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Technology roadmapping for competitive technical intelligence

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ABSTRACT

Understanding the evolution and emergence of technology domains remains a challenge, particularly so for potentially breakthrough technologies. Though it is well recognized that emergence of new fields is complex and uncertain, to make decisions amidst such uncertainty, one needs to mobilize various sources of intelligence to identify known–knowns and known–unknowns to be able to choose appropriate strategies and policies. This competitive technical intelligence cannot rely on simple trend analyses because breakthrough technologies have little past to inform such trends, and positing the directions of evolution is challenging. Neither do qualitative tools, embracing the complexities, provide all the solutions, since transparent and repeatable techniques need to be employed to create best practices and evaluate the intelligence that comes from such exercises. In this paper, we present a hybrid roadmapping technique that draws on a number of approaches and integrates them into a multi-level approach (individual activities, industry evolutions and broader global changes) that can be applied to breakthrough technologies. We describe this approach in deeper detail through a case study on dye-sensitized solar cells. Our contribution to this special issue is to showcase the technique as part of a family of approaches that are emerging around the world to inform strategy and policy.

1. Introduction

Technology roadmapping (TR) is a future-oriented strategic planning device (Winebrake, 2004) that provides a structured approach to help identify relationships between existing and developing technologies, products, and markets, over time (Phaal et al., 2004). If one takes socio-technical change as three interlinked, but distinct, layers (Rip and Kemp, 1998), it is reasonable to classify TR endeavors by scope related to these three layers: 1) TR for national Research & Development (R&D) planning to inform policy involving economic, scientific, technological, and innovation landscapes; 2) TR for industries and sectors, which focus on existing and potential collaborations and collective coordination in target technological areas; and 3) TR for specific technological trajectories (Zhang et al., 2013).

Due to the strategic emphases, expert knowledge plays a determinant role in TR and the development of TR remains a largely qualitative task (Geum et al., 2015). Traditional text mining techniques, although widely applied for technical characterization, mainly defer to expert contributions in devising TRs (Kostoff et al., 2004). Phaal et al. (2004) summarized fourteen examples of general TR cases to offer a guidebook for TR alternatives. There are also quite a few TRs that rely on quantitative methods with diverse emphases (Gerdsri and Kocaoglu, 2007; Lee et al., 2009a; Huang et al., 2014; Zhou et al., 2014; Geum et al., 2015). However, there are still no adaptive criteria and metrics for the selection and evaluation of TRs while applying for actual implementation; existing ones tend to be limited within particular systems. This paper thus focuses on the following research questions:

1. How to balance qualitative and quantitative methodologies to inform TR regarding key components and their relationships?
2. Which criteria and metrics can be used for the selection and evaluation of TR composing models at the implementation stage?
3. How is TR related, similar to, and different from technology foresight projects?

In this paper, we address concerns of Competitive Technical Intelligence (CTI) (Porter and Cunningham, 2005) and aim to develop a series of TR models that balance qualitative and quantitative methods. First, based on traditional text mining techniques and a "Term Clumping" stepwise process (Zhang et al., 2014a), we present a term/topic-based TR composing model (Zhang et al., 2013) that highlights the interaction between core technological components. Then, we introduce Subject–

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Action–Object (SAO) analysis and the Contradiction Matrix concept of TRIZ theory to retrieve Problem & Solution (P&S) patterns (Zhang et al., 2014b). Those can contribute to a problem-solving sequence for technological evolutionary pathways in P&S pattern-based TR model. In parallel, we apply Fuzzy Set theory (Zadeh, 1965) to transfer rough expert knowledge to defined numeric values. This can help generate TR automatically (Zhang et al., 2015b).

This paper draws on Science, Technology & Innovation (ST&I) data – e.g. publications, patents, and academic proposals – to generate historical TRs. We identify developmental patterns and their relationships via text mining and bibliometric techniques, the summarization of which would be used to understand technology evolutionary pathways and to inform R&D program management. Specifically, our model is to seek approaches, e.g. expert knowledge, trend extrapolation, and quantitative methods, to get from the historical data-based TRs to forecast future developmental trajectories. We then compare the strength and weakness among the above TR models, and propose criteria for selecting the most suitable TR at the implementation stage. It is also beneficial to combine TR models with ST&I factors, which concentrate on specific research objectives – e.g., Triple Helix model that emphasizes government–industry–academy relationships (Etzkowitz and Leydesdorff, 1995, 2000) or the GUISPs model that focuses on the Government–University–Industry Strategic Partnerships (Carayannis et al., 2000); incorporation of multiple ST&I data types (Zhang et al., 2015b); and attention to the Technology Delivery System (TDS) for market/user, R&D, and manufacturing factors (Robinson et al., 2013b).

This paper is organized as follows — the Related work section reviews previous studies on qualitative and quantitative methods for TR. The Methodology section presents three models for composing TRs — term/topic-based TR, P&S pattern-based TR, and fuzzy set-based automatic TR. The Empirical study follows, applying our TR models to dye sensitized solar cells (DSSCs) to profile technological evolutionary pathways and foresee possible trends over the near future. We summarize the criteria that could be used for TR selection and evaluation and discuss the similarities and differences between TR and other foresight projects in the Discussion section. Finally, we conclude our research and outline future research priorities.

2. Related work

This section reviews literatures on qualitative methods-based TR, quantitative methods-based TR, and hybrid TR.

2.1. Qualitative methods-based TR

Since Motorola and Corning first applied TRs for commercial strategy and technology evolution & positioning studies (Probert and Radnor, 2003), TR has become a powerful instrument for supporting strategic planning. This stream keys in exploring the dynamic relationships among technological resources, organizational objectives and the changing environment (Phaal et al., 2004). Qualitative methods – e.g. expert interview, Delphi, scenario planning, discussion/seminar/workshop – take leading roles in TR's construction and implementation. These usually involve academic researchers, industrial stakeholders, and government officials (Garcia and Bray, 1997; Phaal et al., 2004; Winebrake, 2004; Zhang et al., 2013).

As a pioneer of TR studies, Sandia National Laboratories constructed fundamental criteria and schemes for roadmapping (Garcia, 1997; Garcia and Bray, 1997).Their 3-phase process and its modified versions were applied to a large range of emerging technologies — e.g. microsystem and nano-system (Walsh, 2004), semiconductor silicon industry (Walsh et al., 2005), and pharmaceutical technology (Tierney et al., 2013). Aiming to outline a general guidance to adapt wider strategic needs, Lee and Park (2005) first developed a modularization method-based TR customizing function. Phaal et al. (2006) designed a catalog for technology management-oriented analytics. Tran and Daim (2008) laid out technology assessment-related approaches for defined levels of public decision making domains and for business and non-government domains. Then, Phaal et al. (2012) proposed a core roadmapping framework for multiple strategic perspectives or a hierarchical family of roadmaps.

What is clear is that, although quantitative methods are increasingly applied to TR, they are outweighed by qualitative methods-based TR which remain the mainstream of current TR activities and, especially, real-world applications — e.g. manufacturing industry (Gerdsri et al., 2009), internet security technologies (Fenwick et al., 2009), produce-service integration (Geum et al., 2011), car-sharing service (Geum et al., 2014), transparent display (Jeong and Yoon, 2015). One reasonable understanding for the popularity of qualitative method-based TR is be that expert knowledge affords powerful credibility to take responsibility for the results; although there is always possible expert biases that could be counterbalanced by quantitative approaches.

2.2. Quantitative methods-based TR

Text mining, as well as bibliometric, scientometric, and informetric techniques have been increasingly used to retrieve textual elements for ST&I studies since the 1990s (Kostoff et al., 2004). Additionally, computer-based graphical techniques first have been introduced to provide aids for developers and to convey information to users (Walsh, 2004). Now, the development of intelligent information techniques – e.g. artificial intelligence, pattern recognition, and machine learning – dramatically increases the capability to identify and visualize potential relationships semi-automatically, although this is still far away from standard applications.

Narrowing our focus on ST&I text analyses, one technique, which is widely recognized, is to retrieve topics via textual elements – e.g. words, terms, or phrases – and then to identify their relationships via defined association rules. There has been a substantial contribution in the form of automated techniques, although most of them could only be defined as quantitative methods for information extraction and visualization rather than strictly quantitative method-based TR. As an example, based on co-occurrence analysis, Zhu and Porter (2002) developed a semi-automatic approach to extract and visualize information for network analysis; Chen (2006) developed a general approach to detect emerging trends from co-citation networks and applied this for visualizing TR automatically; Waltman et al. (2010) defined an association link to blend linkages – e.g. co-occurrence, co-citation, and bibliographic coupling – and visualized grouped nodes as networks. In parallel, novel statistical techniques also started to occupy a position in historical data-based trend analyses. e.g. Allan et al. (1998) proposed approaches to find and follow new events in a stream of broadcast news stories; Kim et al. (2009) complemented a probabilistic approach to retrieve linguistic relationships from patents and discover technological trends; and Blei (2012) applied a topic model algorithm to analyze all of the issues of *Science* magazine from its launch in 1880 to 2002.

Today, the techniques and methodologies for quantitative method-related TR are still under construction. Decades ago Kostoff et al. (2001) asserted that "the proper use of automated techniques for text mining is to augment and amplify the capabilities of the expert by providing insights to the database structure and contents, not to replace the experts by a combination of machines and non-experts"; this still pertains for ST&I studies.

2.3. Hybrid TR

It is commonly accepted that, in a hybrid TR model, computer-based techniques help process massive raw data and reduce scalable data dimensions for further manual operations, and expert-based qualitative methods play active roles in result selection and evaluation.

Kostoff and Schaller (2001), exploring the combination of qualitative and quantitative methodologies, aggregated TR variants into two