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A hybrid selection model for emerging technology

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ABSTRACT

Technology selection, which influences the advantages of an enterprise or a country, is a multi-criteria decision issue that can be improved by integrating different methods. In addition, it is more and more difficult to identify the right technologies because the technologies are increasing in number and complexity. This study proposes a technology selection process integrating fuzzy Delphi method, analytic hierarchy process (AHP), and patent co-citation approach (PCA) for technology selection. The former effectively gathers experts' judgments toward technology selection criteria and conducts the fuzziness existing in their responses. The analytic hierarchy process has the strength of identifying criteria and obtaining their relationship and their weights. The patent co-citation approach identifies the major R&D fields of a specific technology from patent data. Through this proposed process, the key technology fields can be identified in the end. The organic light emitting diode (OLED) technology in Taiwan is used to be an example to illustrate the proposed technology selection process.

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1. Introduction

Technology-based enterprises rely on the renewal of existing technological resources and exploitation of new technologies to remain competitive and to sustain growth [1]. This type of firm needs expert technological planning and strategizing to maintain its competitive advantages or to grasp new opportunities. Therefore, technology selection is one of the most challenging decision-making areas that the management of a technology-based company encounters [2]. A company has to select and invest in a technology field with comparative advantage from various technology alternatives under multiple economic, technological, and social criteria in a complicated environment [3]. On the other hand, selection of key technologies helps these firms and countries to establish their advantage in a competitive environment [2,4–6]. In a broader sense, at the national level, selecting and supporting key emerging technologies helps countries to establish their strategic advantage in the international market [7].

However, technology selection is a multi-criteria decision-making challenge [8]. To address this challenging decision-making issue, this study proposes a hybrid technology selection process integrating the fuzzy Delphi method and the analytic hierarchy process (AHP). The fuzzy Delphi method is applied to identify critical economic or social criteria for technology selection. The AHP proposed by Saaty [9] is a widely used tool for decision-makers to evaluate each technology alternatives against the set of previously identified criteria. The combination of fuzzy Delphi method and AHP is employed to construct a technology selection structure for the first step in this study.

Another problem in technology selection is how to derive technology options. Patent data provides an effective way to learn R&D information of a specific technology and is useful for conducting an analysis on technology trend [10,11]. Researchers can learn the R&D status of a specific industry using patent analysis and then employ this information for research planning and technology

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forecasting [12,13]. 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 a specific industrial need. Lai & Wu [12] develop the patent co-citation approach 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. Hence, the second step of this study adopts the PCA to extract key technology fields as the alternatives in the technology selection model.

Due to the importance of technology selection, it is necessary to carefully identify the technology fields with strategic importance and technological competitive advantage to invest in for a technology-based island country such as Taiwan, when facing developing any emerging technology, i.e., organic light emitting diode (OLED). The OLED display is praised as the third generation display technology, after the cathode ray tube and the liquid crystal display. Since 2005, Taiwan's OLED display industry has occupied the third position in the global market, and has become increasingly competitive in the world [14]. The original OLED patent, owned by Kodak, had matured for renewal in 2005. Kodak began to cross-license its key technology of OLED, thereby diminishing the technological barrier and attracting more competitors to enter the fields of this emerging technology. Therefore, industry in Taiwan needs to select important and competitive OLED technologies to sustain the development of this emerging display technology in the country. In this study, the Taiwan's OLED display technology is adopted as a case to verify the feasibility of the proposed technology selection process or model.

The remainder of this study is organized as follows. Section 2 reviews related literature. Section 3 describes the proposed technology selection process integrating the fuzzy Delphi method, the AHP, and the PCA. Section 4 briefly introduces the OLED technology. A case of OLED is used to verify the technology selection process proposed by this study in Section 5. Finally, Section 6 provides conclusions.

2. Literature review

2.1. Technology selection

Technology as a major source of competitive advantage for manufacturing industries is widely accepted by practitioners, governments and academics. 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 [15]. Gregory [16] 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 [16]. 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 [8]. Accordingly, Gregory [16] 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 et al. [17] defines the technology selection process as identification and selection of new or additional technologies which the firm seeks to master. However, 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 [18,19].

On the other hand, it is becoming more and more difficult to identify the right technologies, mainly because that the number of technologies is increasing and that the technologies tend to become more complex [2]. Additionally, decision makers need to face other challenges such as the rising cost of technological development, abundance of technological options, and rapid diffusion of technologies [20–22]. For example, technology usually accounts on average for more than one-third of all business capital spending [23]. And the abundance and complexity of technological options makes the task of accessing as well as selecting suitable technologies more difficult [24].

Besides the increasing cost of technological development and the abundance of technology options, many studies have also shown that companies fail to assess new technologies. Hackett [25] and Greenberg & Cazoneri [26] point out that projects to incorporate new technology in a majority of companies are failing or are not fulfilling expectations. Huang & Mak [27] 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 [28]. These studies demonstrate the necessity for a careful assessment to overcome the difficulties of technology selection before introducing a new technology [29].

2.2. Technology selection methods

As mentioned in the previous section, technology selection is a process that involves identifying and evaluating alternatives and choosing among them. Identifying criteria for the evaluation is the basis for a sound decision [30]. Therefore, a method to systematically aggregate group judgments is required. A technique integrating Delphi method and AHP, namely the Delphic hierarchy process (DHP) introduced by Khorramshahgol & Moustakis [30], meets this requirement in a sense. Although they limit their discussion to evaluating a set of objectives, their results provide an important consideration for the development of a decision hierarchy for a more general problem [31]. This study, in contrast, aims to hierarchize the technology selection problem in order to systematically evaluate technology alternatives.

Many published studies on technology selection have developed a wide variety of models related to experts' judgments [32–34]. 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 [35–39]. The Delphi method aims to improve group decision making by seeking opinions without face-to-face interaction. It 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" [40,41]. Several features characterize the Delphi method and distinguish it from face-to-face group interrogative methods, including anonymity, iteration, controlled feedback, statistical group response, and stability in responses among the experts on a specific issue [42–47]. 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 [48].
(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" [49].
(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 [50].
(4) Opinions using the Delphi method can be received from a group of experts who may be geographically separated from one another [50].

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 [51,52]. Ishikawa et al. [53] introduce the fuzzy Delphi method to avoid the above defects using fuzzy logic. The fuzzy Delphi method can converge experts' responses with fewer survey rounds and effectively conduct their ambiguity and uncertainty [54]. Furthermore, recent studies have widely adopted the fuzzy Delphi method together with AHP to conduct decision making at a different stage, such as the e-marketplace [55], public transport system project selection [56], and managerial talent assessment [57]. This study employs the fuzzy Delphi method to integrate experts' opinions on technology selection criteria.

After obtaining technology selection criteria by the fuzzy Delphi method, decision makers have to evaluate each alternative against the set of criteria [2,8]. AHP, introduced by Saaty [9], aims to derive solutions from complex, multi-criteria problems. Since the introduction of AHP in 1976, it is widely used in the research fields of technology selection [58], such as technology choice in the less developed countries [59], communication technology [60], soap-making technology [61], hydrogen fueling systems [62], healthcare technology [63], the internet [64], desalination plants [65], operation system [66], and R&D projects [67]. In this study, the AHP is utilized to construct a technology selection model due to its wide applications in this type of multi-criteria decision-making problem.

2.3. Patent analysis

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 sources to overcome this problem. One is to perform technological cluster analysis using survey data with questionnaires [68,69]; the other one is to implement bibliometrics, such as citation analysis and patent mapping [6]. Technological 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 [6]. Instead, past studies 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 [70–74].

A patent is a contract between an inventor and the government, whereby, in return for full public disclosure of an invention, the government grants the inventor the right to exclude others for a limited time from making, using and selling the invention [75]. By the use of bibliometrics, patent data become useful for technology trend analysis and R&D planning [10,11,13]. In addition, patent analysis has been applied to many different tactical and strategic assessments [76], such as intellectual property management [77,78], technology assessment [79], human resources management [80], mergers and acquisition [81,82], and company valuation [83].

In order to generate valuable information from patent data, it is necessary to group patents for further analysis [76]. Past studies on patent management apply the International Patent Code (IPC) or the United States Patent Code (UPC) to identify patents [84,85]. However, in terms of patent management, the IPC or the UPC system is too general to satisfy the

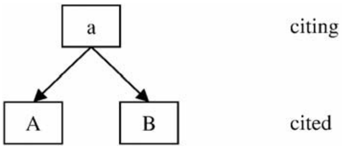

Fig. 1. Co-citation.

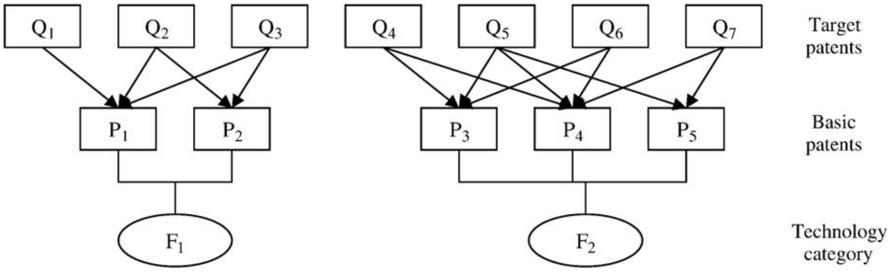

Fig. 2. The concept of the PCA.

needs for technological forecasting, research planning, technological positioning or strategy making [86]. Alternatively, one can use a co-occurrence technique, i.e., co-citation analysis, to cluster the patents [12,76]. The co-citation analysis proposed by Small [87] was originally used to measure the relationship between two publications in the scientific literature. Using co-citation analysis, the similarity among patents can be determined based on common patterns of citation.

The focus of the co-citation analysis is on computing the frequency of Documents A and B co-cited by specific documents to demonstrate their similarity. The number of A and B being co-cited is not subject to limitation because there may be other new documents 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 [88]. The co-citation is illustrated in Fig. 1.

The purpose of the assessment of document similarities is to classify documents. Lai & Wu [12] proposed the patent co-citation approach (PCA) 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 [12]. The concept of the PCA is shown as 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 [12]. In order to objectively generate technology alternatives for our technology selection process, this study adopts PCA to identify key research fields of a specific technology from patent data.

3. Methodology: the integrated technology selection process

This study proposes a process integrating fuzzy Delphi method, AHP and PCA to engage the challenge of technology selection. The fuzzy Delphi method effectively gathers information toward developing critical technology selection criteria regarding the aspects of economic or social prospects and problems, and at the same time reduces the uncertainty and ambiguity existing in experts' judgments. The AHP is used to construct a hierarchical structure to evaluate the aimed technology against the set of criteria previously identified by the fuzzy Delphi method. The PCA identifies the major R&D fields of a specific technology from patent data. Through this proposed process, these technology fields are regarded as

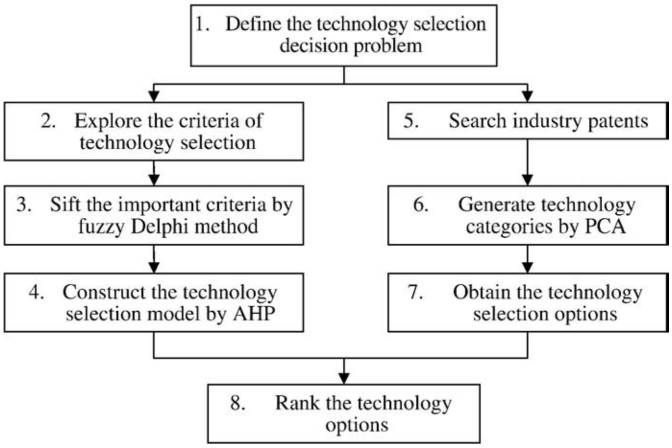

Fig. 3. The technology selection process.

most appropriate technology alternatives; that is, the key technology fields can be identified. This technology selection process includes eight steps, described in details below and in Fig. 3:

(1) Define the technology selection problem. Identify the scope for which technology will be analyzed and selected.
(2) Explore the technology selection criteria, such as benefit, cost, risk, and so on.
(3) Sift through the important criteria by applying the fuzzy Delphi method to integrate the views of experts of different backgrounds.
(4) Obtain the weights of technology selection criteria by employing the AHP to construct the technology selection hierarchy.
(5) Search the industry patents. The proper database, technology keywords, assignee, application date, and issue date should be decided on patent searching.
(6) Generate the technology categories by applying the PCA described in Section 3.3 of this study.
(7) Subsequently obtain the technology selection options. The technology categories generated by the PCA are named by industry experts and are treated as the technology options in the technology selection model constructed in Step 4.
(8) Finally, rank the technology options. Experts evaluate every technology option based on the technology selection model.

As a small summary, the previous technology selection methods such as DHP, (Fuzzy) Delphi, and AHP mostly involve the assessment of social and economic benefits toward an efficient selection of new technology. The patent analysis, PCA, on the other hand, focuses more on the selection of significant technology fields associated with a stream of major technology. Inviting two groups of experts in order, this research combines these two types of approaches in the hope of entailing a more objective and practical technology selection process, concerning from prospects and problems of the technology to what exact technology patents in the regard should be developed virtually. This proposed model has not been employed in other researches yet.

3.1. Fuzzy Delphi method

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 in Eq. (1):

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

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 [54]. Where S_k denotes the clear value in Eq. (2):

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

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

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

3.2. The AHP

A literature review, brainstorming, and the Delphi method can be used to search for the criteria when establishing a hierarchical structure. After that, the criteria are mutually compared for $n \times (n-1)/2$ times if there are n criteria. A nine-point scale recommended by Saaty [9] 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. A matrix can be formed to represent the pairwise comparisons as Eq. (3):

$$A = \left[a_{ij}\right] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{3}$$

where a_{ij} represents the value that experts compare the criterion i with criterion j.

Table 1
Random index (RI).

n	1	2	3	4	5	6	7	8
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41
n	9	10	11	12	13	14	15	
RI	1.45	1.49	1.51	1.53	1.56	1.57	1.59	

To estimate the relative weights of the criteria in this matrix, the priority of the criteria is compared by computing the Eigenvalues and eigenvectors with the following Eq. (4):

$$\boldsymbol{A} \cdot w = \lambda_{max} \cdot w \tag{4}$$

where w is the Eigenvector of the matrix $\boldsymbol{A}$, and $\lambda_{\max}$ is the largest Eigenvalue of the matrix $\boldsymbol{A}$.

The consistency of the matrix is done by examining the reliability of judgments in the pairwise comparison. The Consistency Index (CI) and the Consistency Ratio (CR) are defined as Eqs. (5) and (6):

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{5}$$

$$CR = \frac{CI}{RI} \tag{6}$$

where n is the number of criteria being compared in this matrix, and RI is the Random Index. The average consistency index of a randomly generated pairwise comparison matrix of similar size is shown as Table 1.

3.3. The PCA

The PCA is divided into three phases to complete this classification system, as detailed in Fig. 4. 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.

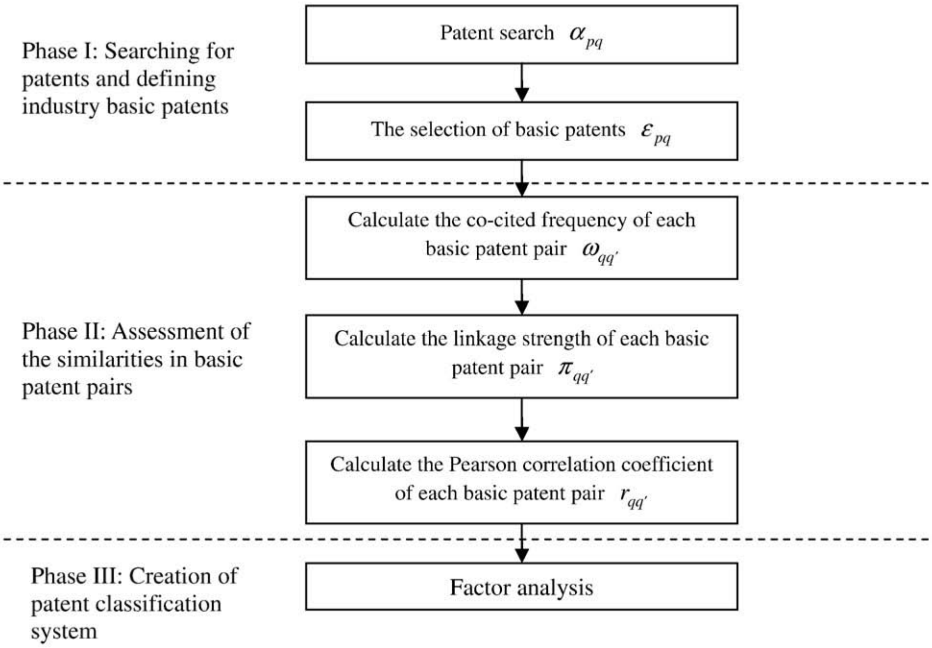

Fig. 4. The analysis process of the PCA. Phase I: Searching for patents and defining industry basic patents. Phase II: Assessment of the similarities in basic patent pairs. Phase III: Creation of patent classification system.

3.3.1. 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.

3.3.1.1. 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):

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

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

3.3.1.2. 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 [77]; thus, a so-called basic patent is a patent repeatedly cited by later patents [12]. 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):

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

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.

3.3.2. 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 [89]. There are three steps required to obtain the similarities in the basic patent pairs.

3.3.2.1. 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):

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

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

3.3.2.2. Calculate the linkage strength of each basic patent pair. The linkage strength of each basic patent pair is derived to measure how related two patents are [90]. The linkage strength of a basic patent pair is calculated as Eq. (11) which normalizes the co-citation frequency by taking into the account of the total number of citations for both basic patent q and q' [91].

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

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

3.3.2.3. 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):

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

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

3.3.3. 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 [12].

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

4. Brief description of OLED

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 [92]. 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, Soon-Taek Kim claimed that OLED is the ultimate display of the future [93]. The development status of OLED can be illustrated by the driving, coloring, and manufacturing process.

4.1. Driving process

The driving techniques of OLED are passive matrix (PMOLED) and active matrix (AMOLED). PMOLED is emitted by an electronic current. AMOLED is driven by thin film transistors (TFT) to control the illumination and the grayscale of the panel [92]. AMOLED, which is suitable for large panels, needs to operate with LTPS or a-Si TFT LCDs, which create a higher technology barrier. PMOLED has a simple structure and low materials and production costs; however, PMOLED is not fit for large panels due to its higher consumption of electricity.

4.2. Coloring process

There are at least five coloring techniques presently developed. In these coloring techniques, the RGB parallel method, the color conversion method, and the color filter method are the most mature and widely applied techniques [92].

4.3. Manufacturing process

The structure of OLED is not as complicated a manufacturing process as that of LCD; however, there is still no standard process to produce OLED panels. Every manufacturer has its own know-how, techniques, and equipment. There are many bottlenecks to overcome. Take organic material evaporation for example, organic molecules are sublimated or vaporized by thermal vacuum evaporation without a stable direction. Much of the material is plated on the vacuum cavity, so the ratio of material use is very low. In addition, the organic material is easily affected by water and oxygen, which jeopardizes the life of OLED. Hence, the key to the whole manufacturing process is the packing process, which must eliminate the water and the oxygen in the air [92].

5. The case for OLED

The following illustrates details of the technology selection process as shown in Fig. 3:

5.1. Step 1: defining the technology selection problem

Defining the technology selection problem requires identifying the scope for which the technology will be selected. This study focuses on the proper OLED technology fields for OLED panel manufacturers in Taiwan. The technology alternatives and the technology selection criteria both need to be carefully explored for this emerging display technology.

Table 2
Description of OLED technology selection criteria.

Criteria	Description
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.
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.
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.
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.

5.2. Step 2: explore the criteria of OLED technology selection

The selection model developed by Arbel & Shapira [94] focuses on benefit and cost. Piipo & Tuominen [95] 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 & Souder [96] 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. [3] focus on the strategic importance, business effect, business opportunity, risk, present technology position, and the cost to obtain the technology to evaluate feasibility. Coldrick et al. [97] consider the technical, corporate and strategic factors; as well as the regulatory, market, financial, and application factors of the R&D project selection. Huang et al. [98] 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. [19] 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 [3,19,94,95,96–98] to four scales: technological merit, business effect, technology development potential, and risk with 18 criteria. These criteria are presented in Table 2 with a short description.

5.3. Step 3: integrate the important criteria of technology selection

In this step, the snowball sampling is applied to inviting six technology based experts and five industry analysts and researchers to evaluate the relative importance of these criteria regarding the measuring aspects of economic or social prospects for the new technology, as 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. Table 3 shows the linguistic scale employed by this study.

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 4:

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. The reasons are based on the in-depth interview with experts:

(1) Every OLED panel manufacturer is presently without revenue. Due to future potential, if a firm determines to invest in this technology, it should prepare for a loss in the short term. Therefore, the potential return on investment is not the most pressing issue in the near future.

Table 3
The linguistic scales.

Linguistic scales	Triangular fuzzy number
Extremely important	(0.7, 0.9, 0.9)
Important	(0.5, 0.7, 0.9)
Normal	(0.3, 0.5, 0.7)
Unimportant	(0.1, 0.3, 0.5)
Extremely unimportant	(0.1, 0.1, 0.3)

(2) Once a firm has decided to invest in OLED, it will endeavor to support the technical resources and the necessary equipment. Therefore, technical resources available and equipment support are not of great importance, according to the experts' concerns.
(3) OLED is an emerging technology within recent years. Most OLED manufacturers lack experience, especially in mass-production. Hence, the OLED manufacturers have had to explore this technology with limited similar experience; therefore, the opportunity of technical success is not the main concern.

In addition, technical personnel support and financial risk are suggested in the in-depth interviews with experts:

(1) OLED, which was first developed by Kodak, is an emerging display technology. In Taiwan, the OLED manufacturers are patent licensed by Kodak or CDT and lack experienced technical personnel; therefore, technical personnel support is suggested.
(2) Some OLED manufacturers, such as Pioneer in Japan and Opto Tech in Taiwan, abandoned their businesses in this market owing to continued financial loss. Financial risk should be considered when investing in this type of emerging technology.

5.4. Step 4: obtain the weight of criteria by AHP

After verifying the importance of criteria, the OLED display technology selection hierarchy can be constructed. The snowball sampling employed 6 technology experts and 6 industry research experts, and the weights of criteria are obtained by adopting the AHP. The CI and CR for technological merit, business effect, risk, and the entire hierarchy are smaller than 0.1, indicating the experts' judgment with consistency. The result is shown in Table 5:

According to the results, technical personnel support, timing of technology, and financial risk all rank first, second, and third in all criteria, respectively. 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.

5.5. Step 5: search industry patents

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,

Table 4
The sifting result of important OLED technology selection criteria.

Scale	Criteria	*S*	Result
Technological merit	Advancement of technology	0.76061	
	Innovation of technology	0.66364	
	Key of technology	0.66970	
	Proprietary technology	0.76061	
	Generics of technology	0.63333	
	Technological connections	0.65152	
	Technological extendibility	0.66364	
Business effect	Potential return on investment	0.54242	Cancel
	Effect on existing market share	0.67576	
	New market potential	0.68182	
	The potential size of market	0.66970	
	Timing for technology	0.65758	
Technology development potential	Technical resource availability	0.56061	Cancel
	Equipment support	0.57879	Cancel
	Opportunity of technical success	0.53030	Cancel
Risk	Commercial risk	0.74849	
	Technical risk	0.74242	
	Technical difficulties	0.58485	Cancel

Table 5
The weights of OLED display technology selection.

Scale	Weight	Rank	Criteria	Weight	Rank
Technological merit	0.16319	3	Advancement of technology	0.02613	14
			Innovation of technology	0.02791	13
			Key of technology	0.05108	8
			Proprietary technology	0.04394	10
			Generics of technology	0.01555	15
			Technological connections	0.02918	12
			Technological extendibility	0.03043	11
			CI=0.01503, CR=0.01139		
Business effect	0.36079	1	Effect on existing market share	0.08450	5
			New market potential	0.07376	6
			The potential size of market	0.08785	4
			Timing for technology	0.11469	2
			CI=0.00138, CR=0.00153		
Risk	0.20423	2	Commercial risk	0.05551	7
			Technical risk	0.05079	9
			Financial risk	0.09793	3
			CI=0.00408, CR=0.00703		
Technical personnel support				0.21077	1
CI=0.007651, CR=0.008501					

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.

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 U.S. [12]. Therefore, this study adopted the database of USPTO to be the source for patent search.

This study searched 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 2,834 patents, and 13,175 cited patents (candidates for basic patents) in this time frame.

5.6. Step 6: generate technology fields by PCA

Table 6 lists the result of the search in step 5, i.e. 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 citing patents [77]. As shown in Table 6, 137 candidates for basic patent have the cited frequency greater or equal to 10 times, and the percentage of the 137 patents out of the 13,175 candidates is 1.04%. Thus, this study uses the cited frequency greater than 10 as the criterion to identify a basic patent, with 137 basic patents selected from the 13,175 candidates for basic patent. We find that 832 patents out of the 2,834 target patents refer to basic 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

Table 6
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	11790	13.75	89.49
3	544	12334	4.13	93.62
4	317	12651	2.41	96.02
5	158	12809	1.20	97.22
6	79	12888	0.60	97.82
7	73	12961	0.55	98.38
8	45	13006	0.34	98.72
9	32	13038	0.24	98.96
10	28	13066	0.21	99.17
11	15	13081	0.11	99.29
12	13	13094	0.10	99.39
13	10	13104	0.08	99.46
14	5	13109	0.04	99.50
>15	66	13175	0.50	100.0

Table 7
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

pairs, and the result is demonstrated in the matrix $\left[\pi_{qq'}\right]_{137\times137}$. The linkage strength matrix $\left[\pi_{qq'}\right]_{137\times137}$ is then taken into Eq. (12), and as a result, the correlation coefficient matrix $\left[\gamma_{qq'}\right]_{137\times137}$ for the basic patent pairs is derived. Finally, the Pearson correlation matrix $\left[\gamma_{qq'}\right]_{137\times137}$ 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 7. The marginal variance explained by the 7th factor is low. Thus, 6 factors are retained, which account for 84.834%.

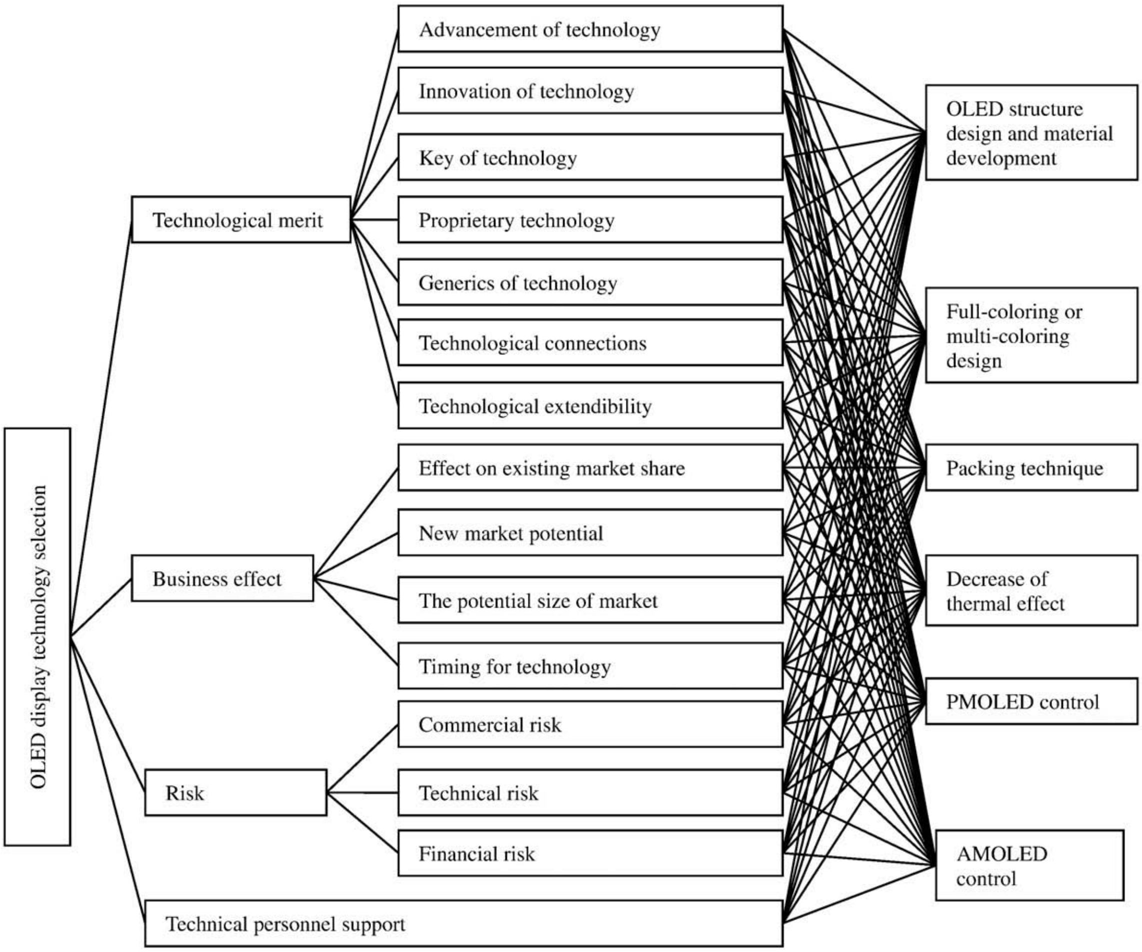

Fig. 5. The hierarchy of OLED display technology selection.

Table 8
The ranking of OLED display technology alternatives.

Alternative	Total score	Rank
OLED structural design and material development	4.06	1
Full-color and multi-color design	3.36	3
Packaging technique	2.92	4
Decrease of thermal effect	2.58	6
PMOLED device control	2.71	5
AMOLED device control	3.79	2

5.7. Step 7: obtain the technology alternatives

After the factor analysis, the six technology fields–OLED structural design and material development, full-color or multi-color design, packaging technique, decrease of thermal effect, PMOLED device control, and AMOLED device control–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 Step 3 to be the technology selection alternatives. The completed OLED technology selection model is represented in Fig. 5:

5.8. Step 8: rank the technology selection options

After completing the OLED display technology selection model, the six technology fields are evaluated by our chosen technological experts who are R&D managers of OLED display manufacturers or research institutions, in order to determine the most suitable OLED technology fields. This study adopts simple weighting to evaluate each technology alternative with Eq. (13):

$$V_l = \sum_{l=1}^{L} w_i \times y_{li} \tag{13}$$

where V_l is the l alternative's total score out of L alternatives, w_i represents the weight of criterion i, and y_{li} is the l alternative's score on criterion i. The result indicates that OLED structural design and material development is the key technology field for domestic industry. The ranking is represented in Table 8, after having computed the scores of each technology alternative:

As the result of this ranking, OLED structural design and material development, AMOLED device control, and full-color and multi-color design are the three main technology fields for Taiwan's industry. The organic material applied by OLED is easily oxidized and affected by vapor to reduce the OLED devices' life. Therefore, the material development and the structural design to overcome the flaws are important for improving the yield and reducing the cost. Secondly, AMOLED has to be driven by LTPS TFT-LCD technology, which is one of Taiwan's most competitive technologies. Finally, in order to apply the OLED display to more diverse products, full-coloring or multi-coloring design is also important. 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 ranks of OLED technology alternatives also represent the efforts or resources that should be allocated.

6. Conclusions and suggestions

Technology selection, which is a multi-criteria decision-making issue, influences an enterprise or a country's technological advantage or disadvantage. 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 [2]. A country can obtain its competitive advantages by investing in emerging technologies with comparative advantages [3,6]. However, systematic evaluation of technology options requires considering many contradictory and complex criteria. Moreover, owing to increasing cost and complexity of technology, it is more and more difficult to identify the right technology fields [2]. Therefore, research and development in emerging technologies should be planned through a carefully designed structural process.

To meet the challenge of technology selection, this study suggests a hybrid technology selection approach integrating the fuzzy Delphi method, the AHP, and the PCA to be utilized for identifying key technology areas. The previous technology selection methods such as DHP, (Fuzzy) Delphi, and AHP mostly involve the assessment of social and economic benefits toward an efficient selection of new technology. The technology selection criteria in these aspects are constructed in a hierarchical structure. The patent analysis, PCA, on the other hand, focuses more on the selection of significant technology fields associated with a stream of major technology. Particularly, in order to obtain technology alternatives, this study adopts the PCA based on co-citation analysis to generate a classification system which is more suitable for a specific technology. The result of PCA helps decision-makers more effectively realize the overall R&D status of a specific technology and assess the major research trends for possible alternatives, even if they do not understand the details of the technology [99,100].

Inviting two different groups of experts at former and latter stages, this research combines these two types of approaches in the hope of entailing a more objective and practical technology selection process, concerning from prospects and problems of the technology to what exact technology patents in the regard should be developed virtually. This proposed model has not been employed in other researches yet.

Further, to demonstrate the technology selection process proposed by this study, we took 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 [101].

However, there are still some limitations to this hybrid technology selection approach. Because the technology fields generated by the PCA depend on basic patents with a higher cited frequency, there could be keen competition inside these technology fields, with rare opportunities for followers. Fortunately, the OLED display technology is still in the introduction stage, according to analysis for the industry [93]. The six OLED technology fields are still valuable references for future R&D in this area. Additionally, older patents tend to have higher cited frequency because they have been available longer than newer patents. Newer patents are less likely to be chosen as basic patents, which means that new technological development could possibly be ignored. One applicable solution is to update the classification system generated by PCA constantly. Future research should apply this technology selection process to verify its feasibility.

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