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The future of rail automation: A scenario-based technology roadmap for the rail automation market

Christoph Hansen [a], Tugrul Daim [b,*], Horst Ernst [c], Cornelius Herstatt [a]

[a] Technical University of Hamburg, Harburg, Germany
[b] Portland State University, USA
[c] Siemens AG, Germany

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ABSTRACT

This paper proposes a four-step approach based on technology roadmapping and scenario-based roadmapping. The objective is to evaluate the relevance of new products and technologies and its variation under a range of possible future conditions or scenarios. A case study on rail automation for passenger transport systems is conducted to demonstrate the applicability of the proposed method. Market drivers, new systems, products and technologies are identified in a literature review and then verified and linked by expert judgments. Analyzing the resulting graphical representation of relevance and robustness from the proposed approach leads to a periodization of products and technologies for future development and an evaluation of the most influential market driver. The proposed approach for scenario-based technology roadmapping facilitates robust decision making under future uncertainties.

1. Introduction

A general objective of technology roadmapping approaches is to provide a structured way of forecasting the future developments of a market or industry and to review this prediction in an ongoing process. While initial research was limited to the mapping of multiple paths (Strauss and Radnor, 2004), recent research propose approaches, relying on graphical tools for guiding companies towards building scenarios and realizing strategic goals (Lee et al., 2014). The instrument for scenario-based technology roadmapping, one of the most recent approaches, already includes analytical power for the process, in order to "provide a concrete way to facilitate decision making against different future conditions" (Lee et al., 2014, p. 2). The proposed approach for scenario-based technology roadmapping in the paper at hand is designed as a four-step approach, analog to the three steps proposed by Lee et al. (2014). The objective is to evaluate the relevance or importance of products and technologies as well as the robustness of this relevance against different future scenarios of market drivers. The respective relevance values are calculated based on sub-relevance values, which can be evaluated by answering what-if questions, being influenced by only a single parameter. In a case study the field of rail automation, limited to passenger transport systems, is analyzed based on the proposed approach.

2. Literature review and theoretical background

There have been several developments advancing technology roadmapping method. Geum et al. (2015) have recently advanced the roadmapping process by using association rule mining. Thus they were able to establish relationships based on keywords. Lee et al. (2013) were able to include services and link them to devices and technologies in their approach. Rinne (2004) introduced a third dimension through use of landscapes to help to identify technological opportunities.

Jeffrey et al. (2013) studied how successful the roadmaps have been in the renewable energy sector. Their conclusions included the discovery of a new type of roadmap aiming political persuasion. Lee et al. (2012) surveyed different firms to identify factors that should be paid attention during the roadmapping project so that the resulting roadmaps would be credible.

McDowall (2012) demonstrated how technology roadmaps can be used for transition management through the case of hydrogen energy. Yasunaga et al. (2009) demonstrated the use of technology roadmaps for the promotion of technology convergence by government. Kajikawa et al. (2008) provided a framework describing engineering knowledge. Daim and Oliver (2008) adopted the technology roadmapping for an energy related government agency. Lee and Park (2005) introduced a process to customize technology roadmaps.

* Corresponding author.

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2.1. Technology roadmapping

Technology roadmaps as known today combine documentation together with a communication purpose (Moehrle et al., 2013). They aim to provide a link between strategy and technology (Albright and Kappel, 2003). In the 1970s, Motorola was the first company to apply this structured form of technology roadmaps, followed by many companies from the electronics and other sectors, including Phillips, Intel and General Motors, as well as governments, most notably the US Department of Energy, the Canadian Department of Industry and the Korean Ministry of Commerce, Industry and Energy (Phaal et al., 2003). Hence, technology roadmapping initially was not introduced as a management theory but as a management practice. Therefore, early research also concentrated on case examples (Lee et al., 2009). More recent research deals with technology roadmapping as a management theory and provides application guidelines (Phaal et al., 2005). Furthermore, it links this theory to other management tools such as SWOT analysis or scenario mapping (Lee et al., 2014), and extends the scope to, for example, product development (Petrick and Echols, 2004) or disruptive technology (Kostoff et al., 2004). Technology roadmapping "has become one of the most widely used management techniques for supporting innovation and strategy, at firm, sector and national levels" (Phaal and Muller, 2007, p. 39) to date.

Technology roadmapping defines a process of a group of stakeholders addressing the "three key questions: Where do we want to go? Where are we now? and How can we get there?" (Phaal and Muller, 2007, p. 39x) The process of technology roadmapping is used for two main purposes. On the one hand, it provides a planning tool for the high-level support of strategic and planning decisions. On the other hand, it offers possibilities for communication of the results (Phaal et al., 2001). Strategic decisions are supported by linking business and technology planning. Together with identification of the technologies' present status, the direction for reasonable R&D programs can be developed. Benefits from the communication possibilities arise both during development of the roadmap (Phaal and Muller, 2007) and after completing the process (Phaal et al., 2001). Key benefits are not only the presentation of key findings, but also a constant enhancement of the roadmap during and even more importantly after completing the process. Long-term and short-term visions and strategic objectives need to be reviewed in an ongoing process, making "the final roadmap a living document" (Probert et al., 2003, p. 1185).

Different approaches and processes for technology roadmapping have been published in literature. Phaal et al. (2004) found 16 clusters or broad areas in an examination of around 40 roadmaps, differentiated by format and purpose. Before starting the roadmapping process, the scope should be limited, in order to "keep the research manageable" (Fenwick et al., 2009, p. 1056). Furthermore, stakeholders should be identified in order to invite them to participate in a series of workshops (Amer and Daim, 2010). The range of proposed technology roadmapping processes is determined by two extreme forms, namely 'market pull' and 'technology push' (Phaal et al., 2004). The market pull approach looks for customer needs, while the technology push process is based on opportunities.

One of the most generic approaches is a time-based chart, first proposed by the European Industrial Research Management Association (1997). This chart comprises three layers, namely the market layer, the product layer and the technology layer. As a result, it thus enables the evolution of these layers to be explored. Furthermore, it allows linkages among the three layers to be highlighted, i.e. between market drivers and products or between products and technologies (Daim et al., 2012). The market layer presents both market and business drivers, including conditions, e.g. in the form of milestones that have to be satisfied. The content of the product layer depends on the kind of business activities and shows products, services or capabilities that describe a way to meet the market layer conditions. The technology layer outlines necessary technologies or resources to deliver the products, services or capabilities presented in the product layer. Prioritization and selection tools are used for all layers, but especially for the technology layer, in order to explore the most important technologies, products or drivers to be shown on the map (Probert et al., 2003).

Future conditions in general are unpredictable and the more complex these conditions become, the higher the related uncertainties are (Ringland, 2006). For each company and for each market, there are different scenarios for future development with different and not exactly quantifiable probabilities. These uncertainties result in risks for markets with both short and long innovation cycles (Coates, 2000). For a market with short innovation cycles, risks are caused by highly dynamic and volatile environments, while, for markets with long innovation cycles, risks are caused by the capital-intensive and long duration of the development. Studies show that inappropriate responses to future conditions may result in difficulties or even failures of long-established companies (Christensen et al., 1998). Therefore, there is a need for scenario planning in order to be prepared for a range of future scenarios, accompanied with an increase in research to facilitate this approach. A current "attempt is to integrate different scenarios into technology roadmapping" (Lee et al., 2014, p. 1).

There are different approaches and processes to integrate scenario planning into technology roadmapping. Lee et al. (2014) grouped them into qualitative and quantitative approaches. The majority of research can be found for qualitative approaches relying on graphical mapping tools, while some recent research also focuses on including quantitative methods into scenario-based technology roadmapping. The approach includes mapping multiple paths in the roadmap. Each path represents one scenario for the future conditions. Further developed quantitative methods, listed by Lee et al. (2014), include a network-based approach by List (2004) and a visual technique based on collage construction by Saunders (2009). As opposed to these qualitative approaches, there are quantitative approaches which claim to offer a concrete way of decision making against changing future conditions. According to Lee et al. (2014), the qualitative approaches of Pagani (2009) and Gerdsri and Kocaoglu (2007) miss a link between future changes and organizational plans due to their focus on analyzing only future changes. Therefore, he proposes a method based on a Bayesian network to include a quantitative evaluation of organizational plans into the technology roadmapping process. The underlying Bayesian network is a graphical tool to examine probabilistic relationships between different random variables.

The proposed 'instrument for scenario-based technology roadmapping' (Lee et al., 2014) is designed in three steps: (1) Designing a roadmap topology and causal relationships, (2) Assessing the impacts of future changes on organizational plans, and (3) Managing plans and activities. The first step consists of qualitative modeling of the structure of the roadmap in the form of a Bayesian network, followed by quantitative modeling of the dependence relationships among the modeled nodes. The approach is designed in a way that these relationships will be provided by expert judgment in a pairwise comparison across all states, since technology roadmapping is generally considered to be driven by experts in the respective field (Kerr et al., 2012). All data received from the pairwise comparison is converted into probability tables for each node. The second step consists of a current state analysis followed by a sensitivity analysis. In the current state analysis, the marginal probabilities for a node are calculated based on the current conditions. Thus, the impact of future changes can be assessed and the most plausible state for each node can be identified as the state having the highest marginal probability of a node. The sensitivity analysis deals with what-if questions in order to estimate the impacts of future changes under different conditions. For this purpose, Lee et al. (2014) developed several indicators, namely the 'change of fitness of organizational plans' (CFOP), the 'ripple impacts on the subsequent activities' (RIA^{out}) and the 'ripple impacts by the antecedent activities' (RIA^{in}). The third and final step summarizes the results of the previous steps in a 'plan assessment map' and an 'activity assessment map'. These