study employs EL, OLED, organic LED, organic light emitting diode, organic light emitting device, OEL, organic EL, organic electroluminescence, polymer light emitting diode, PLED, and polymer LED in order to search the industry's patents.

Table 6
The total-relation matrix ***T*** of risk (D_3).

	i_{12}	i_{13}	i_{14}
i_{12}	0.99	0.82	1.02
i_{13}	1.77	0.84	1.31
i_{14}	1.38	0.87	0.82

Table 7
Unweighted super-matrix.

		D_1							D_2				D_3			D_4
		i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}	i_{15}
D_1	i_1	0.10	0.13	0.13	0.12	0.12	0.12	0.12	0.06	0.12	0.06	0.08	0.07	0.12	0.12	0.12
	i_2	0.14	0.11	0.14	0.13	0.13	0.14	0.14	0.07	0.11	0.05	0.07	0.05	0.07	0.09	0.11
	i_3	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.32	0.36	0.16	0.27	0.28	0.19	0.16	0.36
	i_4	0.16	0.17	0.16	0.13	0.15	0.15	0.15	0.14	0.22	0.15	0.17	0.10	0.27	0.11	0.22
	i_5	0.12	0.13	0.13	0.13	0.11	0.13	0.13	0.12	0.07	0.14	0.11	0.13	0.10	0.15	0.07
	i_6	0.16	0.15	0.16	0.16	0.16	0.13	0.16	0.15	0.06	0.20	0.11	0.18	0.14	0.16	0.06
	i_7	0.16	0.15	0.16	0.16	0.16	0.16	0.13	0.14	0.07	0.24	0.19	0.18	0.12	0.21	0.07
D_2	i_8	0.13	0.07	0.17	0.35	0.24	0.36	0.17	0.23	0.28	0.28	0.28	0.16	0.20	0.17	0.28
	i_9	0.21	0.24	0.28	0.19	0.20	0.26	0.29	0.26	0.12	0.27	0.26	0.20	0.18	0.20	0.12
	i_{10}	0.22	0.25	0.30	0.23	0.26	0.23	0.32	0.28	0.12	0.23	0.28	0.22	0.21	0.17	0.12
	i_{11}	0.44	0.44	0.25	0.24	0.31	0.15	0.23	0.23	0.48	0.23	0.18	0.42	0.40	0.46	0.48
D_3	i_{12}	0.18	0.21	0.36	0.34	0.26	0.34	0.18	0.21	0.33	0.31	0.50	0.33	0.46	0.46	0.11
	i_{13}	0.29	0.21	0.22	0.29	0.30	0.42	0.26	0.55	0.53	0.20	0.14	0.30	0.20	0.29	0.26
	i_{14}	0.52	0.58	0.42	0.37	0.44	0.24	0.56	0.24	0.14	0.49	0.37	0.37	0.34	0.25	0.64
D_4	i_{15}	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 8
Limiting super-matrix.

		D_1							D_2				D_3			D_4
		i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}	i_{15}
D_1	i_1	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	i_2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	i_3	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
	i_4	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
	i_5	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	i_6	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	i_7	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
D_2	i_8	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
	i_9	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
	i_{10}	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
	i_{11}	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
D_3	i_{12}	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
	i_{13}	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	i_{14}	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
D_4	i_{15}	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

The patent database providing the most abundant patents should be used. The database of the United States Patent and Trademark Office (USPTO) is one of the favored sources to conduct patent search because the U.S. market is an important market for technology transfer and international trade, combined with the territoriality of patent protection, thereby luring inventors to file patent applications in the US (Lai & Wu, 2005). Therefore, this study adopted the database of USPTO to be the source for patent search. This study searches the OLED patents from the application dates of 01/01/2002 through 12/31/2006 in order to reflect the recent research status of OLED. There are 2834 patents, and 13,175 cited patents in this time frame.

Table 9 lists the result of the search in step 5; the cited frequency of candidates for basic patents. The definition of basic patents is the patents repeatedly cited by later patents. The more a patent is cited by later patents, the greater the possibility that it is the basis of these patents (Mogee, 1997). There are 137 basic patents cited greater or equal to 10, and the percentage of the 137 basic patents out of the 13,175 candidates is 1.04%. Thus, this study used the cited frequency greater than 10 as the criterion to select a basic patent, with 137 basic patents selected from the 13,175 candidates for basic patent. These 137 basic patents are then used to create a classification system for the OLED display industry; 832 patents out of the 2834 target patents refer to basic

Table 9
The cited frequency of candidates for basic patent.

Cited frequency	Number of candidates for basic patent	Cumulative patent	Percentage	Cumulative percentage
1	9978	9978	75.73	75.73
2	1812	11,790	13.75	89.49
3	544	12,334	4.13	93.62
4	317	12,651	2.41	96.02
5	158	12,809	1.20	97.22
6	79	12,888	0.60	97.82
7	73	12,961	0.55	98.38
8	45	13,006	0.34	98.72
9	32	13,038	0.24	98.96
10	28	13,066	0.21	99.17
11	15	13,081	0.11	99.29
12	13	13,094	0.10	99.39
13	10	13,104	0.08	99.46
14	5	13,109	0.04	99.50
>15	66	13,175	0.50	100.0

patents. Thus, the referential relationship between the basic patents and the target patents can be demonstrated by the matrix $[\varepsilon_{pq}]_{832\times137}$ in Eq. (9).

Next, calculate the co-cited frequency of C_2^{137} basic patent pairs by 832 target patents with Eq. (10), and the result is shown in the matrix $[\omega_{qq'}]_{137\times137}$. The matrix $[\omega_{qq'}]_{137\times137}$ is then input into Eq. (11) to obtain the linkage strength between basic patent pairs, and the result is demonstrated in the matrix $[\pi_{qq'}]_{137\times137}$. The matrix $[\pi_{qq'}]_{137\times137}$ is then taken into Eq. (12), and as a result, the correlation coefficient matrix $[\gamma_{qq'}]_{137\times137}$ for the basic patent pairs is derived. Finally, the Pearson correlation matrix $[\gamma_{qq'}]_{137\times137}$ is factor-analyzed using a principal component analysis with promax rotation. Based on eigenvalue greater than 1 as the criterion, 13 factors are retained. The result is shown in Table 10. The marginal variance explained by the 7th factor is low. Thus, 6 factors are retained, which account for 84.834%.

After the factor analysis, the six technology fields—OLED structural design and material development (A_1), full-color or multi-color design (A_2), packaging technique (A_3), decrease of thermal effect (A_4), PMOLED device control (A_5), and AMOLED device control (A_6)—are named by the photonics professors of National Changhua University of Education. These six technology fields are taken into the technology selection model constructed in previous step to be the technology selection alternatives. The completed OLED technology selection model is represented in Fig. 3.

Table 10
Eigenvalues and variances explained by factors.

Factor	Eigenvalues	Variance explained %	Cumulative variance %
1	53.244	38.864	38.864
2	24.151	17.629	56.493
3	18.744	13.682	70.175
4	7.918	5.780	75.954
5	6.822	4.980	80.934
6	5.343	3.900	84.834
7	3.225	2.354	87.188
8	2.767	2.020	89.207
9	2.050	1.496	90.704
10	1.693	1.236	91.939
11	1.260	0.920	92.859
12	1.017	0.742	93.601
13	1.007	0.735	94.337

4.3. Performance evaluation for improving and ranking for the technology options

After completing the OLED display technology selection model, the six technology fields are evaluated by technological experts and industry research experts to rank the six technology alternatives. This study adopts simple average weight to evaluate each technology alternative. The result indicates that OLED structural design and material development is the most significant technology field for domestic industry. The results can then be suggestions for the research direction should go in Taiwan's research institutes and manufacturers in OLED display technology. Additionally, the

Table 11
The evaluation of OLED technology fields for each criterion.

Criteria	Local weight	Global weight	OLED structural design and material development	Full-color and multi-color design	Packaging technique	Decrease of thermal effect	PMOLED device control	AMOLED device control
1. Technological merit	***0.261***		***8.102***	***5.969***	***6.055***	***5.115***	***4.845***	***7.424***
Advancement of technology	0.102	0.027	8.333	6.429	6.190	5.119	5.000	8.095
Innovation of technology	0.094	0.024	8.333	5.952	6.190	4.881	5.000	7.619
Key of technology	0.256	0.067	9.048	6.429	5.952	4.643	4.286	7.857
Proprietary technology	0.168	0.044	9.524	5.714	5.714	5.119	4.524	7.381
Generics of technology	0.107	0.028	6.667	5.238	5.952	4.643	5.476	6.429
Technological connections	0.129	0.033	7.619	6.190	6.429	6.071	5.714	7.619
Technological extendibility	0.145	0.038	5.952	5.476	6.190	5.595	4.762	6.667
2. Business effect	***0.273***		***7.773***	***6.827***	***5.135***	***4.686***	***5.275***	***7.690***
Effect on existing market share	0.238	0.065	7.619	6.905	5.000	4.881	5.238	7.619
New market potential	0.203	0.055	6.905	5.952	4.762	4.167	4.762	6.905
Potential size of market	0.211	0.058	7.857	6.667	5.476	4.643	5.476	7.857
Timing for technology	0.348	0.095	8.333	7.381	5.238	4.881	5.476	8.095
3. Risk	***0.197***		***7.500***	***5.974***	***5.109***	***4.310***	***4.524***	***6.733***
Commercial risk	0.281	0.055	7.381	6.190	5.714	4.167	4.524	6.905
Technical risk	0.264	0.052	6.190	6.190	5.476	5.119	4.524	6.667
Financial risk	0.455	0.090	8.333	5.714	4.524	3.929	4.524	6.667
4. Technical personnel support	***0.269***		***8.095***	***6.905***	***5.952***	***5.833***	***5.714***	***7.381***
Technical personnel support	1.000	0.269	8.095	6.905	5.952	5.833	5.714	7.381
Total performance score			**7.892**	**6.456**	**5.590**	**5.033**	**5.133**	**7.349**

ranks of OLED technology alternatives also represent the efforts or resources that should be allocated. The evaluation is represented in Table 11, after computing the scores of each technology alternative.

Accordingly, the OLED structural design and material development (performance score = 8.102), the AMOLED device control (performance score = 7.424), and the packaging technique (performance score = 6.055) are the key technological fields under the evaluation of the technological merit. The organic material applied by OLED is easily oxidized and affected by vapor to reduce the OLED devices' life. The organic material development and the device design, and the packaging, to overcome the flaws are important for improving the yield and reducing the cost. Therefore, the material development and the structural design, and the packaging technique are the technological field with technological benefit. In addition, the AMOLED technology has the potential to develop large display panel with more technological advantage than PMOLED.

The OLED structural design and material development (performance score = 7.773), the AMOLED device control (performance score = 7.690), and the full-color and multi-color design (performance score = 6.827), however, perform better business benefit. Once the OLED devices' life is extended, the OLED display technology will have more business effect on the expansion of market share due to its ascendant features mentioned above. The AMOLED device control, and the full-color and multi-color design are both important for the application of large display panel which is widely used on many types of consuming products.

Similarly, the OLED structural design and material development (performance score = 7.500), the AMOLED device control (performance score = 6.733), and the full-color and multi-color design (performance score = 5.974) perform lower risk. With more technological and business advantages analyzed above, the three technological fields suffer lower risk.

Finally, Taiwan has competitive TFT-LCD and LED industry which can provide related technological personnel for the need of the OLED structural design and material development (performance score = 8.095), the AMOLED device control (performance score = 7.381), and the full-color and multi-color design (performance score = 6.905).

In addition to determine the relationship among dimensions and criteria, the other contribution of DEMATEL method is to draw the impact-direction map to show the causal relation among "dispatchers" and "receivers". To draw the impact-direction map, the sum of rows and the sum of columns in total-relation matrix $\boldsymbol{T}$ are respectively denoted as vector $\boldsymbol{r}$ and vector $\boldsymbol{c}$ through Eqs. (13)–(15). The vector $\boldsymbol{r}$ indicates the level of influence to others. The vector $\boldsymbol{c}$, in contrast, reveals the level of relationship with others. The values of $\boldsymbol{r}+\boldsymbol{c}$, named "prominence", show the importance of factors. Similarly, the values of $\boldsymbol{r}-\boldsymbol{c}$, named "relation", divide factors into dispatchers and receivers (Wu, 2008). Factors having positive values of $\boldsymbol{r}-\boldsymbol{c}$ have greater influence on one another and are assumed to have higher priority and are named dispatcher; others with negative values of $\boldsymbol{r}-\boldsymbol{c}$ receiving more influence from another are assumed to have lower priority and are called receiver. On the other hand, the value of $\boldsymbol{r}+\boldsymbol{c}$ indicates the degree of relation between each factor with others, and factors with more values of $\boldsymbol{r}+\boldsymbol{c}$ have more relationship with another. Those having little values of $\boldsymbol{r}+\boldsymbol{c}$ have less relationship with others (Seyed-Hosseini, Safaei, & Asgharpour, 2006). In this case, the vector $\boldsymbol{r}$ and vector $\boldsymbol{c}$ in the total-relation matrix $\boldsymbol{T}$ of four main dimensions, as shown in Table 12, are calculated to draw the impact-direction map in order to reveal the major causal relationship among the dimensions. The values of prominence and relation in the matrices $\boldsymbol{T}$ of technological merit, business effect and risk are similarly derived by using Eqs. (13)–(15) and shown in Table 12 as well.

$$\boldsymbol{T} = [t_{ij}]_{l\times l} \tag{13}$$

$$\boldsymbol{r} = \left[\sum_{j=1}^{n} t_{ij}\right]_{l\times 1} = [t_{i\cdot}]_{l\times 1} \tag{14}$$

$$\boldsymbol{c} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times l} = [t_{\cdot j}]_{l\times 1} \tag{15}$$

The impact-direction map of the four main dimensions is shown in Fig. 4. As revealed in this figure, the risk (D_3) and the technical personnel support (D_4) are defined as the dispatchers owing to their positive values of $\boldsymbol{r}-\boldsymbol{c}$. In contrast, the technological merit (D_1) and the business effect (D_2) can be defined as receivers in terms of the negative values of $\boldsymbol{r}-\boldsymbol{c}$. According to Fig. 4, the risk determines the technical personnel support, the technological merit, and the business effect. Using the same procedure, the impact-direction maps of criteria within the dimensions of technological merit, business effect, and risk are also shown in Fig. 4. In risk (D_3), the technical risk (i_{13}) is regarded as the dispatcher; contrarily, the financial risk (i_{14}) and the commercial risk (i_{12}) are defined as receivers. In the impact-direction map of technological merit (D_1), the advancement of technology (i_1), the key of technology (i_3) and the technological extendibility (i_7) are defined as dispatchers to enhance the technological benefit. Similarly, the technical risk (i_{13}) is regarded as dispatcher in the impact-direction map of risk (D_3).

4.4. Discussion and implications

Decision makers can simultaneously consider the industrial criteria and the significant technological stream on the selection of OLED display technology by applying this proposed hybrid technology selection process. According to the result of the ANP shown in Table 11, the technical personnel support, timing of technology and financial risk are the most critical economic and industrial criteria. With OLED being such an emerging technology area, the adequate technology professionals' support directly determines the success of the technology development. Moreover, OLED technology is considered to be taking a chance to increase the margin for the flat display industry in Taiwan instead of OEM. Hence, the R&D resources should be invested to make the essential first move, thereby creating an advantage when a technology is emerging. So timing with technology ranks the second. Finally, the OLED technology is still in the emerging stage so that it is important for the manufacturers in this industry to carefully evaluate the financial risk involved.

Table 12
The values of prominence and relation.

Dimensions/criteria	$\boldsymbol{r}$	$\boldsymbol{c}$	$\boldsymbol{r}+\boldsymbol{c}$	$\boldsymbol{r}-\boldsymbol{c}$
Technological merit (D_1)	***8.06***	***8.85***	***16.91***	***−0.78***
Advancement of technology (i_1)	4.94	3.72	8.66	1.23
Innovation of technology (i_2)	3.94	4.13	8.07	−0.19
Key of technology (i_3)	5.30	4.86	10.16	0.44
Proprietary technology (i_4)	4.00	4.72	8.72	−0.73
Generics of technology (i_5)	3.12	3.88	7.00	−0.76
Technological connections (i_6)	4.74	4.75	9.49	−0.01
Technological extendibility (i_7)	4.76	4.75	9.51	0.01
Business effect (D_2)	***7.46***	***8.73***	***16.19***	***−1.27***
Effect on existing market share (i_8)	3.92	4.61	8.54	−0.69
New market potential (i_9)	4.15	4.37	8.52	−0.22
The potential size of market (i_{10})	4.15	4.61	8.76	−0.47
Timing for technology (i_{11})	5.07	3.69	8.76	1.38
Risk (D_3)	***7.58***	***5.69***	***13.26***	***1.89***
Commercial risk (i_{12})	2.04	3.01	5.05	−0.97
Technical risk (i_{13})	2.85	1.82	4.67	1.03
Financial risk (i_{14})	2.23	2.28	4.51	−0.05
Technical personnel support (D_4)	***8.72***	***8.56***	***17.28***	***0.16***

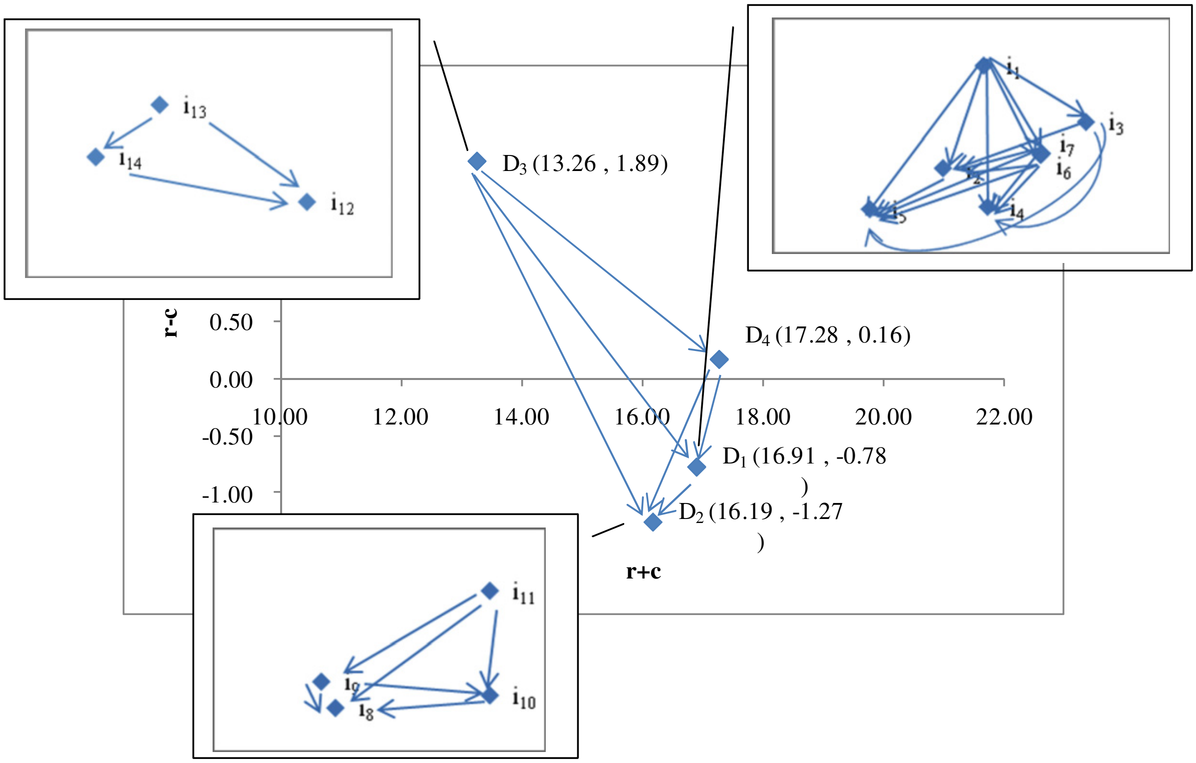

Fig. 4. The impact-direction map.

In contrast to the economic and industrial criteria evaluated through the ANP, the current significant OLED technology trends are identified by using the PCA. The six OLED technological fields obtained in Section 4.2 represent the major research and development streams in the world. The hybrid process facilitates decision makers to take economic and industrial requirements and critical technological development into account by taking the six key OLED technological fields into the technology selection model as alternatives. Therefore, the evaluation is more objective and comprehensive.

The evaluation of OLED technology alternatives provides decision makers with a guideline to determine the future R&D direction. The ranks of OLED technology alternatives also represent the efforts or resources that should be allocated. For investors, the result indicates that companies having these technologies are the targets to invest.

Moreover, the impact-direction map of DEMATEL method facilitates decision makers to realize the causal relationship among the four dimensions in order to improve the value of a technological field. The relationship between two different dimensions or criteria in the impact-direction map is derived from the total-relation matrix $\boldsymbol{T}$. For example, technological merit (D_1) impacting on business effect (D_2) has the greater value of 2.28; in contrast, the value of business effect (D_2) impacting on technological merit (D_1) is 2.16. Therefore, the relation of technological merit (D_1) impacting on business effect (D_2) is drawn as shown in Fig. 4. Decision makers are able to determine other relations between any two different dimensions and criteria by using the same approach. As a result, reducing the risk can attract more professionals, and raise the technological merit and the business effect for OLED display technology, according to Fig. 4. Similarly, the technological merit and the business effect are enhanced while this emerging industry attracts more R&D and marketing professionals.

Further, decision makers or top managers should reduce the technical risk which the OELD technology encounters to trigger the risk decrease based on the impact-direction map of risk in Fig. 4. Introducing mature technology and adequate researches are the practicable approaches to overcome the technical risk. Once the technical risk is reduced, the possibility of successful commercialization will be increased and financial institutions will be willing to fund the OLED manufacturers so that the financial risk is lowered. Accordingly, the impact-direction map of technological merit indicates that decision makers and top managers can improve the technological benefit by selecting and investing in the technology fields with advancement, significance and technological extendibility to trigger the refinement of technological merit. If manufacturers concentrate resources on the technology fields with technological advancement, the advanced technology fields will be naturally innovative, significant for other related technologies, applicable for many new products or new development, generic to become a standard in this industry, and will generate more patents. Manufacturers can obtain similar effect by investing in significant technology fields and those with the potential for further development. Likewise, OLED manufacturers are able to improve the business benefit by choosing a right time to develop the new technology. At a right time more and more consumers are willing to adopt new OLED display technology, and then the potential market size is larger so that the manufacturers can more easily expand their market share.

5. Concluding remarks

Technology selection, which is a multi-criteria decision-making problem, influences an enterprise or a country's technological advantage or disadvantage. As mentioned in previous section, technology is a major source of competitive advantage. In order to realize the competitive advantage from technologies, it is essential for technology-based firms or governments to carefully evaluate each technology alternative. However, decision makers encounter various economic or industrial influences such as cost, risk, potential benefit, and limited resources when conducting this type of decision making problems. On the other hand, the increasing number and the complex development of technologies also raise the difficulty of technology selection. In this study, a hybrid process is proposed to engage the challenge of technology selection. The proposed technology selection process is basically composed of two parts: (1) construction of a technology model regarding critical economic or industrial factors, and (2) identification of important technology fields.

Since the various economic and industrial prospects influence the decision making of technology selection, the technique such as AHP, assuming the criteria independent, is not effective to reflect the reality. The combination of DEMATEL and ANP, hence, is employed to construct the technology selection model regarding economic and industrial criteria. The DEMATEL objectively determines the interdependent relationship among criteria and constructs the network for ANP by group judgments. In addition, the fuzzy Delphi method widely gathers information concerning various economic and industrial aspects and effectively conducts the vagueness and imprecision within the experts' judgments in order to identify the critical technology selection criteria for obtaining the weights of each criterion in the next step of the combination of DEMATEL and ANP. Additionally, the impact-direction maps drawn by DEMATEL help decision makers or top managers to indicate which dimension and criterion is the dispatcher that influences other dimensions and criteria in a managerial system. This information facilitates decision makers or top managers to strategize how to improve the performance of each technology field.

On the other hand, the patent data provides an objective way to understand the overall picture of an emerging technology. The PCA classifies the patent data for a specific technology to reflect the major technology trends. By using PCA, decision makers can objectively identify key technology fields associated with potential technological competitiveness. Decision makers can more efficiently determine what technology alternatives, generated by the PCA, to invest through the proposed hybrid technology selection process. This hybrid process toward a more effective selection on new technology concerns the economic and industrial prospects along with critical technology streams by combining the technology selection model constructed by fuzzy Delphi method, DEMATEL, and ANP with the technology alternatives generated by PCA.

For the managerial meaning, the result of this hybrid technology selection process provides a guideline of future R&D directions for top managers of technology-based firms or policy makers of governments even if they do not completely understand the details of the new technology. Moreover, the impact-direction map drawn by the DEMATEL method helps decision makers to realize how to enhance the value of a technology field. To verify the technology selection process proposed by this study, we take OLED display technology, for example, to select proper technology fields for the industry in Taiwan. The result indicates that the business effect is of most concern, and OLED structure design and material development are the proper fields for domestic industry. This result verifies that the organic material and the OLED structure are the most critical technology fields of OLED technology development. Future research should apply this hybrid process to verify its applicability by demonstrations on other emerging technologies.

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