

---

## **Identifying R&D partners using SAO analysis: a case study of dye-sensitised solar cells**

---

**Xuefeng Wang**

School of Management and Economics,  
Beijing Institute of Technology,  
5 South Zhongguancun Street, Haidian District,  
Beijing, 100081, China  
Email: wxf5122@bit.edu.cn

**Yun Fu\***

National Science Library,  
Chinese Academy of Sciences,  
33 Beisihuan Xilu, Zhongguancun, Haidian District,  
Beijing, 100190, China  
Email: fuy@mail.las.ac.cn  
\*Corresponding author

**Ying Huang**

Department of Public Administration,  
Hunan University,  
Lushan Road (S), Yuelu District,  
Changsha, 410082, China  
Email: huangying\_work@126.com

**Yuqin Liu**

Beijing Academy of Printing and Packaging Industrial Technology,  
Beijing Institute of Graphic Communication,  
25 Xinghua North Road, Daxing District,  
Beijing, 102600, China  
Email: liuyuqin2004@126.com

**Donghua Zhu**

School of Management and Economics,  
Beijing Institute of Technology,  
5 South Zhongguancun Street, Haidian District,  
Beijing, 100081, China  
Email: zhudh111@bit.edu.cn

**Abstract:** This paper proposes a systematic process to identify potential research and development (R&D) partners from a technological perspective based on subject-action-object (SAO) semantic analysis. Improvements to traditional methods are made by combining the SAO structure map and the collaboration network analysis. The SAO structure map reveals the technological development trends, organisations' research contributions and their research experiences in the field, which are the factors that indicate an organisation's R&D capabilities. Furthermore, we explore the organisation's collaboration statuses through collaborative network analysis and their collaborative publications, which make it easier to identify the organisation's sense of cooperation. Potential R&D partners are identified by examining the organisation's R&D capabilities and sense of cooperation. An exploratory study is conducted on dye-sensitised solar cells (DSSCs). The proposed method provides useful information for organisations (firms, institutions, universities, etc.) to identify potential R&D partners or make cooperation related policies.

**Keywords:** subject-action-object; SAO; mapping science; semantic analysis; collaborative network analysis; partner identification; dye-sensitised solar cells; DSSCs.

**Reference** to this paper should be made as follows: Wang, X., Fu, Y., Huang, Y., Liu, Y. and Zhu, D. (2019) 'Identifying R&D partners using SAO analysis: a case study of dye-sensitised solar cells', *Int. J. Technology Management*, Vol. 81, Nos. 1/2, pp.70–93.

**Biographical notes:** Xuefeng Wang is a Professor of the School of Management and Economics, Beijing Institute of Technology. His current specialty is technology innovation management and tech mining.

Yun Fu is an Assistant Librarian in the National Science Library, Chinese Academy of Sciences. Her current specialty is patent analysis, technology innovation management and text mining.

Ying Huang is an Associate Professor of the Department of Public Administration, Hunan University. He was in the School of Public Policy at Georgia Institute of Technology as a Visiting Scholar from 2014 to 2015. His specialty is bibliometrics, patent-metrics and science and technology policy, particularly for study of emerging technology.

Yueqin Liu is a Senior Engineer of the Beijing Academy of Printing and Packaging Industrial Technology, Beijing Institute of Graphic Communication. His current specialty is text mining and data visualisation.

Donghua Zhu is a Professor of the School of Management and Economics, Beijing Institute of Technology and was a Senior Visiting Scholar at School of Public Policy, Georgia Institute of Technology. His current specialty is data mining, technology assessment and forecasting.

---

## 1 Introduction

In recent times, product and technological life cycles have become much shorter. To manage their technological research and development (R&D) more effectively, many organisations have been forced to reconsider their approach to R&D (Gupta and Wilemon, 1996). The increased complexity, risk, cost and time of the technological innovation process has led these R&D-based organisations to search beyond their internal boundaries to obtain the necessary technologies and capabilities (Ahuja, 2000). With the help of collaborative R&D partners, firms can widen their internal knowledge (Hoang and Rothaermel, 2010), gain access to complementary technological resources (Pralhad and Hamel, 1990), insulate themselves from environmental uncertainty (Burgers et al., 1993), access new markets (García-Canal et al., 2008) and preserve technological leadership (Mortehan, 2004). As argued by Faria et al. (2008) from a resource-based view, the aim of any firm is to use external resources to optimise competitiveness and profit through knowledge exchange and cooperative ventures. However, many benefits of collaboration are not risk-free. Some firms have failed to meet the objectives of their partners, mainly due to the collaborative development process (Das and Kumar, 2007). Some studies have demonstrated that partner selection is one of the most essential steps for a successful partnership (Nijssen et al., 2001; Chen and Tseng, 2005). Because a partner can offer not only tacit but also codified knowledge that can adversely or positively influence performance and collaborative results (Du et al., 2014). Therefore, effective partner identification methods should be implemented to assist organisations in identifying potential R&D partners. Some of the conventional methods to identify potential R&D partners are based on expert experiences, human relationships, e-mail requests or online communities (Jeon et al., 2011). However, these methods geographically limit the scope of external resources and normally depend on word of mouth (Lee et al., 2010). To improve the scope on the limits of partner candidates, some researchers propose that the partner selection process include not only the partner selection step but also the candidate identification process (Samadhi and Hoang, 1998; Talluri et al., 1999). Additionally, qualitative and quantitative methods have been proposed to make the partner selection process more objective, such as multi-objective mathematical programming and formal concept analysis (Sølesvik and Encheva, 2010), the fuzzy analytical hierarchy process (AHP) approach (Azadnia et al., 2014) and artificial intelligence including genetic algorithms, ant colony optimisation, etc. (Tao et al., 2011).

However, partner selection is an aim driven process. Due to the various motivations for establishing collaboration, the factors that influence collaboration can be different (Chen et al., 2010). For example, if an organisation's motivation is based on sharing the costs of R&D activities or to strengthen its existing technological capacities, the organisation with a similar research background is the more suitable choice. While, if the organisation wants to learn new technologies or fill a technological vacuum, the organisations with complementary technologies are more suitable (Wang et al., 2017). Creating a generally applicable partner selection method that meets the needs of all organisations is difficult. Therefore, in this paper, we focus on the first step of the R&D partner selection process: potential partner identification.

Many methods have been proposed to identify partner candidates, such as technological complementarity in products consisting of multidisciplinary technologies

(Wang, 2012), designing 14 indices to guide strategic partner selection (Geum et al., 2013), using morphology analysis and a generative topology map (Yoon and Song, 2014), using bibliographic coupling analysis and latent semantic analysis (Park et al., 2015) and solution similarities (Wang et al., 2017). These systematic processes for potential R&D partner identification have made some remarkable advancement compared to the conventional word of mouth-based methods. However, these papers still limit the scope of partner candidates by setting the organisations' research background, either having similar research interests or having complementary research interests. Therefore, in this paper, we pay more attention to the organisation itself. We propose a systematic process of identifying R&D partner candidates by evaluating the organisations' R&D capabilities and willingness to collaborate. More specifically, to identify suitable R&D collaboration candidates, we mainly consider the following three main research questions.

First, what is the technological trend in a research field? Based on this question, we can determine the potential technological directions. Technological trend related research has already been proposed (Zhang et al., 2016, 2017). In this paper, we use a subject-action-object (SAO) structure-based map to show the development trend of technology.

Second, what are the involved organisations' research themes and their main contributions? Due to SAO structures' advantage, we could also know each organisation's solution to the specific research problem. The organisation's R&D capability is evaluated by research experiences, contributions to the target research field and technological trends. Then, the selected organisations could be seen as the leading organisations in a specific technological field.

Third, what are the related organisations' collaboration statuses? The organisation's collaboration network is used to evaluate its collaboration statuses. If organisations have excellent betweenness centrality this means they are important in the network. Then, the leading organisations with high numbers of collaborative publications and excellent betweenness centrality mean they are the potential R&D collaboration candidates.

Therefore, we propose a systematic process of potential R&D partner identification by combining the SAO structure map and the collaboration network analysis. The contributions of this paper compared to previous methodologies are as follows. First, SAO-based bibliometrics can reveal the semantic relationships between the research problems and solutions, which can better reveal the research themes of diverse organisations compared to the existing keyword/term-based bibliometrics methods. Second, an SAO structure map helps to more easily highlight technological development trends and to see the organisation's contributions in a specific research field. Finally, this approach incorporates the organisation's current cooperative status to assess their potential sense of cooperation – very few studies have shown this. In short, the potential R&D partner, in this paper, is the candidate with advanced R&D capabilities and a high sense of cooperation.

The remainder of this paper is organised as follows. Section 2 summarises related studies on R&D partner selection and SAO semantic analysis. Section 3 explains the proposed framework in detail. Section 4 employs the proposed framework to study the dye-sensitised solar cells (DSSCs). Finally, Section 5 presents concluding remarks, limitations of the current research and future considerations.

## 2 Literature review

### 2.1 R&D partner selection

According to Noseleit and Faria (2013), firms actively search for technological knowledge outside their own company as they feel they cannot rely solely on their internal knowledge sources to develop innovation. As a result, R&D partnerships have been regarded as important means through which firms can reduce cost and risk uncertainties (Das and Teng, 2000), shorten innovation cycles (Pisano, 1990) and get external technological knowledge and know-how (Verspagen and Duysters, 2004). Firms employ various ways to implement this open model, such as enacting cross-firm R&D collaboration, developing licensing (-in and -out) arrangements, forming alliances and mergers and acquiring new firms (Bianchi et al., 2011). From these successes, it can be seen that the positive effect on the innovation of external R&D partnerships is dependent on the characteristics of cooperative innovation partners (Sampson, 2007). Yet, even though the importance of partner choice is apparent, the question, “How to discover a potential R&D collaboration partner?” still remains.

Currently, there are many R&D collaboration partner identification studies. Different researchers divided partner selection into different phases. Samadhi and Hoang (1998) summarised the process of partner selection and divided it into three phases: scanning potential partners, matching partners for compatibility and logistic considerations. Additionally, Talluri et al. (1999) proposed a two-phase quantitative framework to aid the decision-making process of effectively selecting an efficient and a compatible set of partners, which has been widely applied in the partner selection process. Phase 1 identifies efficient candidates for each type of business process and phase 2 involves the execution of an integer goal programming model to determine the best portfolio of efficient partners.

To identify partner candidates, lots of methods have been proposed. Wang (2012) provided a framework for exploring potential R&D collaborators with technological complementarity in products consisting of multidisciplinary technologies. The framework applies two methods: association analysis and nonlinear principal components analysis. Geum et al. (2013) presented a literature-based approach based on patent and science publications to guide strategic partner selection by designing 14 indices. Yoon and Song (2014) constructed a systematic process to explore proper partners by using morphology analysis and a generative topology map. Park et al. (2015) also proposed a systematic framework for R&D collaborator exploration using bibliographic coupling analysis and latent semantic analysis. Wang et al. (2017) presented a novel process for identifying R&D partners on the basis of solution similarities that assist technology managers in understanding the relationships between research targets.

In order to determine the best portfolio of efficient partners, there are several qualitative and quantitative methods that can be used to derive a ranking value for a set of candidate partners. These methods include: rating approaches that are mostly dependent on the involvement of experts (Saen, 2009), mathematical programming approaches, such as multi-objective mathematical programming and formal concept analysis (Sølesvik and Encheva, 2010), fuzzy decision-making – for example, analytic network process, AHP, fuzzy-AHP approach (Azadnia et al., 2014) and artificial intelligence including genetic algorithms, ant colony optimisation, etc. (Tao et al., 2011). These different methods can be combined and applied to improve the utility of partnership in a hybrid way. For

example, combining the analytic hierarchy process and fuzzy sets theory was proposed to develop a partner selection mechanism (Chen et al., 2010).

## 2.2 SAO semantic analysis

SAO semantic analysis was developed from the theory of inventive problem solving (TRIZ) and is an ontological model based on knowledge (Mann, 2001). SAO structures are composed of a subject (noun phrase), action (verb phrase) and object (noun phrase) (Choi et al., 2012a). Since S and O express the technology or the component and A expresses the relationship or effect between the technology or component (Cascini and Zini, 2008), some research has described SAO analysis as ‘key concepts’ and has also denoted the relationships between these concepts (Choi et al., 2011). It has also been suggested that the subject (S) forms the solution and the action-object (A-O) presents the problem, so SAO analysis can also be thought of as a problem and solution (P&S) approach (Moehrle et al., 2005).

Traditional bibliometrics, such as IPC analysis, co-word analysis, co-citation analysis and coupled analysis, are not based on the research or patent content. For example, an IPC analysis can only identify those patents that are similar but is unable to identify the differences between them or the content of these patents. Other traditional bibliometrics also can only identify the similarities and not the differences. Therefore, the SAO structure is preferred as it can overcome the limitations of traditional bibliometrics because of its specific focus on the core content of the research or patent. SAO semantic analysis has been widely used for technological monitoring (Gerken and Moehrle, 2012), the identification of future technological development trends (Choi et al., 2011; Wang et al., 2015), the construction of a technological tree for technology planning (Choi et al., 2012a), the analysis of patent infringement or risk (Park et al., 2012), the construction of a function-based technological database to find solutions to new problems (Choi et al., 2012b), the identification of technological competition trends (Janghyeok et al., 2013) and the determination of the direction of technological change and forecasting technology innovation opportunities (Guo et al., 2016).

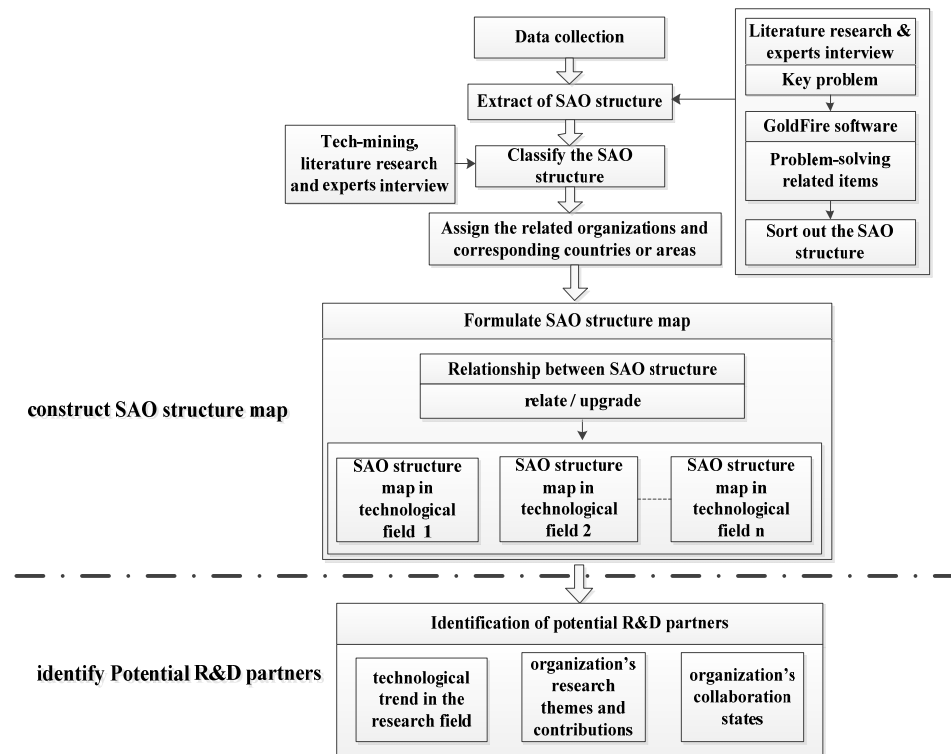
SAO semantic analysis has been used in many fields as the SAO structure is generally accepted for the description of patents and research. However, to date, there have been few attempts to use SAO semantic analysis for technologically driven potential partner identification. In this paper, we apply SAO semantic analysis to a new application: potential R&D partner identification. We propose a systematic process by combining the SAO structure map and the collaboration network analysis to identify potential R&D partners.

## 3 Frameworks and methodology

In this paper, we mainly focus on the partner candidates’ identification. The potential R&D partner candidates are those with advanced R&D capabilities and a high sense of cooperation. R&D capability means the organisations have made great contributions, have many years of research experience and follow technological trends in a target field. In this paper, ‘many years’ means the organisations have published papers in at least two different years. A high sense of cooperation means the organisations have high

betweenness centrality in the collaboration network of the target field and have lots of collaborative publications. Thus, we propose a systematic process based on SAO semantic analysis and the collaboration network, which can assist in identifying potential R&D partner(s) in selected technological fields. The proposed systematic process of identifying potential R&D partners is shown in Figure 1. The process consists of two parts: to construct an SAO structure map and to identify potential R&D partners.

**Figure 1** The systematic process of identifying potential R&D partners



### 3.1 Constructing the SAO structure map

The SAO structure map formulation contains the following five steps:

- 1 Research data collection. Bibliometrics and ‘tech mining’ studies depend on a crucial foundation – the search strategy used to retrieve relevant research publication records (Huang et al., 2015). For the data collection, however, the main challenge was to ensure an appropriate research retrieval query, so as to ensure the selection of the most relevant papers from the research database. Retrieval queries mainly consisted of keywords, publication dates and type of research. With suitable research retrieval query, the initial data could be obtained.
- 2 Extraction of SAO structures. We used GoldFire Innovator, a commercial linguistic analyser (Vicente-Gomila 2014), to extract SAO structures from the collected data.

Considering that GoldFire Innovator is problem-solving-oriented, we first needed to clearly identify the problem to be solved in the target research field. Experts' interviews, literature research or tech-mining techniques can be used to ascertain the research issues in the target research field (Zhang et al., 2014a). In the case of DSSCs, according to literature research and experts' interviews, the main research issues include the following aspects:

- a How to improve/increase/enhance conversion efficiency?
- b How to reduce/decrease manufacturing costs?
- c How to extend the cell life?

In this paper, we chose (a) as the focus problem since there is more literature related to conversion efficiency. The systematic process proposed in this paper could also be used for other DSSC issues. Since the abstract and title have the most meaningful words and phrases (Bergmann et al., 2008), we searched for problem related sentences from the abstract and title using GoldFire Innovator based on semantic analysis, further obtaining SAO structures.

- 3 Classification of SAO structures into specific technological fields to construct the SAO structure map. We use tech-mining and 'term clumping' to find the high-frequency items (Zhang et al., 2014b), then combine the literature research and experts' interviews to finally confirm the technological fields. It would be much easier for organisations to identify R&D partners if a more detailed technological field has been classified. However, the number of technological fields' layers that should be classified is dependent upon the experts' suggestions and target research areas. Finally, we determine specific technological fields for every SAO structure with the help of experts' advice.
- 4 Assignment of the related organisations (firms, research institutions or universities) and the corresponding countries/areas to enrich additional SAO structure information. This step aims to assign a unique code to each organisation and the relevant countries or areas related to the SAO structures. In the SAO structure map, we put not only the SAO structures but also the related organisation code and the corresponding country/area code. An extraordinary amount of information can be shown in the SAO structure map within the same space.
- 5 SAO structure map formulation. The SAO structure map, with a horizontal axis representing time and a vertical axis set according to the classified technological field in Step 3, is developed to illustrate the technological development trend. As shown in Figure 5–Figure 8, the information in these rectangles include 'S' of SAO structure, corresponding organisation code, country/area code and the detailed conversion efficiency results, if they exist. The different colour for each rectangle represents its technological field. It must be pointed out that all SAO structures have the same 'AO' for the research issue "improve/increase/enhance conversion efficiency", so we only show 'S' structures in the SAO structure map. Additionally, we introduce the two relationships shown in Table 1 between SAO structures according to the research of (Zhang et al., 2014b).



**Table 1** The two relationships between the SAO structures

No.	Relationships	Explanation
1	Relate	Two technologies share the same field
2	Upgrade	One technology is generated based on another

### 3.2 Identify potential R&D partners

To identify potential R&D partners, the analysis process involves the three essential questions we proposed in the introduction:

- 1 The technological trend. From the SAO structure map, we can see the related technologies in target fields, the starting points for each technological field and which technologies are still in development and which technologies are not present. Then, we can explore the technological directions.
- 2 The organisations' research themes and contributions. From the SAO structure map, we can analyse which organisations are involved in every technological field and what contributions are made by these organisations. The organisations with many years (published papers in at least two different years) of research experience, excellent research results and follow the technological trends, could be seen as the leading organisations in a specific technological field.
- 3 The involved organisation's collaboration statuses. We use the collaboration network map to express the organisation's collaboration status. On the map, a node represents an organisation. The links between organisations mean they have already collaborated. The width of links indicates the cooperation intensity. The node label includes the organisation's name and code. We can analyse the organisation's collaboration partners and also their cooperation intensity from the collaboration network map. Based on the map, we can calculate every organisation's betweenness centrality, which is an indicator to show an organisation's centrality in a network. Combining the organisation's betweenness centrality and the number of collaborative publications, we can construct a willingness to cooperate map, as shown in Figure 4. The willingness to cooperate map is divided into four parts using the median of betweenness centrality and the number of published papers. We can conclude from this map that first, organisations with a high betweenness centrality and a large number of published papers are more likely to cooperate; second, organisations with low betweenness centrality and a large number of published papers means they are very experienced in the target field but are less willing to cooperate; third, organisations with high betweenness centrality and a small number of published papers means they have less experience in the target field but are more willing to cooperate; and fourth, it is not a good idea to cooperate with organisations with low betweenness centrality and a small number of published papers.

In this paper, we conclude that suitable potential R&D partners are not only the leading organisations in the target field but are also willing to cooperate with others. With the analysis of the above three questions, the organisations' decision-makers can finally identify suitable potential R&D partners in every technological field.

## 4 Case study: the DSSCs

In this section, we present the potential R&D partners in DSSCs following the above proposed systematic process. DSSCs, the third-generation solar cells, are new and emerging technologies, which have gained increased worldwide development interest. DSSCs have been seen as the most promising technology to alleviate the current fossil fuel crisis because of their easy fabrication process, low manufacturing costs and high conversional efficiency. DSSCs are believed to be one of the most attractive new energy sources for the future.

### 4.1 Construct SAO structure map for the DSSCs

In this section, we describe the SAO structure map construction using the first five steps defined in Section 3.

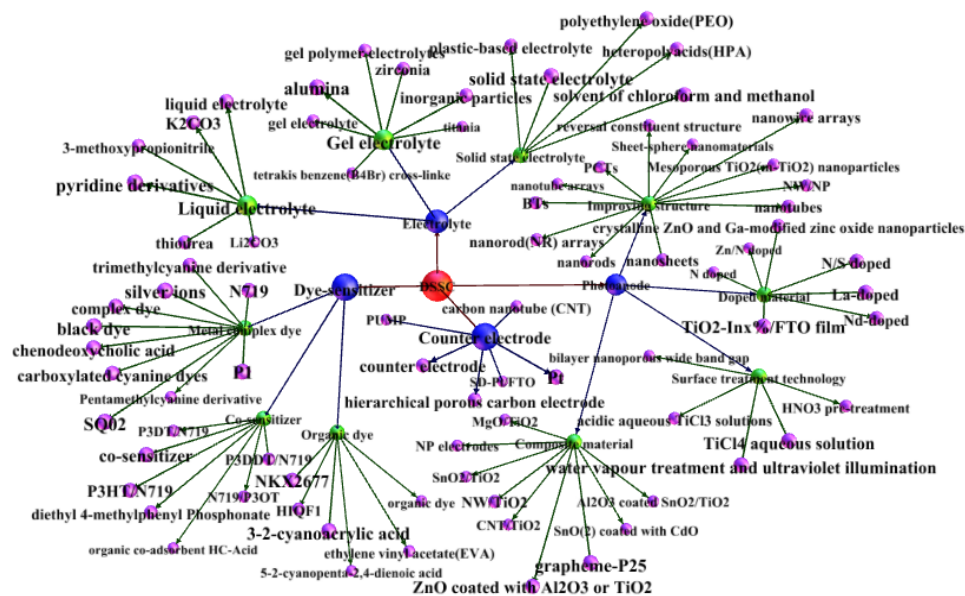
- Step 1 Download the literature data. For this research, we chose the SCI-expanded database to collect DSSCs research papers published from 1991 to 2012. The retrieval strategy is indicated in our previous publication (Guo et al., 2012). Finally, we obtained 7,884 research papers with the document type of *article*.
- Step 2 Extraction of SAO structures. We selected “How to improve/increase/enhance conversion efficiency?” as the key problem for the empirical analysis. With the help of GoldFire Innovator, a total of 3,056 research items were initially identified. We then selected 227 closely related items by using verbs related to the key problems that could explicitly express the positive effect of conversion efficiency, such as improve, enhance, increase, achieve and yield. Table 2 shows some of the exemplifications from the GoldFire Innovator.
- Step 3 Classification of the SAO structure. We first used tech-mining and ‘term clumping’ to find the high-frequency items (Zhang et al., 2014b). We then combined the literature reviews and experts’ interviews to finally confirm the technological classification fields. The DSSCs are classified into two layers. The first layer includes photoanodes, counter-electrodes, electrolytes and dye-sensitisers. The second layer contains composite material, improving structure, doped material and surface treatment technology for photoanodes. Electrolytes can be classified into liquid electrolyte, gel electrolyte and solid electrolyte. Dye-sensitiser includes metal complex dye, organic dye and co-sensitiser. No further classification has been given to counter electrode because less attention has been paid to it. As shown in Figure 2, the DSSC node (red) directly points to four blue nodes. These four blue nodes are the first layer. Except for the counter electrode node, the other three blue nodes also directly point to a number of green nodes. These green nodes are the second layer. What is more, the green nodes also point to the purple nodes. These purple nodes are the related SAO items, which are shown as the node’s label.
- Step 4 Assignment of the related organisations and the corresponding countries/areas. We assigned a unique code for each organisation and the relevant countries or areas related to the SAO structures based on description information from the papers (see Table A1).

**Step 5** SAO structure map formulation. To make the map much clearer, we drew four SAO structure maps according to different technological fields: photoanode, dye-sensitiser, electrolyte and counter-electrode. In the SAO structure map, we put every ‘S’ of the SAO structures, referred organisation’s code, country/area code and the detailed conversion efficiency results of existence into one rectangle, as shown in Figure 5–Figure 8. The colour shows the technological field of the SAO structures, which is shown in Figure 5 and also applied to Figure 6–Figure 8.

**Table 2** Examples extracted by the GoldFire software for DSSCs

<i>Solution name</i>	<i>Solution description</i>	<i>Organisation</i>
TiCl <sub>4</sub> aqueous solution	Treatment of the electrodes with a <i>TiCl<sub>4</sub> aqueous solution improved the overall conversion efficiency</i> of the dye-sensitised solar cells.	Osaka University (Japan)
HNO <sub>3</sub> pre-treatment of TiO <sub>2</sub> particles	The <i>HNO<sub>3</sub> pre-treatment of TiO<sub>2</sub> particles improved the overall conversion efficiency</i> of the DSSC by about 14%.	Chonnam National University (South Korea), Inha University (South Korea)
Hierarchical porous carbon electrode	The overall <i>conversion efficiency</i> of dye-sensitised solar cells with the hierarchical porous carbon electrode increased by 11.5% compared with that of the cell with a pristine mesoporous carbon electrode.	Shandong University of Technology (China)

**Figure 2** Technological classifications and the related items (see online version for colours)



A scatter plot showing the relationship between the number of published papers (x-axis) and Betweenness Centrality (y-axis) for 65 researchers. The x-axis ranges from 0 to 120, and the y-axis ranges from 0.000000 to 0.140000. A vertical line is drawn at x=10. The data points are labeled F1 through F65. Most points are clustered at low betweenness centrality values, with a few outliers showing higher values. The points are color-coded: purple for F1-F10, blue for F11-F20, cyan for F21-F30, green for F31-F40, orange for F41-F50, and pink for F51-F65.

Researcher	Number of Published Papers (x)	Betweenness Centrality (y)
F1	4	0.025000
F2	5	0.025000
F3	6	0.025000
F4	7	0.025000
F5	8	0.025000
F6	9	0.025000
F7	10	0.025000
F8	11	0.025000
F9	12	0.025000
F10	13	0.025000
F11	14	0.025000
F12	15	0.025000
F13	16	0.025000
F14	17	0.025000
F15	18	0.025000
F16	19	0.025000
F17	20	0.025000
F18	21	0.025000
F19	22	0.025000
F20	23	0.025000
F21	24	0.025000
F22	25	0.025000
F23	26	0.025000
F24	27	0.025000
F25	28	0.025000
F26	29	0.025000
F27	30	0.025000
F28	31	0.025000
F29	32	0.025000
F30	33	0.025000
F31	34	0.025000
F32	35	0.025000
F33	36	0.025000
F34	37	0.025000
F35	38	0.025000
F36	39	0.025000
F37	40	0.025000
F38	41	0.025000
F39	42	0.025000
F40	43	0.025000
F41	44	0.025000
F42	45	0.025000
F43	46	0.025000
F44	47	0.025000
F45	48	0.025000
F46	49	0.025000
F47	50	0.025000
F48	51	0.025000
F49	52	0.025000
F50	53	0.025000
F51	54	0.025000
F52	55	0.025000
F53	56	0.025000
F54	57	0.025000
F55	58	0.025000
F56	59	0.025000
F57	60	0.025000
F58	61	0.025000
F59	62	0.025000
F60	63	0.025000
F61	64	0.025000
F62	65	0.025000
F63	66	0.025000
F64	67	0.025000
F65	68	0.025000

In the process of R&D partner identification, we need to explore the organisation's collaboration status to evaluate their willingness to cooperate. Therefore, we first developed the collaboration network map based on organisation information related to the papers on "improve/increase/enhance conversion efficiency" as shown in Figure 3. In Figure 3, we show the organisations that cooperated with each other more than once. This lets us know which organisations cooperate with each other and the collaboration intensity. Second, we construct a willingness to cooperate map with the organisation's betweenness centrality and the number of collaborative publications, as shown in

Figure 4. To make the map much clearer, we removed an outlier, the Chinese Academy of Science (F13). However, we should indicate that F13 has high scores in both betweenness centrality and published papers. From this map, we can quickly and easily analyse every organisation's willingness to cooperate. For example, the Swiss Federal Institute of Technology (F65) has high scores in both betweenness centrality and published papers, which means F65 has more willingness to cooperate with others. Detailed analyses will be illustrated in the process of R&D partner identification.

## 4.2 *Identifying potential R&D partners*

### 4.2.1 *Identification of partners in the photoanode field*

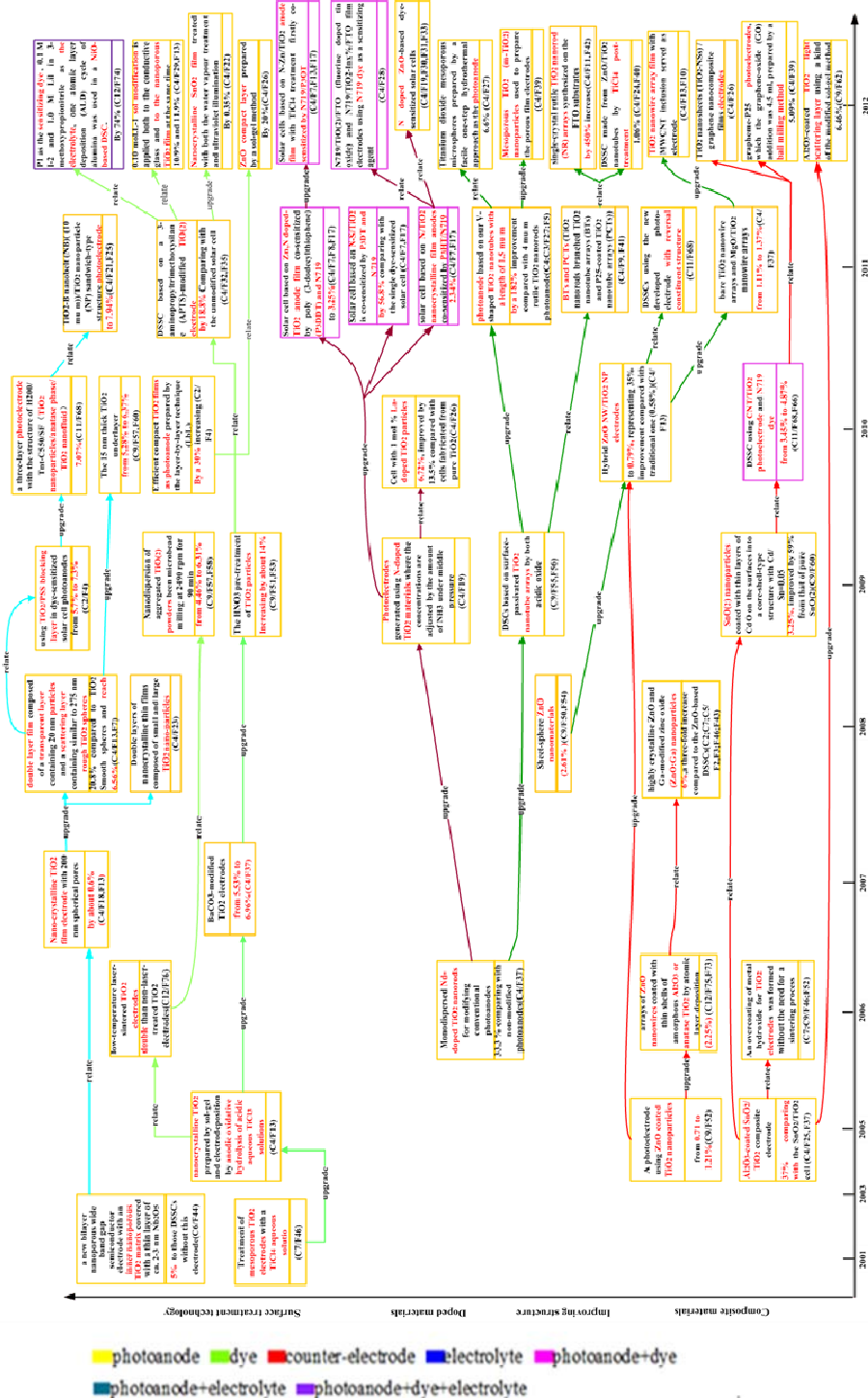
It can be seen from Figure 5 that photoanode researchers concentrate on composite materials, improving structures, doped materials and some surface treatment technologies. These four sub-technologies have different starting dates, but as of now, they are still developing.

The criteria to determine the leading organisations in a target field are the leading organisation evaluation, many years of research experience, excellent research results and following the technological trends. From Figure 5, in the sub-technology 'composite materials', the most common technique is to use  $\text{TiO}_2$  coated with some metallic oxides, such as  $\text{ZnO}$ ,  $\text{Al}_2\text{O}_3$  and  $\text{MgO}$ . Figure 5 shows that after 2010, only the School of Semiconductor & Chemical Engineering (F62) and Tsinghua University (F37) still conducted research using this traditional method. Since 2010, a new type of coated material carbon nanotube (CNT) was created by Academia Sinica (F66) and National Taipei University of Technology (F68). Then in 2012, the Chinese Academy of Science (F13) and the China Shipbuilding Industry Corporation (F10) improved the CNT/ $\text{TiO}_2$  by using a different structure of  $\text{TiO}_2$ . In 2012, grapheme-P25 was used as a new type of photoanode material by Wuhan University (F39). At the same time, Nanjing University (F26) combined grapheme-P25 with  $\text{TiO}_2$  to improve the previous photoanode. So, we can say that all these organisations have made great contributions and are following the technological trend in the composite materials field. Additionally, analysing these organisation's research experiences in the photoanode field, we can easily determine from Figure 5 that F37, F13 and F26 have all been tracking this field for more than two years. So, these three organisations are considered to be the leading organisations in the composite materials field.

In addition, F13, F37 and F26 all have high scores in both betweenness centrality and the number of published papers. Based on the above analysis, we think F13, F37 and F26 are more likely to be a potential R&D partner. In the following sections, we will only discuss which organisations could be identified as potential R&D partners.

In the sub-technology 'improving structure', the structures of photoanode materials include nanoparticles, nanotube, nanowire arrays and nanorod arrays. The main purpose is to increase specific surface area, which could help to improve conversion efficiency. It is easy to see that the Chinese Academy of Science (F13), Tsinghua University (F37), Nanjing University of Technology (F27) and Wuhan University (F39) have all been selected as the leading organisations. By considering the willingness to cooperate, we can select F13 and F37 as potential R&D partners.

Figure 5 Photoanode SAO structure map (see online version for colours)



In the sub-technology ‘doped material’, the most common doped materials are N, S and Zn. Using mixed materials to dope photoanode material has become more popular and also has higher conversion efficiency than using single materials. The Academy of Science (F13), Beijing University of Chemical Technology (F7) and Hainan Institute of Science & Technology (F17) can be thought of as the leading organisations. Concerning these organisations’ willingness to cooperate, we think F13, F7 or F17 could be potential R&D partners.

In the sub-technology ‘surface treatment technology’, the research theme is to enlarge the surface area by adding more layers or by using a chemical treatment. For adding more layers, the Korea Institute of Science & Technology (F57), Jilin University (F25) and National Taipei University of Technology (F68) all have improved conventional methods. They are considered as the leading organisations. Using these organisations’ cooperation statuses, we select F57, F25 and F68 as potential R&D partners. We also select Peking University (F32) as a potential R&D partner for surface chemical treatments.

#### *4.2.2 Identification of partners in the dye-sensitiser field*

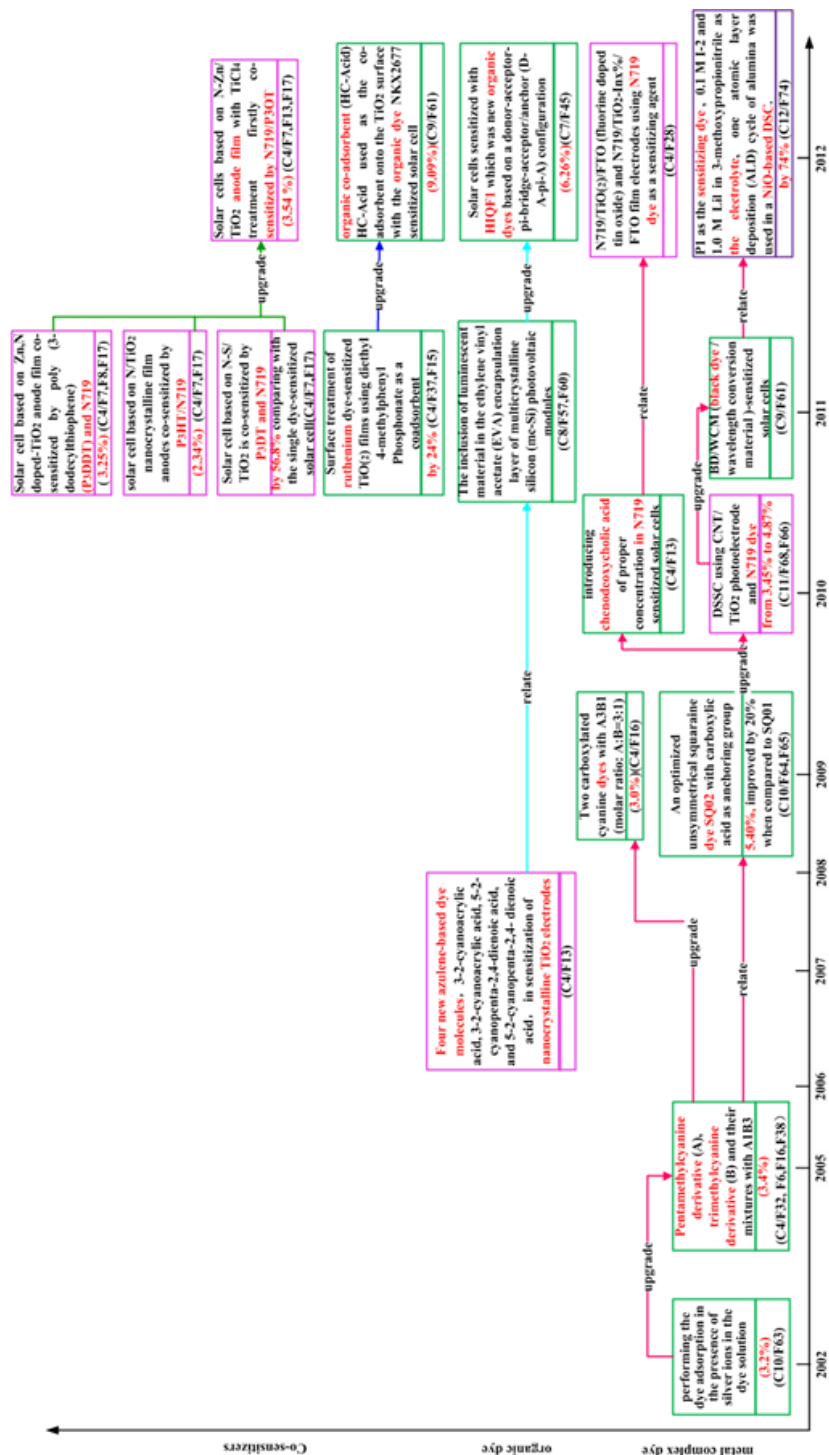
We can see from Figure 6 that dye-sensitiser research can be divided into metal complex dyes, organic dyes and co-sensitisers. The metal complex dyes have very high conversion efficiency and thermal stability. However, the materials are very expensive. Organic dyes were developed with low cost, easy synthesis and relatively high conversion efficiency; however, they present poor thermal stability and chemical stability. To take full advantage of metal complex dyes and organic dyes, co-sensitisers were developed.

In the metal complex dyes field, Nankai University (F28), National Taipei University of Technology (F68), Academia Sinica (F66) and the Solar Energy Research Center (F61) can be seen as the leading organisations. Using these organisations’ cooperation statuses, we selected F28 or F61 as potential R&D partners. For this same reason, we selected Sungkyunkwan University (F60) as a potential R&D partner in the organic dyes field. In the sub-technology ‘co-sensitiser’, Beijing University of Chemical Technology (F7) or Hainan Institute of Science & Technology (F17) can be identified as potential R&D partners. Cooperating with F17 or F7 is one of the fastest ways to enter the co-sensitiser field. The Chinese Academy of Science (F13) began to engage in co-sensitiser by cooperating with F7 and F17 in 2012, which indicates the validity of the proposed method. Now, F13, F7 or F17 can be thought of as potential R&D partners in co-sensitisers.

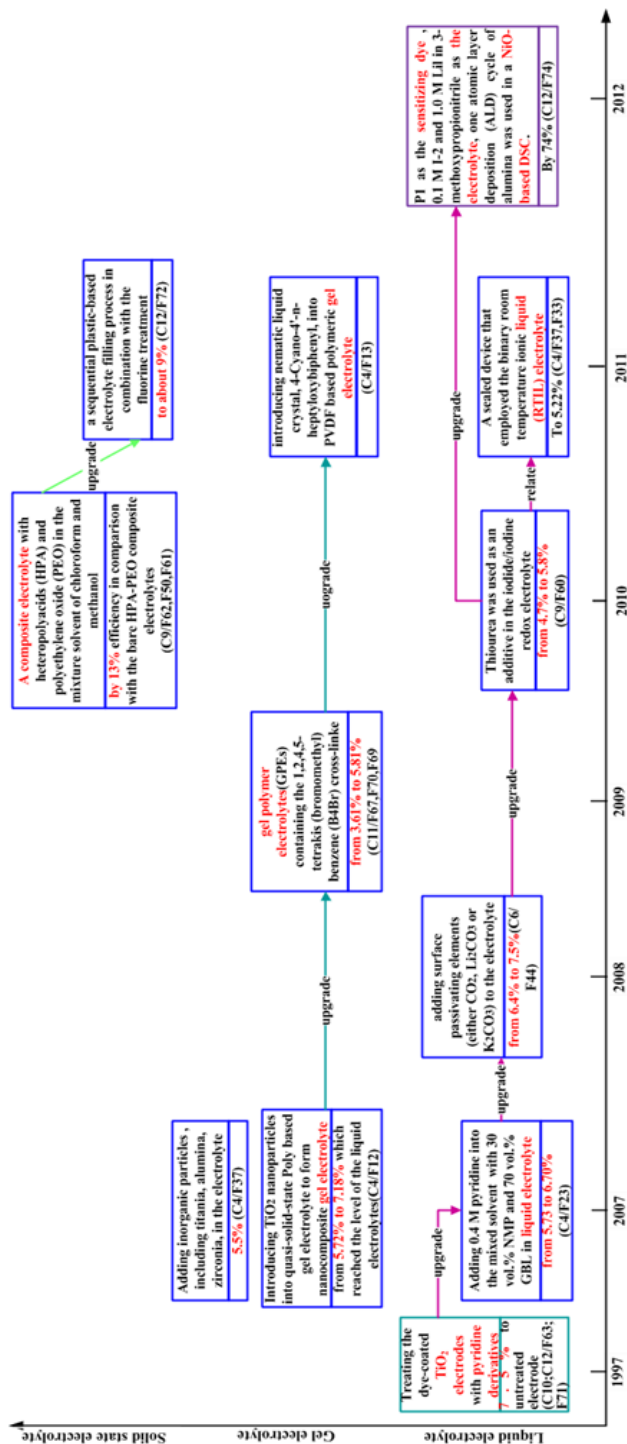
#### *4.2.3 Identification of partners in the electrolyte field*

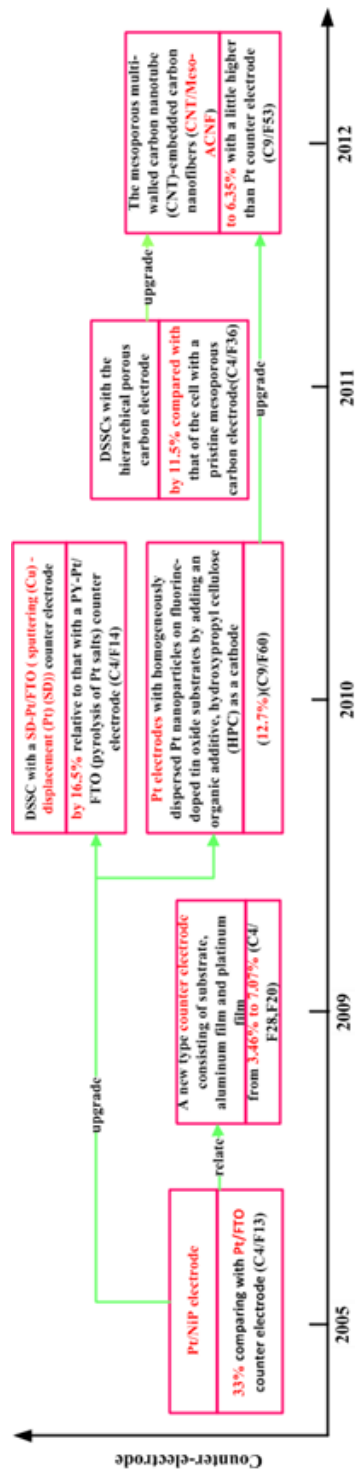
Liquid electrolytes have been researched since 1997, as shown in Figure 7. Currently, some organisations still focus on liquid electrolytes because of their high dissolubility, which is good for conversion efficiency. In the liquid electrolytes field, Tsinghua University (F37), Sungkyunkwan University (F60) and Ohio State University (F74) are identified as leading organisations. Using these organisations’ cooperation statuses, we selected F37 or F60 as potential R&D partners. Likewise, the Chinese Academy of Science (F13) was selected as a potential R&D partner in the organic electrolytes field and Chonbuk National University (F50) was selected in the solid-state electrolyte field.

Figure 6 Dye-sensitiser SAO structure map (see online version for colours)





**Figure 7** Electrolyte SAO structure map (see online version for colours)

**Figure 8** Counter-electrode SAO structure map (see online version for colours)

#### 4.2.4 *Identification of partners in the counter electrode field*

We can infer from Figure 8 that the common counter electrode material is carbon and platinum (Pt). Pt counter electrodes that are chemically stable were commonly used in the first several years; however, Pt is expensive. Carbon counter electrodes were developed in 2011 and carbon material is less expensive and widely available. In Pt counter electrodes, leading organisations were Sungkyunkwan University (F60) and Chongqing University (F14). Considering F60 has high betweenness centrality and a large number of published papers. But F14 has a low score in both sides. We think F60 is more likely to be a potential R&D partner. Likewise, we select Inha University (F53) as a potential R&D partner in carbon counter electrodes.

Note that the purpose of the paper is to identify the potential R&D partner candidates. It may occur that there is more than one potential partner in the target field. People cannot easily tell organisation's relationships as competitors or partners because these are decided by their strategic decisions. Because different organisations, such as firms, research institutions and universities, would have totally diverse partner seeking strategies the definition of the relationships between those potential partners is the problem that the next step of partner selection should solve, which is not the key issue in this paper.

## 5 Conclusions and discussions

In this paper, we proposed a systematic process combining an SAO structure map with collaboration network analysis to identify potential R&D collaboration partners. An SAO structure map helps to analyse organisations' R&D capabilities in the target technological field. Collaboration network analysis is helpful for identifying leading organisations' willingness to cooperate. Considering these factors, we can finally determine the best potential R&D partners in every technological field. The proposed method is demonstrated in DSSCs and some results have been verified. We also believe the method could be widely applied in other technological fields to help identify potential R&D partners.

This study adds three contributions to the conventional methods. First, compared to the existing keyword/term-based bibliometrics methods, SAO-based bibliometrics can reveal the semantic relationships between the research problems and solutions. Second, an SAO structure map helps to more easily highlight technological development trends and to see the organisation's contributions in a specific research field. In addition, this approach incorporates the organisations' current cooperative status to assess their potential sense of cooperation – few studies have shown this.

However, the proposed method does have some intrinsic limitations. First, the SAO structures are extracted from abstracts and titles only. Obviously, abstracts and titles may omit certain technological details, although the titles and abstracts contain most of the main research content of the paper and are used by many researchers to conduct SAO analyses. To improve the results, both the abstract and full text could be used to extract the SAO structure in the future. Second, this paper only chooses one issue of DSSCs to verify the effectiveness of the proposed method. It would be more sufficient to describe all the issues in the DSSCs field by applying this systematic process. In our future studies, we will continue this work on how to select an optimal R&D partner from the

potential R&D partners by constructing more comprehensive criteria, such as geographic proximity, organisation proximity and an organisation's strategy.

## Acknowledgements

This work is supported by the General Program of National Natural Science Foundation of China (Grant No. 71774012, 71373019 and 71673024). The findings and observations in this paper are those of the authors and do not necessarily reflect the views of the supporters. The authors would like to thank colleagues from the Beijing Institute of Technology, National Science Library of CAS, Hunan University and Beijing Institute of Graphic Communication.

## References

- Ahuja, G. (2000) 'The duality of collaboration: inducements and opportunities in the formation of interfirm linkages', *Strategic Management Journal*, Vol. 21, No. 2, pp.425–455.
- Azadnia, A.H., Saman, M.Z.M. and Wong, K.Y. (2014) 'Sustainable supplier selection and order lot-sizing: an integrated multi-objective decision-making process', *International Journal of Production Research*, Vol. 53, No. 2, pp.383–408.
- Bergmann, I., Butzke, D., Walter, L., Fuerste, J.P. and Moehrl, M.G. (2008) 'Evaluating the risk of patent infringement by means of semantic patent analysis: the case of DNA chips', *R&D Management*, Vol. 38, No. 5, pp.550–562.
- Bianchi, M., Cavaliere, A., Frattini, F. and Chiesa, V. (2011) 'Organizational modes for open innovation in the bio-pharmaceutical industry: an exploratory analysis', *Technovation*, Vol. 31, No. 1, pp.22–33.
- Burgers, W.P., Hill, C.W.L. and Kim, W.C. (1993) 'A theory of global strategic alliances: the case of the global auto industry', *Strategic Management Journal*, Vol. 14, No. 6, pp.419–432.
- Cascini, G. and Zini, M. (2008) 'Measuring patent similarity by comparing inventions functional trees', *Computer-Aided Innovation (CAI). The International Federation for Information Processing*, Vol. 277, Boston, MA, pp.31–42.
- Chen, H.M. and Tseng, C.H. (2005) 'The performance of marketing alliances between the tourism industry and credit card issuing banks in Taiwan', *Tourism Management*, Vol. 26, No. 1, pp.15–24.
- Chen, S.H., Wang, P.W., Chen, C.M. and Lee, H.T. (2010) 'An analytic hierarchy process approach with linguistic variables for selection of an R&D strategic alliance partner', *Computers & Industrial Engineering*, Vol. 58, No. 2, pp.278–287.
- Choi, S., Park, H., Kang, D., Lee, J.Y. and Kim, K. (2012a) 'An SAO-based text mining approach to building a technology tree for technology planning', *Expert Systems with Applications*, Vol. 39, No. 13, pp.11443–11455.
- Choi, S., Kang, D., Lim, J. and Kim, K. (2012b) 'A fact-oriented ontological approach to SAO-based function modeling of patents for implementing function-based technology database', *Expert Systems with Applications*, Vol. 39, No. 10, pp.9129–9140.
- Choi, S., Yoon, J., Lee, J.Y. and Kim, C.H. (2011) 'SAO network analysis of patent for technology trends identification: a case study of polymer electrolyte membrane technology in proton exchange membrane fuel cells', *Scientometrics*, Vol. 88, No. 3, pp.863–883.
- Das, T.K. and Kumar, R. (2007) 'Learning dynamics in the alliance development process', *Management Decision*, Vol. 45, No. 4, pp.684–707.
- Das, T.K. and Teng, B.S. (2000) 'A resource-based theory of strategic alliances', *Journal of Management*, Vol. 26, No. 1, pp.31–61.

- Du, J., Leten, B. and Vanhaverbeke, W. (2014) 'Managing open innovation projects with science-based and market-based partners', *Research Policy*, Vol. 43, No. 5, pp.828–840.
- Faria, P.D., Lima, F. and Rui, S. (2008) 'Cooperation in innovation activities: the importance of partners', *Research Policy*, Vol. 37, No. 1, pp.19–25.
- García-Canal, E., Valdés-Llaneza, A. and Sánchez-Lorda, P. (2008) 'Technological flows and choice of joint ventures in technology alliances', *Research Policy*, Vol. 37, No. 1, pp.97–114.
- Gerken, J.M. and Moehrl, M.G. (2012) 'A new instrument for technology monitoring: novelty in patents measured by semantic patent analysis', *Scientometrics*, Vol. 91, No. 3, pp.645–670.
- Geum, Y., Lee, S., Yoon, B. and Park, Y. (2013) 'Identifying and evaluating strategic partners for collaborative R&D: index-based approach using patents and publications', *Technovation*, Vol. 33, Nos. 6–7, pp.211–224.
- Guo, J., Wang, X., Li, Q. and Zhu, D. (2016) 'Subject-action-object-based morphology analysis for determining the direction of technological change', *Technological Forecasting and Social Change*, Vol. 105, No. 4, pp.27–40.
- Guo, Y., Ma, T., Porter, A.L. and Huang, L. (2012) 'Text mining of information resources to inform Forecasting of innovation pathways', *Technology Analysis & Strategic Management*, Vol. 24, No. 8, pp.843–861.
- Gupta, A.K. and Wilemon, D.L. (1996) 'Changing patterns in industrial R&D management', *Journal of Product Innovation Management*, Vol. 13, No. 6, pp.497–511.
- Hoang, H. and Rothaermel, F.T. (2010) 'Leveraging internal and external experience: exploration, exploitation, and R&D project performance', *Strategic Management Journal*, Vol. 31, No. 7, pp.734–758.
- Huang, Y., Schuehle, J., Porter, A.L. and Youtie, J. (2015) 'A systematic method to create search strategies for emerging technologies based on the Web of Science: illustrated for 'big data'', *Scientometrics*, Vol. 105, No. 3, pp.2005–2022.
- Janghyeok, Y., Hyunseok, P. and Kwangsoo, K. (2013) 'Identifying technological competition trends for R&D planning using dynamic patent maps: SAO-based content analysis', *Scientometrics*, Vol. 94, No. 1, pp.313–331.
- Jeon, J., Lee, C. and Park, Y. (2011) 'How to use patent information to search potential technology partners in open innovation', *Journal of Intellectual Property Rights*, Vol. 16, No. 5, pp.385–393.
- Lee, S., Geum, Y., Yoon, B., Kim, M. and Shin, J. (2010) 'Strategic partner selection for collaborative R&D: literature-based technology intelligence', *Proceedings of R&D Management Conference*, Manchester, UK, p.30.
- Mann, D. (2001) 'An introduction to TRIZ: the theory of inventive problem solving', *Creativity and Innovation Management*, Vol. 10, No. 2, pp.123–125.
- Moehrl, M.G., Walter, L., Geritz, A. and Muller, S. (2005) 'Patent-based inventor profiles as a basis for human resource decisions in research and development', *R&D Management*, Vol. 35, No. 5, pp.513–524.
- Mortehan, O. (2004) 'The role of firms' collaborative agreements in the information technology industry transformation', *Technology Analysis & Strategic Management*, Vol. 16, No. 1, pp.53–65.
- Nijssen, E.J., Van Reekum, R. and Hulshoff, H.E. (2001) 'Gathering and using information for the selection of technology partners', *Technological Forecasting and Social Change*, Vol. 67, Nos. 2–3, pp.221–237.
- Noseleit, F. and Faria, P. (2013) 'Complementarities of internal R&D and alliances with different partner types', *Journal of Business Research*, Vol. 66, No. 10, pp.2000–2006.
- Park, H., Yoon, J. and Kim, K. (2012) 'Identifying patent infringement using SAO based semantic technological similarities', *Scientometrics*, Vol. 90, No. 2, pp.515–529.
- Park, I., Jeong, Y., Yoon, B. and Mortara, L. (2015) 'Exploring potential R&D collaboration partners through patent analysis based on bibliographic coupling and latent semantic analysis', *Technology Analysis & Strategic Management*, Vol. 27, No. 7, pp.759–781.

- Pisano, G.P. (1990) 'The R&D boundaries of the firm: an empirical analysis', *Administrative Science Quarterly*, Vol. 35, No. 1, pp.153–176.
- Prahalad, C.K. and Hamel, G. (1990) 'The core competence of the corporation', *Harvard Business Review*, Vol. 68, No. 3, pp.79–91.
- Saen, R.F. (2009) 'Suppliers selection in volume discount environments in the presence of both cardinal and ordinal data', *International Journal of Information Systems & Supply Chain Management*, Vol. 2, No. 1, pp.69–81.
- Samadhi, T.M.A.A. and Hoang, K. (1998) 'Partners selection in a shared-CIM system', *International Journal of Computer Integrated Manufacturing*, Vol. 11, No. 2, pp.173–182.
- Sampson, R.C. (2007) 'R&D alliances and firm performance: the impact of technological diversity and alliance organization on innovation', *Academy of Management Journal*, Vol. 50, No. 2, pp.364–386.
- Solesvik, M.Z. and Encheva, S. (2010) 'Partner selection for interfirm collaboration in ship design', *Industrial Management & Data Systems*, Vol. 110, No. 5, pp.701–717.
- Talluri, S., Baker, R.C. and Sarkis, J. (1999) 'A framework for designing efficient value chain networks', *International Journal of Production Economics*, Vol. 62, Nos. 1–2, pp.133–144.
- Tao, F., Qiao, L., Zhang, Z.L. and Nee, A.Y.C. (2011) 'GA-BHTR: an improved genetic algorithm for partner selection in virtual manufacturing', *International Journal of Production Research*, Vol. 50, No. 8, pp.1–22.
- Verspagen, B. and Duysters, G. (2004) 'The small worlds of strategic technology alliances', *Technovation*, Vol. 24, No. 7, pp.563–571.
- Vicente-Gomila, J.M. (2014) 'The contribution of syntactic–semantic approach to the search for complementary literatures for scientific or technical discovery', *Scientometrics*, Vol. 100, No. 3, pp.659–673.
- Wang, M. (2012) 'Exploring potential R&D collaborators with complementary technologies: the case of biosensors', *Technological Forecasting and Social Change*, Vol. 79, No. 5, pp.862–874.
- Wang, X., Qiu, P., Zhu, D., Mitkova, L., Lei, M. and Porter, A.L. (2015) 'Identification of technology development trends based on subject-action-object analysis: the case of dye-sensitized solar cells', *Technological Forecasting & Social Change*, Vol. 98, pp.24–46, DOI: 10.1016/j.techfore.2015.05.014.
- Wang, X., Wang, Z., Huang, Y., Liu, Y., Zhang, J., Heng, X. and Zhu, D. (2017) 'Identifying R&D partners through subject-action-object semantic analysis in a problem & solution pattern', *Technology Analysis & Strategic Management*, Vol. 29, No. 10, pp.1167–1180.
- Yoon, B. and Song, B. (2014) 'A systematic approach of partner selection for open innovation', *Industrial Management & Data System*, Vol. 114, No. 7, pp.1068–1093.
- Zhang, Y., Porter, A.L., Hu, Z., Guo, Y. and Newman, N.C. (2014a) 'Term clumping' for technical intelligence: a case study on dye-sensitized solar cells', *Technological Forecasting and Social Change*, Vol. 85, pp.26–39, DOI: 10.1016/j.techfore.2013.12.019.
- Zhang, Y., Zhou, X., Porter, A.L., Vicente-Gomila, J.M. and Yan, A. (2014b) 'Triple Helix innovation in China's dye-sensitized solar cell industry: hybrid methods with semantic TRIZ and technology roadmapping', *Scientometrics*, Vol. 99, No. 1, pp.55–75.
- Zhang, Y., Zhang, G., Chen, H., Porter, A.L., Zhu, D. and Lu, J. (2016) 'Topic analysis and forecasting for science, technology and innovation: methodology with a case study focusing on big data research', *Technological Forecasting and Social Change*, Vol. 105, pp.179–191, DOI: 10.1016/j.techfore.2016.01.015.
- Zhang, Y., Zhang, G., Zhu, D. and Lu, J. (2017) 'Scientific evolutionary pathways: identifying and visualizing relationships for scientific topics', *Journal of the Association for Information Science and Technology*, Vol. 68, No. 8, pp.1925–1939.

**Appendix****Table A1** Indexes of organisations and related countries/areas

<i>Country/area code</i>	<i>Country/area name</i>	<i>Organisation code</i>	<i>Organisations name</i>
C1	Bangladesh	F1	Rajshahi University of Engineering & Technology
C2	Brazil	F2	Universidade Estadual Paulista
		F3	Universidade Estadual de Campinas
		F4	University of São Paulo
C3	Canada	F5	University of Toronto
C4	China	F6	Beihang University
		F7	Beijing University of Chemical Technology
		F8	BOE Technology Group Co. Ltd.
		F9	Cent China Normal University
		F10	China Shipbuilding Industry Corporation
		F11	China University of Mining & Technology
		F12	Chinese Academy of Science ASIPP
		F13	Chinese Academy of Science
		F14	Chongqing University
		F15	Dalian University of Technology
		F16	East China University of Science & Technology
		F17	Hainan Institute of Science & Technology
		F18	Harbin Engineering University
		F19	Harbin Institute of Technology
		F20	Hebei University of Technology
		F21	Heilongjiang University
		F22	Henan University
		F23	Huaqiao University
		F24	Hubei University
		F25	Jilin University
		F26	Nanjing University
		F27	Nanjing University of Technology
		F28	Nankai University
		F29	Nantong University
		F30	Northeast Dianli University
		F31	Northeast Normal University
		F32	Peking University
		F33	Qinghai University
		F34	Qiqihar University
		F35	Research & Development Center Haier Group
		F36	Shandong University of Technology
		F37	Tsinghua University
		F38	University of Science & Technology Beijing
		F39	Wuhan University

**Table A1** Indexes of organisations and related countries/areas (continued)

<i>Country/area code</i>	<i>Country/area name</i>	<i>Organisation code</i>	<i>Organisations name</i>
C4	China	F40	Wuhan University of Technology
		F41	Xiangfan University
		F42	Zhejiang University
C5	England	F43	University London (Imperial College of Science Technology & Medicine)
C6	Israel	F44	Bar-Ilan University
C7	Japan	F45	National Institute for Materials Science
		F46	Osaka University
		F47	Toyama University
C8	Scotland	F48	Heriot Watt University
		F49	University Edinburgh
C9	South Korea	F50	Chonbuk National University
		F51	Chonnam National University
		F52	Gwangju Institute of Science & Technology (GIST)
		F53	Inha University
		F54	Korean Institute of Energy Research (KIER)
		F55	Kangnung National University
		F56	Korea Advanced Institute of Science & Technology
		F57	Korea Institute of Science & Technology
		F58	Korea University
		F59	Kyungpook National University
		F60	Sungkyunkwan University
		F61	Solar Energy Research Center
		F62	School of Semiconductor & Chemical Engineering
C10	Switzerland	F63	Ecole Polytech. Fed. Lausanne
		F64	Empa
C11	Taiwan	F65	Swiss Federal Institute of Technology
		F66	Academia Sinica
		F67	National Taiwan University
		F68	National Taipei University of Technology
		F69	National Chiao Tung University
C12	USA	F70	Industrial Technology Research Institute
		F71	National Renewable Energy Laboratory
		F72	Northwestern University
		F73	Lawrence Berkeley Laboratory
		F74	Ohio State University
		F75	University of California Berkeley
		F76	United States Naval