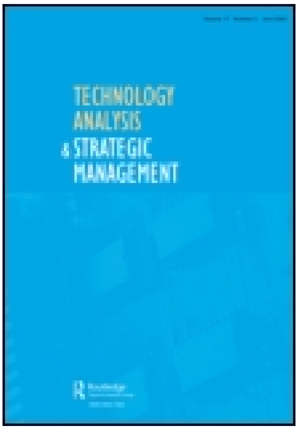

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A hybrid visualisation model for technology roadmapping: bibliometrics, qualitative methodology and empirical study

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A hybrid visualisation model for technology roadmapping: bibliometrics, qualitative methodology and empirical study

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Technology roadmapping offers a flexible instrument to portray development status in support of technology forecasting and assessment. This paper integrates bibliometrics with qualitative methodologies and visualisation techniques to construct a hybrid model for composing technology roadmaps. The mapping arrays details on the evolution of the technology under study and contributes to understanding the macro-technology development status. We generate a global technology roadmap for electric vehicles to demonstrate the approach in an empirical study.

Keywords: technology roadmapping; bibliometrics; term frequency analysis; qualitative methodologies; electric vehicles

Introduction

With the coming of the knowledge-based economy, the boom of emerging technology is not only an obvious global feature of today's scienceand technology (S&T) development, but is also becoming a key factor in national R&D programmes. Organisations operating in competitive environments demanding process improvements, new product introductions, or technology-enhanced services must obtain and use information on emerging technologies (Porter and Detampel 1995). The strategic importance of technology in delivering value and competitive advantage is becoming more critical as the cost, complexity and rate of technology change increase, along with growing competition and multiplying sources of technology globalisation (Phaal, Farrukh, and Probert 2004). Considering this, the following questions ought to be considered seriously by governments, enterprises and institutions:

- How do you describe the macro scale development status of an emerging technology?
- How do you indicate the dynamic development directions of an emerging technology?

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- How do you visualise the potential development trends of that emerging technology, incorporating market, the product and technique elements?

Since Willyard and McClees (1987) indentified the progress of the early technology roadmap development for Motorola and Corning, technology roadmapping has become a significant instrument for both government and enterprises to deal with the three questions presented above. Beginning from 2004, researchers are advancing technology roadmapping in two directions: Delphi-based technology roadmapping and bibliometric mapping, emphasising either qualitative or quantitative methodology.

Obviously, qualitative methodologies (e.g. Delphi) provide chances to compile diverse experts' opinions. This approach is time-consuming, costly and sometimes has a low questionnaire return rate because it tries to obtain converged results through repetitive surveys (Shen, Chang, and Lin 2010). Moreover, qualitative methodologies depend on experts' intuitive knowledge and they may be biased since the opinion of experts may be influenced by subjective elements and limited cognitive horizons (Van Raan 1996; Choi and Park 2009; Juznic et al. 2010). In the opposite case, quantitative methods indicate both actual and potential features from science, technology and innovation (ST&I) activity tabulation, document text mining and other data. However, limitations of quantitative methods (e.g. bibliometrics) include: (1) not all R&D is published or patented, and counts do not distinguish quality (Porter and Detampel 1995); (2) not all publications or patents are similarly valuable; for example, patent barriers could have more business value than the technology itself; (3) ST&I database coverage lags can be important in analysing search results.

With this background, this paper aims to construct a visualisation model for technology roadmapping combining qualitative and quantitative methodologies on the micro-level. We draw on the data objectivity of quantitative methods and introduce qualitative methods to improve these results with experts' checking and interpretation. Thus, we call our methods a 'hybrid' model with the purpose of exploring the technology details during research and innovation, and indicating the technology evolution paths along a time dimension. In addition, we also add national strategic planning and industry development items to the model to enrich its capacity at the macro- and meso-levels of technology forecasting.

This paper is organised as follows: the next section summarises key literature, including technology roadmapping, bibliometrics and, especially, technology opportunities analysis. The third section describes a hybrid visualisation model for technology roadmapping. Following this, an empirical study of electric vehicles is used to verify the scientific and practical value of the model. Finally, the conclusions are presented.

Literature review

Technology roadmapping

As defined by Winebrake (2003), technology roadmapping is a future-based strategic planning device that outlines the goals, barriers and strategies necessary for achieving a given vision of technological advancement and market penetration. Currently, technology roadmapping is considered a flexible strategic planning technique for collaborative technology planning and coordination for corporations (Garcia and Bray 1998; Gerdsri, Assakul, and Vatananan 2010; Jeon, Lee, and Park 2011). The approach provides a structured means for exploring and communicating the relationships between evolving and developing markets, products and technologies over time

(Phaal, Farrukh, and Probert 2004). In general, technology roadmapping identifies (1) a particular industry's common product and process performance targets, (2) the technology alternatives and milestones for meeting these targets and (3) a common technology path for R&D activities (Garcia 1997).

Rip and Kemp (1998) classified the dynamics of socio-technical change under three layers: (1) macro – evolving socio-technical landscapes; (2) meso – a patchwork of regimes; (3) micro – novel configurations. Therefore, it is rational to organise technology roadmapping into this classification spectrum (Phaal, Farrukh, and Probert 2004; Lee and Song 2007; Garcia and Bray 1998; European Industrial Research Management Association (EIRMA) 1997):

- Macro-level technology roadmapping for national R&D planning involves considerations of future economy, market outlook, technological trends and current levels of S&T;
- Meso-level technology roadmapping for industry focuses on areas of common needs and adversarial conditions;
- Micro-level technology roadmapping for technology explores the evolution of markets, products and technologies over time.

Modern technology roadmapping emphasises technology visualisation methods that help to comprehend overall relationships and explain the trends and characteristics of technology with maps or networks (Yoon 2010). Sometimes, its efforts heavily rely on computer-based graphical techniques to convey information to their users and provide constructs for their developers. These efforts often link technologies to components, components to products and products to markets in visual displays (Walsh 2004). Based on the generalised roadmap architecture of Phaal, Farrukh, and Probert (2004), a simple version is shown as Figure 1, which highlights the capacity of supporting strategic planning with the technology push and market pull among organisational purposes, product development and technology resources.

No 'official guide book' outlines how to develop technology roadmapping. The process usually begins with informal discussions and then becomes a conference agenda item or a dedicated feature workshop, engaging industry stakeholders, government officials and/or researchers (Winebrake 2004). Currently, literature reviews, expert interviews, Delphi, scenario planning and other qualitative approaches take leading roles in the implantation of technology roadmapping (Phaal, Farrukh, and Probert 2004; Garcia and Bray 1998). Walsh (2004) modified a model for a disruptive technology roadmapping process and provided an empirical study of the international industrial microsystems and top-down nano systems industry. Gerdsri, Assakul, and Vatananan (2010) constructed a guideline to implement technology roadmapping and outlined a case study on manufacturers. Although researchers have introduced quantitative methodology into the construction of technology roadmapping, studies still neglect the objectivity of quantitative methodology or struggle to determine how to blend the two methodologies together.

Bibliometrics

Modern bibliometrics is rooted in Derek Price's (1963) observations on scientific activity patterns. It is an important quantitative method and also a common research instrument for systematic analysis (Van Raan 2005). Bibliometrics uses counts of publications, patents, or citations to measure and interpret scientific and technological advances (Porter and Detampel 1995), summarise scientific activities (Kajikawa and Takeda 2009), explore basic scientific efforts and technological capabilities (McMillan and Hicks 2001), and indicate research performance over time

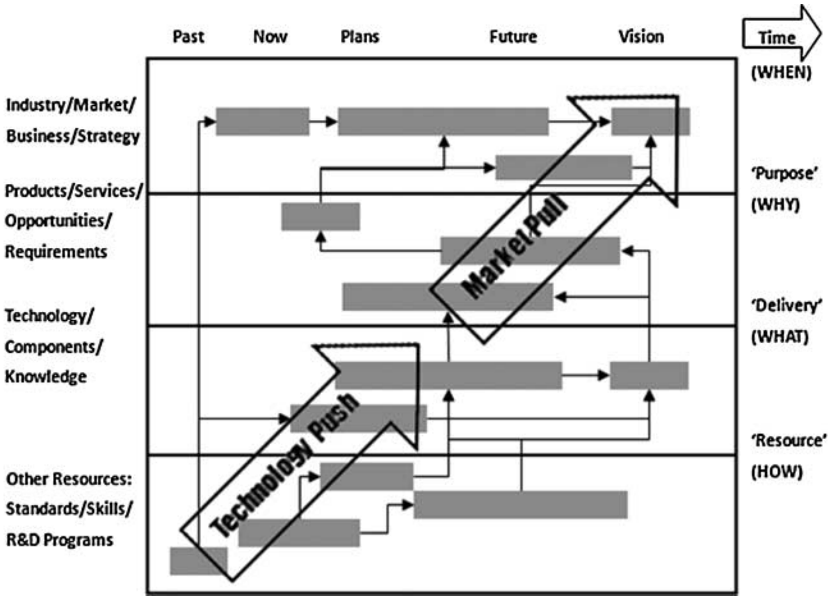

Figure 1. Generalised technology roadmap architecture (based on Phaal, Farrukh, and Probert 2004).

(Van Raan 2003). Bibliometrics is now economical, non-invasive and simple to implement for massive amounts of data in a manner that individuals previously could not handle (Abramo, D'Angelo, and Caprasecca 2009; Kajikawa and Takeda 2009).

At present, bibliometrics usually entails statistical analysis and data mining techniques involving literature analysis, patent analysis, citation analysis and terms analysis (Hufker and Alpert 1994; Daim, Rueda, and Martin 2006; Liu and Sun 2009; Fu, Ho, and Sui 2010; Goodall 2009; Cozzens et al. 2010; Meyer, Debackere, and Glänzel 2010; Chen and Chang 2010; Waltman, Van Eck, and Noyons 2010; Duan 2011). In general, bibliometrics is based on a somewhat simple premise: the greater the merit, influence or importance of a particular paper or patent, the more frequently it will be cited (McMillan and Hamilton 2000). Bibliometric applications range from national policy considerations to tactical ones – for example, providing information on particular domains to help managers make decisions on R&D project selection, new product design or marketing approaches (Porter and Detampel 1995). Though most analyses of bibliometrics employ large samples, case studies are particularly useful when complex processes are to be understood (Yin 1988). Especially, Van Eck, Waltman, and Noyons (2010) introduced the probabilistic latent semantic analysis to automate term identification and developed a freely available computer programme, 'VOS viewer', for constructing and viewing bibliometric maps (Van Eck and Waltman 2010). These effective works should be considered a significant milestone for the combination of bibliometrics and visualisation studies, which reinforce the 'term clustering' approaches and help the study of technology roadmapping in the future.

The Science Citation Index (SCI), Social Science Citation Index (SSCI) and the associated indexes made available through the Web of Science are leading sources of information on publications in a broad range of disciplinary areas (Cozzens et al. 2010). Furthermore, SCI and SSCI databases are used to analyse research performance from an international perspective (Moed

2002) and, undoubtedly, it is one of the most important international literature search tools and data sources for S&T statistical analysis and R&D assessment.

We further chose the United States Patent and Trademark Office (USPTO) as a patent data source. Since many assignees, who perceive an invention to possess global commercial potential, choose to patent in the USA, the USPTO is a premier source. At the same time, the US 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 USA (Lai and Wu 2005). Moreover, the analytic versions of the USPTO include citations, both to other patents and to the scientific literature (Cozzens et al. 2010).

Combination of qualitative and quantitative methodologies in bibliometrics

As we mentioned before, because of the limitation of either qualitative or quantitative methodologies, more and more researchers are working to combine them. Based on a national R&D programmes in Korea, Lee and Song (2007) selected the key research area in nanotechnology by fuzzy clustering methods with a questionnaire of 600 experts from government, enterprises and institutions; Shen Chang, and Lin (2010) constructed a hybrid model using the analytic hierarchy process (AHP) and patent co-citation for technology selection; Gerdsri and Kocaoglu (2007) built a strategic framework for technology roadmapping with the combination of the Delphi model and the AHP model. Jeon, Lee, and Park (2011) implemented a technology roadmapping approach with supplier selection and AHP methods for semiconductor manufacturing companies; experts participated in the selection and weighting. In particular Lee and Park (2005) provided a modularisation method for mass customisation and suggested a set of different roadmaps for different purposes. Meanwhile, Lee, Yoon, and Lee (2009) also proposed the technology-driven roadmapping processes, which start from capability analysis for technology planning and end with business opportunity analysis for market planning. Undoubtedly, this continuous work enhances the combination of qualitative and quantitative methodologies. The research on technology roadmapping with this kind of combination provides the foundation for this paper.

Technology opportunities analysis

Technology opportunities analysis (TOA) has been under development at the Georgia Institute of Technology (Georgia Tech) since 1990. The premise is that useful information on the prospects of particular technological innovations can be extracted from abstracts collected by searching the given topic in suitable publication, patents citation and/or project databases (Zhu and Porter 2002). TOA performs value-added data analysis for the research or technology manager, strategic planner, or market analyst by identifying the related component technologies, developers who are active with the technologies, locations where the developers are, and the relationships among the identified developers (Porter and Detampel 1995). In particular, the professional text-mining software VantagePoint (http://www.thevantagepoint.com/), developed by Search Technology Inc. and Georgia Tech, could handle not only regular statistical analyses, but also science and technology visualisations.

From a macroscopic perspective, TOA contributes to two fields: automated S&T intelligence extraction and visualisation, and future-oriented analysis (FOA). For example, Zhu and Porter (2002) constructed an automatic information extraction and visualisation model with formal publication and patent databases. Yoon and Park (2005) realised a systematic approach to identifying technology opportunities by keyword-based morphology analysis, which is also a bibliometric method. Meanwhile, Guo, Huang, and Porter (2010) profiled the research patterns to capture

Table 1. Differences between our approaches and related previous work.

Research	Reference	Purpose of research	Differences
Theory of TRM	Phaal, Farrukh, and Probert 2004	This paper overviews the origins of TRM, and summarises the general composing model for TRM	Our approach draws on several TRM models, but we introduce quantitative methods (e.g. bibliometrics) into this model, the original version of which only has qualitative parts
TOA	Porter and Detampel 1995; Zhu and Porter 2002; Guo, Huang, and Porter 2010; Huang et al. 2011	Continuous work for efficiently generating effective intelligence on emerging technologies, drawing on monitoring and bibliometrics to mine the wealth of ST&I information to be extracted from topical database search results	Our paper also follows the TOA approach. We blend bibliometric methods with the help of the 'text mining' software 'VantagePonit' to retrieve 'core terms' and their relationships from ST&I document analyses, and visualising them. However, our paper applies these methods and techniques to build TRM models, which is new
Bibliometrics, and methodologies of TRM	Lee and Park 2005; Yoon and Park 2005; Lee, Yoon, and Lee 2009; Jeon, Lee, and Park 2011	The research group of Park has focused on TRM methodology. They also focus on bibliometric methods, and their work has explored valuable information from ST&I documents (especially patent records), and presented results in compelling TRM graphs	Our approach reviews this research and gets really helpful ideas on visualisation methods. However, we construct our framework differently. On the one hand, we emphasise the terms 'frequency analysis' and 'co-occurrence analysis', while they prefer citation analysis, although both belong to bibliometrics. On the other hand, we combine publication and patent records, which is also different from Park's approach
Bibliometric mapping	Van Eck, Waltman, and Noyons 2010; Van Eck and Waltman 2010	Their work emphasised the probabilistic latent semantic analysis for automatic term identification. Also, the software 'VOS viewer' is used for constructing and viewing bibliometric maps	The software 'VantagePoint' and the 'VOS viewer' are both used for 'text mining' based on the term 'co-occurrence analysis'. However, our approach introduces 'relationship-based objects-associated mapping' to get the relationships among terms, which is one key part of our TRM composing model

Note: TRM – technology roadmapping; TOA – technology opportunity analysis.

key technological attributes, leading actors and networks by tech-mining techniques. Huang et al. (2011) devised an approach to look into the potential features of emerging technologies with FOA tools.

This paper differs from that of other research, as described in Table 1.

Methodology: the hybrid visualisation model for technology roadmapping

This paper draws on 'semi-structured' qualitative methodologies such as literature review, expert interviews and expert workshops. It adds bibliometric methods, especially term frequency and term association analyses, to construct a hybrid visualisation model for technology roadmapping.

Some key definitions for this modelling include:

- *Object*: Core terms and IPCs (international patent classifications) retrieved from publications and patents by term frequency analyses
- *Relationships*: Related links among objects retrieved by term association analysis; mostly this task is semi-automated (software based)
- *Time dimension*: The advent of the objects and their relationships over years.

Based on the former research on technology roadmapping by Zhang et al. (2011a), this paper constructs the framework of the hybrid visualisation model for technology roadmapping (as shown in Figure 2). The first step, called 'object definition', follows after the definition of the research target, in which we retrieve the objects of technology roadmapping from publications and patents. We introduce bibliometric methods, especially terms' frequency analysis, to set up an exact terms' dataset as precisely as possible from the SCI/SSCI database and the USPTO database. At the same time, the special 'search strategy' and 'term retrieval' processes use a combination of qualitative and quantitative analyses, the results of which significantly influence the objects list. In the second step, 'relationship definition', we retrieve the relationships between different objects by association analysis and cluster analysis in the aid of software. It is a visualised process performed with the help of object-associated mapping, which is the foundation of expert modification in the third step. 'Construction of technology roadmapping' is the last step of the model, during which expert workshops are emphasised. The phases 'definition of technology development phases' and 'ordinate and time axis locations of objects' particularly need feedback and modification from experts.

Objects definition

Information retrieved from scientific and technological documents helps to discern the current research hotspots. Among them, publications lay emphasis on the fundamental research such as theories, concepts and algorithms. In contrast, patents have long been recognised as a very fruitful source of data for the study of innovation and technical change (Choi and Park 2009), extending the focus from fundamental research to industrial research. Therefore, it is reasonable to consider the terms, extracted from title, abstract, keywords (only for publications) and even the full text of a publication or patent document by data mining techniques as the exact summary for these documents. Furthermore, high-frequency terms and IPCs (only for patents) of massive publication and patent databases represent conclusions of the research hotspots and internal relationships of a specific research field. Based on this, this study tries to pick up core technology terms and IPCs as the objects of technology roadmapping by strict 'search strategy' and 'terms retrieve' processes in order to make sure the objects are significant.

Because of the differences between patents and research publications, it is critical to collect and represent patent and publication database searches in the same technology roadmapping process. Comments are discussed as below:

(1) It is a consensus that publications emphasise fundamental research, while patents pay more attention to the technological innovation (Li and Meng 2010).

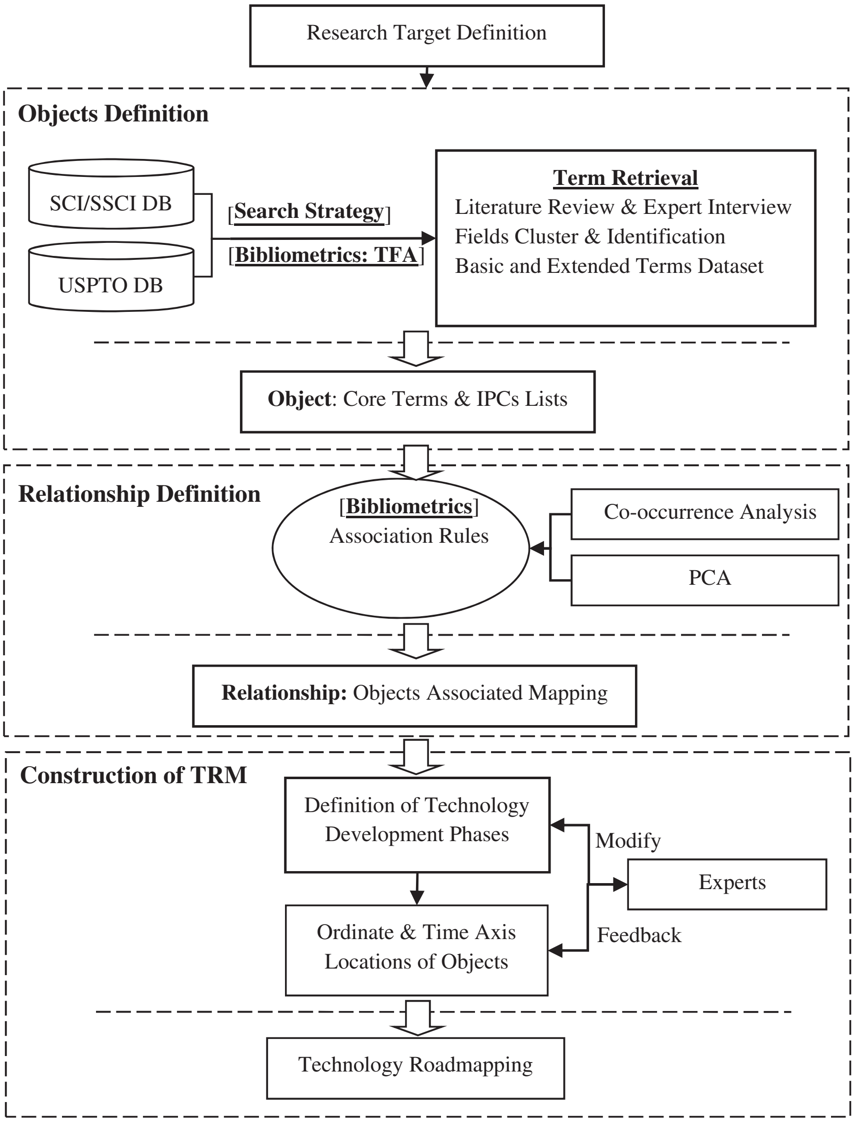

Figure 2. Framework of the hybrid visualisation model for composing technology roadmapping.

(2) Authors present their ideas, models or results in the publications for knowledge sharing, but those (especially lawyers) applying for patents are more guarded. Thus, the content of publications will be much more 'open' than patents (Criscuolo and Verspagen 2008).
(3) The time lag is another difference between publications and patents, because patents require more time in the phases of invention and practice than publications, as well as being subject to sometimes lengthy examination processes.

Above all, the terms in patents and publications, respectively, have distinct characteristics. Thus, we focus on the terms from the 'open' publications. However, classification codes, especially

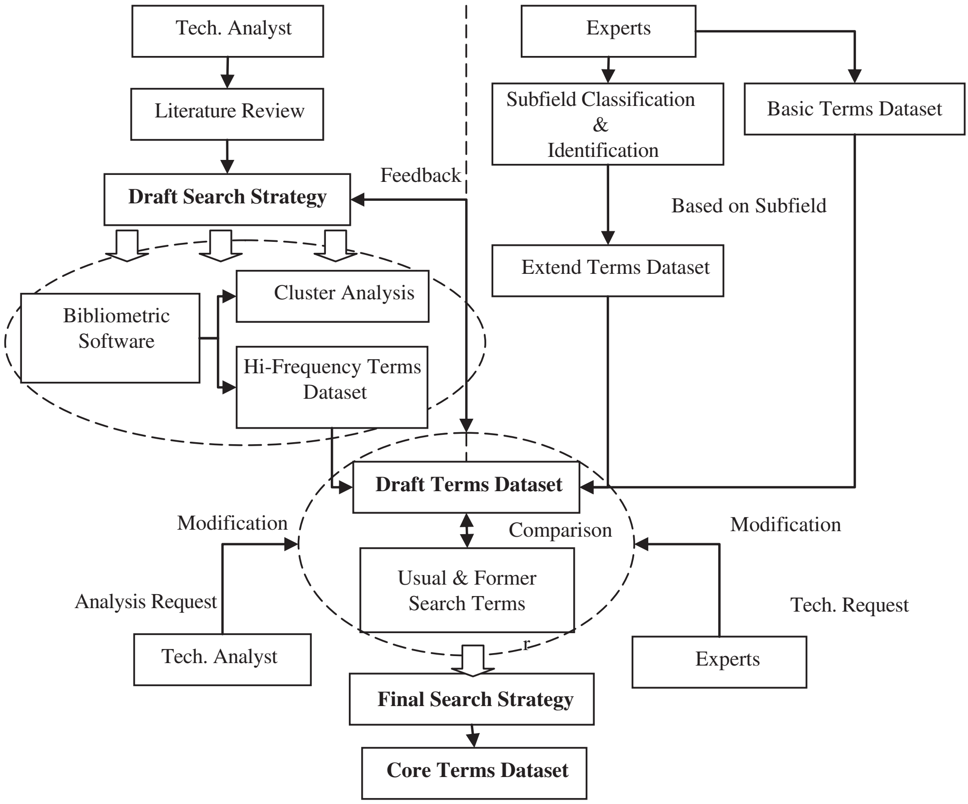

Figure 3. Process of search strategy and term retrieval.

IPCs, are a helpful feature of patents. The description of IPCs reflects accepted categorisation of specific technological domains and could support building conceptual thesauri (Russo 2010). Therefore, we extract the IPC information from the patent search sets. In this case, we use the terms in the publications to emphasise the theoretical level, while the IPCs represent application level information.

Search strategy is the process of defining and refining the search terms and datasets with the feedback of experts and then obtaining the final dataset (Zhang et al. 2011b). Term retrieval is a subsequent task in this phase, which entails compiling the high-frequency terms retrieved by software. Drawing upon the Georgia Tech ‘nanotechnology’ search algorithms (Porter, Youtie, and Shapira 2008) – and also extending the research of China’s patent search strategy devised by Zhang et al. (2011b) – this paper presents the search strategy and terms retrieve model in Figure 3.

The model in Figure 3 combines bibliometrics and qualitative methodologies, and in this step we engage both technology analysts and experts. After the general literature review, technology analysts define the draft search strategy and generate the high-frequency terms dataset and cluster mapping via desktop text analysis software (VantagePoint). Experts identify and classify the subfields with the support of cluster mapping, summarise the basic terms’ dataset and extend the terms’ dataset (which we scope within the identified subfields) based on their experience. Finally, the draft terms' dataset is composed of high-frequency terms', basic terms' and the extended terms' datasets and then we refine the terms by comparison analysis with the participation of both technology analysts and experts. The usual search terms, derived from some general search strategies, only have single keywords or IPCs, while former search terms from former projects in this field have an integrated format with both of them. We finish the final discussions for refining search terms after several informal interviews and expert workshops. The more feedback and modifications are obtained, the better the results that can be expected.

Relationship definition

We define the relationships between the objects by association rules that are based on 'term co-occurrence analysis' and PCA (principal components analysis) methods. On the one hand, term co-occurrence focuses on the pattern of terms occurring simultaneously in the records. If two terms occur together in the records more frequently than expected, a relationship is presumed to exist between them. Extending this, PCA is used to extract the main relationships implicit in a data set. A PCA-related approach called latent semantic indexing generates conceptual indices instead of individual words to improve information retrieval (Zhu and Porter 2002).

The outputs of this step are the objects-associated mappings including the time-based and relationship-based ones. However, we define them as 'maps', but not 'roadmaps', because no time-lines are associated with these figures. They are used to explore the relationships between different time intervals and different topic clusters. We also treat the two quantitative maps as important pieces of evidence for experts to summarise the phases during the technology development cycle in the next step.

Technology roadmapping

We summarise the steps of 'construction of technology roadmapping' in the following three parts:

- Exploring the clusters by relationship-based objects-associated mapping and classifying objects into related clusters;
- Defining the phases of the technology development cycle by the time-based objects-associated mapping, which is shown along the ordinate axis of technology roadmapping;
- Locating the objects for technology roadmapping and then modifying the locations in an appropriate place.

Based on different classification standards, we can divide the phases of the technology development cycle into different parts and the specific features of different technologies are also able to influence the classifications. Aiming to distinguish the differences between different technology fields, this study tries to define the technology development phases by using association analysis among objects. In this step, we generate objects-associated mappings in successive time periods with the help of bibliometrics software. Experts then summarise the phases of the technology development cycle by reviewing the evolution of terms.

More than other steps, qualitative methodologies provide the foundation for the 'construction of technology roadmapping'. According to the objects (core terms and IPCs list) and relationships (objects–associated mappings), experts locate each object on the phases and time axes of the roadmap. The process of locating and its modification include frequent communications with

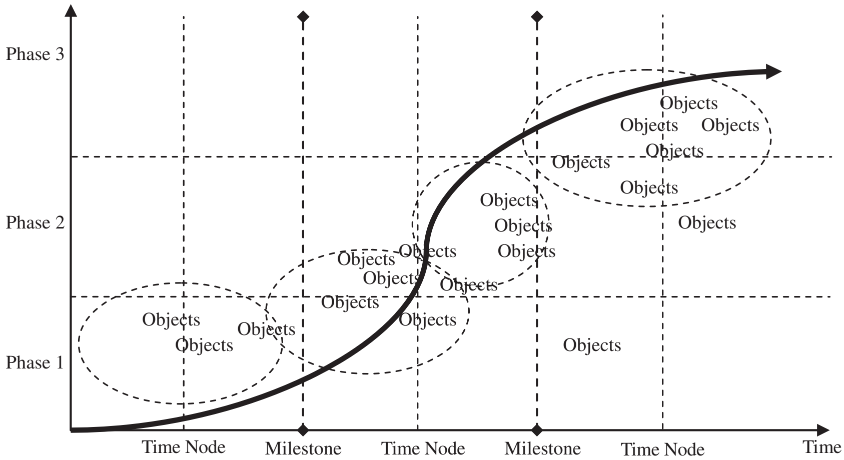

Figure 4. Demonstration of technology roadmapping.

experts through e-mails, interviews and workshops. Especially after the construction of the draft technology roadmap, several formal workshops are needed.

As shown in Figure 4, the ordinate represents the phases of the technology development cycle, summarised from objects-associated mappings and defined by experts, whereas the time dimension is represented on the horizontal axis. Moreover, milestones illustrate the important transition or turning points during the development of technology. In particular, based on the core terms dataset and a yearly high-frequency terms dataset, we locate each object in the time node when it appears in the high-frequency terms list. Sometimes, one object may appear on the mapping more than once, which means this term should be an important one and the technique it mirrors also should be significant. In addition, we are also able to link these objects with a curve to show their development trend. Of course, it is a subjective task of experts.

Case study: Global technology roadmapping for electric vehicles (EVs)

With the increasing energy needs and environmental pressures, the environmentally friendly EVs have become an attractive choice for globally sustainable development in the auto industry. Funded by the Ministry of Science and Technology (MOST) of P.R. China, this paper looks into global R&D programmes. We find that research on EVs dominates the auto industry all over the world. In China, EV research belongs to the 863rd National Key Program of MOST, receives more than 100 million RMB funding from China's government each year, and is becoming one of the seven emerging industries of China. Therefore, this paper tries to describe the technology development status and trends of global EVs from 1985 to 2010 in terms of decision making in governments and enterprises and also to prove the validity of the hybrid visualisation model for composing technology roadmaps.

We select the SCI/SSCI database and the USPTO database as the publication and patent data sources from which we downloaded 3944 publications for the time span of 1 January 2001 to 21 February 2010 and 4144 patents for 1 January 1985 to 21 February 2010. In the step 'object definition', we invite experts from MOST and Beijing Institute of Technology (BIT) to participate in the search strategy and term retrieval. After data cleaning, using VantagePoint and

Table 2. List of electric vehicle objects.

Core terms					
1	hybrid electric vehicle	19	inverter	37	battery electric vehicle
2	control system	20	mathematic model	38	battery state
3	battery	21	vehicle performance	39	electric machine
4	electric motor	22	hydrogen	40	electrochemical society
5	fuel cell	23	battery pack	41	energy management
6	energy	24	drive cycle	42	energy storage
7	control strategy	25	accelerator	43	ripple torque
8	operator	26	conventional vehicle	44	battery system
9	fuel economy	27	cycle life	45	magnet synchronous motor
10	torque	28	dc-dc converter	46	power source
11	consumption fuel	29	drive range	47	specific energy
12	high efficiency	30	drive system	48	wheel
13	regenerative	31	dynamic model	49	stability
14	parameter	32	lithium ion battery	50	converter
15	internal combustion engine	33	energy consumption	51	temperature
16	lead acid battery	34	traction motor	52	induction motor
17	voltage	35	power density	53	energy-efficient
18	electric energy	36	dynamic performance	54	combustion IC engine
Core IPCs					
1	B60K6	5	B60L	9	F16H
2	B60K41	6	B60T	10	H01M
3	B60W20	7	B60W	11	H02K
4	B60K	8	F02D	12	G06F

the modifications of experts, we distinguished 66 objects with 54 core terms and 12 core IPCs (as shown in Table 2).

We generated the relationship-based objects-associated mapping (Figure 5) with VantagePoint, which displays relationships among the technologies. This helps to explore the potential clusters of objects (especially, the terms). In this mapping, it is easy for us to find two big clusters involving the objects ‘battery’ and ‘control system’. A third cluster is made up of the objects ‘energy’, ‘electric motor’, ‘engine’ and ‘consumption fuel’, which form a bridge between the former two clusters.

Also, aiming to define the developmental phases of EV technology, this paper divides the whole time period into three parts. The first comprises the time from 1985 to 1995, the second one spans the time before 2002 and the third encompasses the whole 25 years, containing the former two phases. Based on the term ‘objects’ (not including the IPCs), we generated a time-based objects list via VantagePoint, which illustrates the year when an ‘object’ joins the top 10 high-frequency terms for that year. Subsequently, we use Pajek (http://pajek.imfm.si/doku.php?id=pajek) open source software for network analysis to generate three object-associated mappings in the three time periods. A combined one is shown as Figure 6, in which diamond-shaped, square and circular nodes represent objects in the three time periods. The 10 dispersed diamond-shaped objects are basal terms, reflecting the details of some specific techniques. The 16 square objects lay emphasis on the mechanisms and traditional dynamics. The circular ones reveal a strong developmental trend in battery techniques and the gradually maturing status of hybrid and electric vehicles.

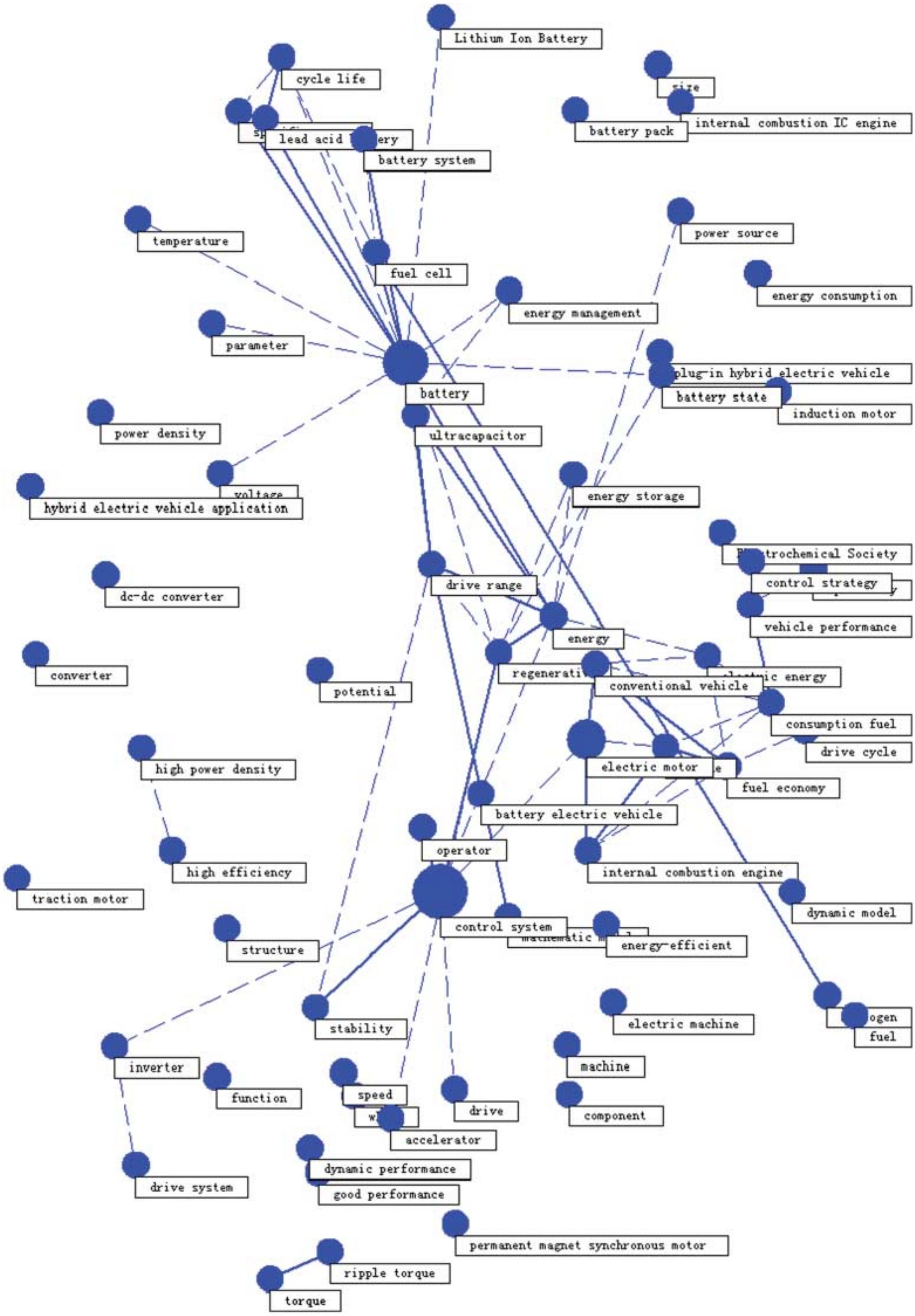

Figure 5. Relationship-based objects-associated mapping of EVs (using VantagePoint).

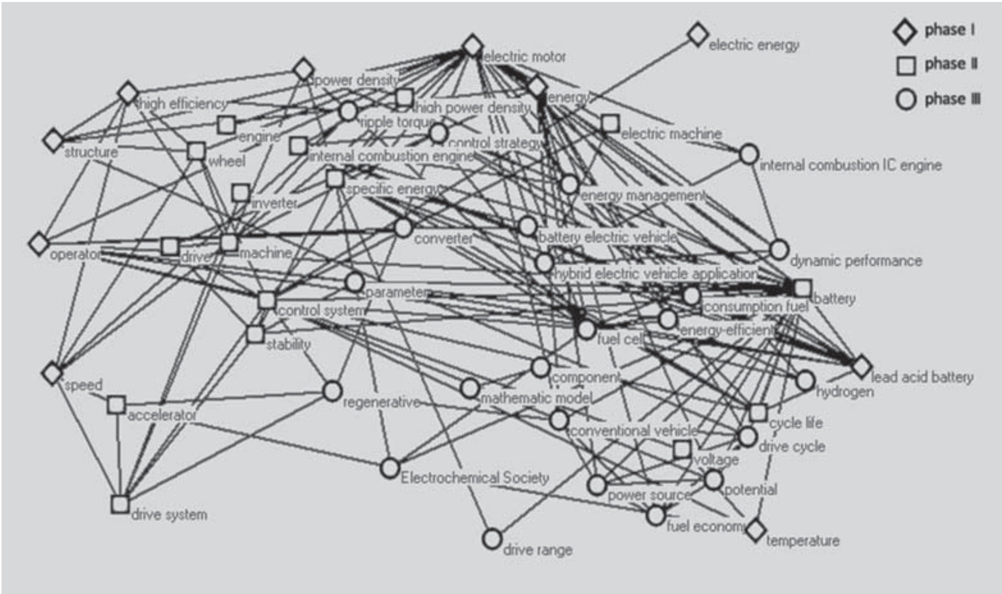

Figure 6. Time-based objects-associated mapping of EVs (using Pajek).

We discussed both object-associated maps with experts in terms of the time trends of objects and the three prominent clusters. Two conclusions emerged:

(1) In the time-based mapping, the development of EVs ranges from foundational research on mechanism, dynamics and battery separately to research on some combination of those components, and then to research on products. This is supported by the radiation of the clusters in the relationship-based mapping in Figure 5.
(2) The two basal clusters (batteries and control systems) concern foundations, while the third one between them reflects the 'battery power techniques', integrating both dynamics and battery techniques.

This is the same result as suggested by Figure 6. Accordingly, this study defines 'materials', 'components and techniques' and 'products' as the three development phases of EV technology. Subsequently, experts helped us classify objects into each phase.

Separately, we have given objects and their relationships in Table 2 and Figure 5, and VantagePoint has also helped to generate the time-based objects list of high-frequency terms. The above steps form the foundation of technology roadmapping. Based on this, the technology analysis staff tried to appropriately locate the objects with the help of some PhD students from BIT, whose majors are concerned with EVs, and to generate the draft for the global EVs roadmap. Regarding the draft mapping, a number of e-mail consultations and interviews collected suggestions and advice from experts, and we also held some small-scale discussions to modify the map. Especially, we organised a large-scale workshop with experts from government (MOST), institutions (Chinese Academy of Sciences), universities (BIT, Hebei University of Science and Technology), and enterprises to discuss several critical or contentious topics. Finally, the complete global technology roadmap of EVs is shown in Figure 7.

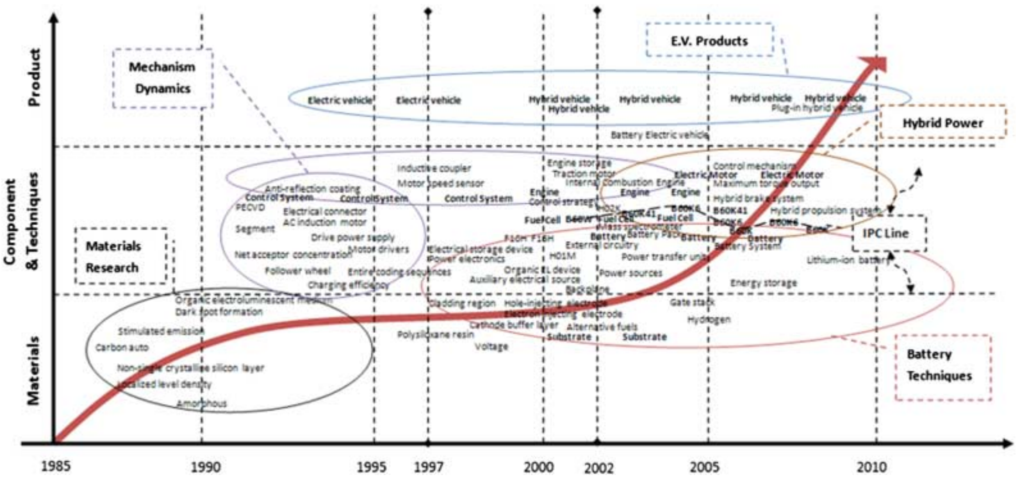

Figure 7. Global technology roadmapping of electric vehicles.

The figure displays the core EV technologies receiving high R&D attention from 1985 to 2010. It also reflects EV macro-development status through the four clusters indicated. The first cluster surrounding 'materials' extends before and after 1990; this is considered the basic research and the foundation of latter researches. The second cluster, which peaks about 1995, concerns mechanism dynamics techniques and is the real starting point for electric vehicles. The third cluster starts in 1997 when objects on battery technology first appear in the time-based objects list and become the most crucial techniques of future R&D. After the research on fuel cell and hybrid power techniques, the fourth cluster follows a milestone for EV technology, especially for the hybrid vehicles. We posted these clusters and the results to experts in our workshop and compared them with conclusions from reports of governments, enterprises and institutions – these generally agree with ours. Therefore, we conclude that this case study successfully demonstrates the validity of the hybrid visualisation model for composing technology roadmaps.

Discussion

This paper constructs a hybrid model for technology roadmapping that combines qualitative and quantitative methods where we retrieve objects and their relationships from publication and patent databases by bibliometric approaches, and then engage experts for the decision-making processes. Therefore, we define the model as a 'hybrid'. In addition, an empirical study generated a global EV technology roadmap, incorporating macro-development status, meso-level research arrangements and micro-level technology details, which demonstrate technology roadmapping modelling based on bibliometric analyses.

Further research will concern enhancing technology visualisation and developing 'macros' to semi-automate object identification, as feasible. We seek more help from other automatic bibliometric software (e.g. 'VOS reviewer'), and devise a more intelligent framework to reduce, but not to eliminate, reliance on experts, while maintaining the veracity of the model. We hope to improve analysis of lower-frequency terms and explore non-co-occurrence analyses for retrieving the latest techniques more effectively. Moreover, we also would like to introduce the 'claims' part of patent records to enrich our research, which should contain richer information than 'abstracts' and ‘titles’. We intend to pursue patent term analyses, seeking ways to better integrate with publication term analyses.

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