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

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.

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Keywords:
Technology roadmap
Scenarios
Rail automation
Germany

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.

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 Philips, 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 was 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 Gerdski 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’ (RIAin), and the ‘ripple impacts by the antecedent activities’ (RIAout). The third and final step summarizes the results of the previous steps in a ‘plan assessment map’ and an ‘activity assessment map’. These...
maps classify organizational plans and activities respectively into different categories, giving the company an indication for its strategic decisions.

2.2. Rail automation

Rail automation initially evolved from the need to increase safety for railway systems. For decades, these requirements fostered rail automation developments and innovations. Triggered by the introduction of computer technology, rail automation was also applied in the controlling and optimization of railway systems. Today, rail automation describes the application of the general concept of automation to railway systems. This general concept of automation is the replacement or execution of manual tasks, processes or functions using technological solutions or machine agents (Parasuraman and Riley, 1997; Horton, 2012). Modern automation can be implemented at different levels, i.e. different combinations of autonomy and intelligence (Riley, 1989). Processes at low autonomy levels require a lot of human interactions to carry out a task, while processes at high autonomy levels are able to carry out functions without any interactions once they are initiated. The highest autonomy level indicates that processes cannot even be overruled by human interaction. Once a processes is fully automated and the replacement of manual interactions is permanent, “the function tends to be seen simply as a machine operation” (Parasuraman and Riley, 1997, p. 4).

Despite the replacement of human interactions and the attended advantages such as higher efficiency, reliability and accuracy (Parasuraman and Riley, 1997), modern automation provides other advantages. Today’s automation allows more data to be analyzed and more relations and correlations of available information to be found and thus creates a new visibility of information and results in more efficient processes (Horton, 2012). Driverless trains as known from several mass transit projects are a good example of a complex automation project resulting in a more efficient process. Despite this efficiency, however, automation does not offer a better effectiveness, meaning that it does not ensure achievement of the intended or expected outcome. According to the definition of automation, rail automation describes the replacement of human interactions in railway systems. In the case of a train driver, this means “responsibility for operation management of the trains is transferred from the driver to the train control system” (UIP, 2012, p. 1).

The development of the rail industry and also rail automation is driven by trends in society, such as globalization, urbanization, increasing mobility and scarcity of energy (ERRAC, 2011). These trends result in an increasing demand for passenger and freight transport. Together with an intended and expected shift towards rail, due to its “potential to support a low carbon economy” (Prof Andrew McNaughton, ERRAC Chairman), the demand for rail transportation is also increasing significantly. This increase in demand is accompanied by different challenges and requirements, such as higher capacity, reliability, energy efficiency, security standards, as well as lower operating costs and additional services for customers. The increase in capacity, as the main challenge, as well as answers to other challenges is best implemented by optimizing the use of current systems and infrastructure (Siemens AG, 2013). Besides optimizing the use of assets, automation still makes great efforts to provide higher safety standards. Automation offers possibilities for further and more efficient optimization in different areas of the rail market. For the control, command and communication theme, which is one of six different themes defined by RTS as “the main operational and engineering technical domains in the rail industry” (TSLG, 2012, p. 14), automation allows distances between trains, conflicts at junctions and energy consumption to be optimized. For the infrastructure and rolling stock themes, automation allows maintenance processes to be optimized and, for the customer experience theme, automation allows customized real-time information to be provided for specific journeys.

Today, rail automation is implemented at different levels in the rail industry. For long-distance trains, single processes are automated, such as rail signaling (Sharples et al., 2011) and logistic scheduling (Horton, 2012). For public transport applications, such as metro trains, whole systems are fully automated (UITP, 2012). Key elements for these fully automated systems are automatic train protection (ATP), automatic train operation (ATO) and automatic train control (ATC). ATP is responsible for basic safety functions, such as red signal overrunning, speed limits and collisions. ATO takes over all functions of the driver, except for closing the doors, and automatically brings a train to the next station after the doors have been closed. ATC brings in train scheduling, route setting and train regulation skills. All three systems working together result in a fully automated rail system where no on-board staff is needed. The advantages of these systems are the optimization of running times, including shorter headways of up to 75 s and shorter dwell times of up to 15 s. Furthermore, these systems have proven to offer safer operations and are financially feasible, especially for new lines (UITP, 2012). In 2012, 25 cities ran an automated metro with 41 lines, 588 km of railway system and 585 stations in total (UITP, 2012, p. 11). The total length of worldwide operated automated metros is expected to grow until 2025 to around 1400 km (UITP, 2012, p. 6).

To date, Siemens is the strongest player in the rail automation market with a long history and the largest market share by far (Sheahan and Jones, 2012). Since the 1850s, Werner von Siemens together with John Saxby and George Westinghouse created innovations making rail travel more efficient and safer and thereby set the foundation for today’s rail automation (Siemens, 2013). The study ‘The future railway’ (TSLG, 2012) conducted by TSLG based on the ‘Rail Technical Strategy 2012’ (RTS) examines six themes over a time span of 30 years and discusses them with respect to the following elements: vision, objectives, strategies and enablers. The discussed themes are (1) Control, command and communication, (2) Energy, (3) Infrastructure, (4) Rolling stock, (5) Information, and (6) Customer experience. The findings of two additional studies, first the ‘Rail Technical Strategy Europe’ (UIC, 2014), conducted by the International Union of Railways (UIC) on behalf of the European Railway Operating Community, and second the ‘Challenge 2050’ (Moretti et al., 2013), conducted by the Community of European Railway and Infrastructure Companies (CER), are similar to those of the first study presented. The vision presented in the ‘Rail Route 2050’ (ERRAC, 2011) study of the European Rail Research and Advisory Council (ERRAC) is governed by an increase in capacity demand, environmental friendliness as well as safety, security and service requirements. The increase in capacity demand results in a position of rail as “the most attractive transport mode” (ERRAC, 2011, p. 24) by 2050. The ‘Survey on operational communications’ (Mason, 2014) produced by Mason on behalf of the European Railway Agency emphasizes the development of new communication standards and a related increase in data connectivity. The ‘Sector Overview and Competitiveness Survey of the Railway Supply Industry’ (Eccorys, 2012) prepared by the consultancy Ecorys for the European Commission proposes a number of products and technologies for the research and development of railway supplier companies. The report ‘Signaltechnik 4.0’ (Deutsche Bahn, 2014b) published by German Railways (DB) elaborates the future developments of signaling systems. The authors argue that

![Quantitative roadmap template driver.](image-url)
3. Methodology

There are particular requirements for methodologies to be applied in companies and organizations. First, they have to be adaptable to the specific conditions and environments of the company. Second, their implementation should be possible with acceptable and proportional effort and complexity compared to the generated benefit. Third, the results derived by the methodology have to be meaningful, sound and clearly representable. Technology roadmapping methodologies presented in Section 2.1.2 Process of technology roadmapping fulfill most of these requirements; however, especially meaningfulness and soundness can be further optimized, particularly by including quantified scenarios into the process of technology roadmapping. Among several scenario-based approaches presented in Section 2.1.2 Process of technology roadmapping by Lee et al. (2014) is most promising for the methodology research approach, quantifying variables are extracted from literature review or expert opinions or workshops, but to use both simultaneously for preparing the qualitative roadmap. While expert workshops generate a good understanding they also provided new ideas for drivers, products and technologies, literature review conducted by non-experts helps to prevent organizational blindness.

3.1. Preparation of qualitative technology roadmap

This step prepares the qualitative technology roadmap in the form of a three-layer chart that will be used as a basis for the following steps. For the proposed methodology, the roadmap is prepared as a market pull approach. Thus, market drivers are identified at first. These market drivers are placed in the top layer of the roadmap. Their identification can be conducted either by literature research or by an expert workshop. In an internal expert workshop, business drivers can also be identified in addition to the market drivers. In a second step, systems and products are determined and placed in the middle layer, providing options to meet the requirements of the market drivers. Similar to the first step, the second step can also be conducted either as literature research or as an expert workshop. In a third step, linkages between drivers and systems or products are ascertained and included in the form of arrows between the top and middle layers of the roadmap. Linkages are evaluated in a matrix on a scale between zero and three. Zero indicates that there is no linkage between the respective driver and product or system at all, while three indicates a strong link between them. The matrix is filled by expert opinions, e.g. using a questionnaire. In a fourth step, similar to the second step, technologies are identified and placed in the third layer of the roadmap, which are necessary to develop the systems and products noted in the middle layer. Analog to the third step, in a fifth step linkages between the identified systems or products and the technologies are also evaluated based on expert opinions. The result of this step is a qualitative technology roadmap consisting of three layers and including linkages between them. There are good reasons for companies not only to base this step on either a literature review or expert opinions or workshops, but to use both simultaneously for preparing the qualitative roadmap. While expert workshops generate a good understanding they also provided new ideas for drivers, products and technologies, literature review conducted by non-experts helps to prevent organizational blindness.

3.2. Scenario identification for quantitative roadmap

This step develops future scenarios for the identified drivers in the qualitative roadmap in order to prepare a quantitative roadmap. For each driver, a variable is defined, representing the future development of the respective driver best in a quantitative form. For each of these variables, a range of values is found and converted into a range of possible future developments and an average or most expected scenario. For the implementation of this step, there are two separate approaches, both consisting of four similar sub-steps. One approach is based on literature research while the other is based on expert workshops. For the literature research approach, quantifying variables are extracted from literature in a first step, followed by different values for these variables in a
second step. Using these values in a third step, the range of possible future conditions can be defined. In a last step, the expected scenario is defined as the average or most named value or scenario. The expert workshop approach also follows these four steps. As opposed to the literature research approach, a group of experts has to agree on variables and collect associated values to define a range of scenarios and an expected scenario. Small groups of experts have to agree on an expected scenario, while larger groups can calculate an average of their respective values for the future scenarios. Besides these two separate approaches, mixed approaches are also possible, where, for example, variables are identified in literature research and the associated values are found in an expert workshop. The result of this step is a set of quantified drivers with a range of possible future conditions and an expected scenario, describing the most likely development.

### 3.3. Evaluation of relevance and sensitivity analysis on basis of quantitative roadmap

This step compiles the quantitative roadmap on the basis of the qualitative roadmap from the first step and the future scenarios from the second step. The objective is to evaluate the relevance of each system, product and technology on a scale from zero to ten. Instead of judging the relevance as a whole, it is calculated considering separate values that are described below. Implementation of the qualitative roadmap in Microsoft Excel is based on templates for drivers, systems and products as well as technologies. For drivers, the identified range of scenarios, in the form of the maximum and minimum value, and the expected scenario are included in the roadmap, resulting in a template shown in Fig. 1.

The output value represents the position of the expected scenario within the range and is used for further calculations. Furthermore, the template offers the possibility to weight the drivers in relation to each other. For the application, up to half the drivers could be double-weighted by setting the value to two, while all other drivers will keep their weight at one. For systems and products, significant links to drivers are included in the roadmap and used to determine the relevance of the product in a specific future scenario. The specific form of the resulting template depends on the number of significant links and is shown in Fig. 2 for three linked drivers.

Significant links are those valued with two, i.e. a medium–strong link, or three, i.e. a strong link, in the first step. For further calculations, the outputs of the linked drivers are included in the template and a weighting factor doubles the impact of a strong linkage. Subsequently, sub-relevance values of the respective system or product are evaluated for the maximum (Rel. max.) and minimum (Rel. min.) scenarios of each linked driver, while the scenarios for all other drivers are fixed at their expected values. The key question to be answered for each sub-relevance value is: “What is the relevance of the system or product, if the future scenario for the considered driver is at its highest or lowest?” By combining all sub-relevance values, the relevance or importance of the system or product (PR) is calculated as the weighted average described by Eq. (1) and is represented in the roadmap as a value as well as displayed in the loading of a bar.

$$PR = \frac{\sum (\text{Input} \times \text{Rel. max} + (10 - \text{Input}) \times \text{Rel. min}) \times \text{Weight}}{10 \sum \text{Weight}}$$

For technologies, similar to systems and products, significant links to systems or products are included in the roadmap and used to determine the relevance of the technology in a specific future scenario. The specific form of the resulting template depends on the number of significant links and is shown in Fig. 3 for three linked products.

For further calculations, the relevance of each linked system or product is included in the template. Sub-relevance values of the technology are evaluated for each linked product. The key question to be answered for each sub-relevance value is: “What is the influence on a linked product, if there is an improvement in the considered technology?” The higher the influence of such an improvement is, the more relevant the technology for a product. The sub-relevance values of the technology for a product together with the relevance of the respective product itself are combined to form a total relevance for the technology by adding two parts in the following calculation, where n describes the number of linked products. The first part describes the lower boundary for the

### Table 4: Business drivers.

<table>
<thead>
<tr>
<th>Business driver</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set standards</td>
<td>B1</td>
</tr>
<tr>
<td>Miniaturization</td>
<td>B2</td>
</tr>
<tr>
<td>Achieve cost leadership</td>
<td>B3</td>
</tr>
</tbody>
</table>

### Table 5: Systems and products.

<table>
<thead>
<tr>
<th>Systems and products</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wireless connectivity</td>
<td>P1</td>
</tr>
<tr>
<td>Intelligent traffic management and control system</td>
<td>P2</td>
</tr>
<tr>
<td>Communications-based train control (CBTC)</td>
<td>P3</td>
</tr>
<tr>
<td>Route operational control for signaling (e.g. ETCS)</td>
<td>P4</td>
</tr>
<tr>
<td>Intelligent automated asset management</td>
<td>P5</td>
</tr>
<tr>
<td>Standardized modular on-board equipment</td>
<td>P6</td>
</tr>
<tr>
<td>Train-centric signaling system</td>
<td>P7</td>
</tr>
<tr>
<td>Driver advisory system (DAS)</td>
<td>P8</td>
</tr>
<tr>
<td>Remote condition monitoring/intelligent maintenance</td>
<td>P9</td>
</tr>
<tr>
<td>Intelligent rail infrastructure/intelligent maintenance</td>
<td>P10</td>
</tr>
<tr>
<td>Passenger guidance information system</td>
<td>P11</td>
</tr>
</tbody>
</table>

### Table 6: Driver/product link matrix.

<table>
<thead>
<tr>
<th></th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>P2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>P3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>P4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>P5</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>P6</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>P7</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>P8</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>P9</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>P10</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>P11</td>
<td>1</td>
<td>1</td>
<td>3</td>
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relevance of the technology. This lower boundary (LB) is the maximum relevance with respect to a single product, calculated as the product of the respective product relevance and the technology relevance for the product (Eq. (2)). The second part of the total relevance is the surplus (S) to the lower boundary and takes into account that a technology that is important for more than one linked product might be more relevant in total than expressed by the lower boundary. The more relevant a technology is for the remaining linked products, the more relevant the technology itself becomes. Therefore, the surplus is calculated taking the remaining distance to the maximum relevance of ten as a basis and multiplies it by two factors. The first factor is the average relevance of the linked products and the second factor describes the average distance of the relevance of the remaining products to the maximum relevance calculated in the first part. Multiplying these factors results in the surplus (Eq. (3)) and adding this surplus to the lower boundary results in the value for the total relevance of the technology (TR) (Eq. (4)).

\[
LB = \max_{0 < i < n} (Rel_{link_i} \times Relevance)
\]  
(2)

\[
S = \sum_{0 < i < n} \left(1 - \frac{Rel_{link_i} \times Relevance_i}{100 \times (n-1)}\right) \times \left(100 - LB\right)
\]  
(3)

\[
TR = LB + S
\]  
(4)

Using the introduced templates, a quantitative technology roadmap can be prepared in which one of the templates is included for every driver, system, product and technology. These templates are then linked according to the linkage matrices completed in the first step. Complementing the quantitative roadmap and inserting missing values in the templates based on expert opinions provides values for the relevance of each system, product and technology for the expected future scenario. In a following sensitivity analysis, the change of these values is evaluated for changing future conditions. For each driver, the scenario is set to the maximum and minimum value and the resulting relevance for each system, product and technology is recorded. Out of these eight values, a maximum and minimum relevance for each system, product and technology can be found and thus an average variance from the expected relevance is calculated. This average variance is a measure for the robustness of the calculated relevance. Moreover, the influence of the market drivers can be assessed in this sensitivity analysis. Market drivers, for which changes in future conditions result in most extreme relevance values, can be considered as most influential. These findings can be supported by calculating the average variance caused by a market driver.

3.4. Graphical representation of results

In this step, the results of the third step, which are the relevance and the robustness of each system, product and technology, are illustrated in a two-axis diagram. The horizontal axis presents the expected relevance for a system, product or technology and the vertical axis the respective average variance or the robustness of the relevance. This graphical representation can be used to provide recommendations for further action to the company. Furthermore, having an indicator of the importance and the change of this importance for different future conditions can serve as a basis for a following scheduling of technologies, products and system on a time axis to complete the qualitative roadmap.

4. Results

4.1. Qualitative technology roadmap for rail automation

4.1.1. Market drivers

Analyzing the studies and reports presented in Section 3.3 Rail automation development resulted in a set of market drivers for the rail automation market. Filtering, grouping and prioritizing different statements from the studies led to the four market drivers stated in Table 1, namely (1) Capacity demand, (2) Energy efficiency, (3) Passenger satisfaction and (4) Cost reduction. In the following, these four market drivers will be presented in more detail, starting with a description of the driver, the current situation and future requirements. Using additional studies, quantified scenarios are identified, which are used at a later point for the scenario-based technology roadmapping process.

4.1.2. D1: Capacity demand

The lack of capacity is attracting a lot of attention in the transport sector (McClellan, 2006). Increases in passenger and freight traffic, a shift of the modal split towards rail, as well as bottlenecks in the network bring many mainline railways to or close to their maximum capacity. To date, great effort is being made to increase the capacity of railways; however, increasing the capacity is a complex issue. Several factors influence the creation of capacity and most of them are interrelated. These are infrastructure, rolling stock, motive power, employees, and operating strategies, such as size, speed and timing of trains. The obvious solution, namely building more tracks, is in most cases impossible due to lack of space and always very costly and therefore at least not attractive. Changing operating strategies offers an alternative, less costly strategy. Since the inception of railway capacity, issues have been answered by technological innovations, such as more powerful locomotives, longer trains or more sophisticated control systems (McClellan, 2006). Constrained by physical and financial limitations, new capacity solutions require further technological innovations, but also longer lead times. Thus, the future demand for rail travel needs to be forecast reliably. Rail approaches for future development and an increase in capacity deal with a more efficient use of existing resources.

Table 7  
Technologies.

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Code</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>New and existing communication standards</td>
<td>T1</td>
<td>Devices</td>
</tr>
<tr>
<td>Cloud/open network/internet of things</td>
<td>T2</td>
<td></td>
</tr>
<tr>
<td>Satellite-based real-time train positioning</td>
<td>T3</td>
<td>Data collection</td>
</tr>
<tr>
<td>Monitoring sensors for rolling stock</td>
<td>T4</td>
<td></td>
</tr>
<tr>
<td>Obstacle detection</td>
<td>T5</td>
<td></td>
</tr>
<tr>
<td>Monitoring sensors for infrastructure</td>
<td>T6</td>
<td></td>
</tr>
<tr>
<td>Optimized interface between train, track and control</td>
<td>T7</td>
<td>Data transfer</td>
</tr>
<tr>
<td>High-capacity voice and data communication systems</td>
<td>T8</td>
<td></td>
</tr>
<tr>
<td>Data management system/big data</td>
<td>T9</td>
<td></td>
</tr>
<tr>
<td>Software-defined radio for coexistence of different communication standards</td>
<td>T10</td>
<td></td>
</tr>
<tr>
<td>Forecasting methods</td>
<td>T11</td>
<td></td>
</tr>
<tr>
<td>Appropriate safety and security mechanism</td>
<td>T12</td>
<td></td>
</tr>
<tr>
<td>Mixed-traffic capabilities</td>
<td>T13</td>
<td></td>
</tr>
<tr>
<td>Automated maintenance and inspection machines</td>
<td>T14</td>
<td></td>
</tr>
</tbody>
</table>

Table 8  
Product/technology link matrix.

<table>
<thead>
<tr>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
<th>P10</th>
<th>P11</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>T2</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>T3</td>
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<td>2</td>
<td>0</td>
<td>3</td>
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<td>3</td>
<td>2</td>
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<td>1</td>
</tr>
<tr>
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<td>1</td>
</tr>
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<td>2</td>
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</tr>
<tr>
<td>T8</td>
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<td>3</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>T9</td>
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<td>0</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>T10</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>T11</td>
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<td>2</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>T12</td>
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<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>T13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>T14</td>
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<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>
Fig. 4. Roadmap for the rail automation market.
Focusing on passenger transport, the capacity demand market driver can be quantified by a percentaged increase in passenger travel kilometers. Forecasting passenger travel kilometers for rail transportation is based on the forecast total amount of travel kilometers for all transport modes and the forecast share of rail transportation. An increase in the total amount of travel kilometers is fostered by the global trends of globalization and urbanization (ERRAC, 2011). The most important factor for the modal split in the transportation market is the journey time. Additional factors are the price, service frequency and quality, access time and reliability (Knight Merz, 2010). The advantages of rail transportation over other modes of transportation in the total journey time, including access time, in service frequency and quality and especially in climate friendliness, foster a shift towards rail. Table 2 summarizes the findings and forecasting of different studies. It shows the source as well as the focus region of the study. Starting from the base year, the projected increase in passenger travel kilometers or passenger volume for the years 2020, 2030 and 2050 are shown. The forecasted values show significant differences, resulting in a range of possible future scenarios.

4.1.3. D2: Energy efficiency

Although the energy efficiency of railways is already on a very high level, there are still possibilities to increase this efficiency even further. Especially in comparison to other transportation modes, “the specific energy consumption of railways is extremely low” (Ganselmann, 2005, p. 1). In 2010, the specific energy consumption of passenger rail transportation was 0.29 kW-hour per passenger kilometer, nearly half the respective consumption for car transportation and a third of that for air transportation. Between 2000 and 2010, the specific energy consumption of rail transportation in Germany was decreased by 26% (Geißler, 2012). Moreover, the carbon dioxide situation is similar with a specific emission for rail transportation of 59.8 g per passenger kilometer, significantly lower than the specific emission for car and air transportation, as well as a reduction by 26% compared to 2000 (Geißler, 2012). Further development will be characterized by environmental topics, such as compatibility with other transportation modes or political targets connected to climate change as a global trend, and cost pressure, as the cost for electricity has a high share of the total cost of rail transportation. Rail automation approaches for future development and a further increase in energy efficiency are energy-optimized timetables, including a prevention of route conflicts, an optimization of speed profiles and automated train operation (Pelz and Griem, 2015; Pelz and Dickgießer, 2015).

In order to quantify the energy efficiency market driver, most data can be found for the decrease in emission, mainly for carbon dioxide emission, caused by railways rather than for the correlated direct decrease in energy demand for railways. At the 16th United Nations Organization (UNO) Climate Conference, the community of states agreed on limiting the temperature drift to two degrees (Geißler, 2012). Achieving this goal requires a significant reduction of greenhouse gas in all different areas, including transportation. Table 3 presents the targets and objectives for decreasing carbon dioxide emission of different organizations, meetings and studies, showing the source, base year and details of the objectives. Minor differences among the different targets result in a smaller range of different scenarios than for the capacity demand market driver.

4.1.4. D3: Passenger satisfaction

Rail transportation is often stated as the most preferred transport mode. This position is based on several factors, including the advantages of rail transportation over other transportation modes, such as environmental factors, or simply perceptions of passengers, such as comfort. In order to maintain this position, companies from the rail industry have to make great efforts in various areas. Important areas for passenger satisfaction are punctuality and delays, service patterns, comfort factors, mobile communications and price (Preston and Jones, 2012). Rail automation plays a significant role for punctuality and delays as well as service patterns, mobile communications and price. For service patterns, high availability and passenger information are most relevant. Both are important factors for passenger satisfaction as they allow a seamless journey. Passenger information compromises accurate real-time information as well as passenger guidance systems. Punctuality and delays are an outstanding issue for the public image of rail transport and thus very important for passenger satisfaction, or mainly for passenger dissatisfaction. Punctuality is taken for granted by passengers and improvements lead to a decrease in dissatisfaction. In fact, punctuality “is the biggest single cause of dissatisfaction for rail users” (Price, 2013).

Surveys among rail passengers show that punctuality is the most relevant driver for passenger satisfaction. A survey by Network Rail (2011) in England and Wales confirmed that, for approximately every second passenger, punctuality is most influential for their satisfaction. Therefore, requirements for punctuality are well suited for quantifying the passenger satisfaction market driver. However, in order to determine these requirements, it is important to define the acceptable delay for a train to be punctual at a station. German Railways define two levels of punctuality, a 5-minute punctuality with a maximum delay of 5:59 min and a 15-minute delay with a maximum delay of 15:59 min (Deutsche Bahn, 2014a). Network Rail distinguishes between the punctuality of regional and long-distance services. For regional services, a train is defined to be on time if it arrives within 4:59 min after the planned arrival while, for long-distance services, the threshold is defined as 9:59 min (Network Rail, 2014c). Obviously, for different definitions, different levels of punctuality can be achieved. However, general targets for punctuality are set for a 5-minute definition. Past developments in Germany and Great Britain have shown a steady increase in punctuality percentages over the last decade, but in recent years there has been a slight decrease (Network Rail, 2014c; Deutsche Bahn AG, 2013). For England and Wales, the moving average for 5-minute punctuality currently is 89.3%, being less than 90% for the first time since 2008. In Germany, the 5-minute average punctuality over all services was 94.9% in 2011 and 94.1% in 2013. For long-distance services, punctuality is significantly lower, being 73.9% in 2013 and 80.0% in 2011. Only a few targets for punctuality are available explicitly. Network Rail (2014b) announced an increasing target from 90.9% in 2010 up to 92% in 2014. For the next control period until 2019, the target is set to be 92.5% (Network Rail, 2014a). The Office of Rail Regulation (2012) published targets increasing by 0.5% per year, resulting in 92.0% for 2012. In other literature (ERRAC, 2011; Network Rail, 2011), a long-term target is formulated explicitly that, out of 20 trains, at least 19 arrive on time, resulting in a target of 95% for 5-minute punctuality.

4.1.5. D4: Cost reduction

Rail has several competitors in the transportation market, e.g. air transport, private car transport or bus services. In order to stay

Table 9

<table>
<thead>
<tr>
<th>Market driver</th>
<th>Minimum scenario</th>
<th>Maximum scenario</th>
<th>Expected scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>21% increase in capacity demand until 2020</td>
<td>22% increase in capacity demand until 2020</td>
<td>50% increase in capacity demand until 2020</td>
</tr>
<tr>
<td>D2</td>
<td>20% decrease in carbon dioxide emission until 2030</td>
<td>50% decrease in carbon dioxide emission until 2030</td>
<td>30% decrease in carbon dioxide emission until 2030</td>
</tr>
<tr>
<td>D3</td>
<td>Five-minute punctuality at 90%</td>
<td>Five-minute punctuality at 95%</td>
<td>Five-minute punctuality at 92%</td>
</tr>
<tr>
<td>D4</td>
<td>20% reduction of O&amp;M costs until 2020</td>
<td>50% reduction of O&amp;M costs until 2020</td>
<td>25% reduction of O&amp;M costs until 2020</td>
</tr>
</tbody>
</table>
competitive, i.e. to offer a competitive ticket price to the passenger, life-cycle, operating and maintenance costs have to be decreased significantly (ERRAC, 2011). Additionally, external environmental costs should be taken into account for fair competition between rail and other transport modes, by implementing the 'polluter pays principle' and thus a stronger incentive to lower pollution. Cost reductions can be achieved by developing cost-competitive technologies, improving the performance of products or benefiting from economies of scale. The area of maintenance costs offers many opportunities for cost reduction as it is "one of the most significant areas of expenditures for the railways" (ERRAC, 2011, p. 17). Moreover, there are many opportunities for rail automation to decrease maintenance costs. Automation of maintenance activities, more reliable track systems, strategies for fewer maintenance interventions up to a maintenance-free infrastructure system illustrate ways to lower maintenance costs (ERRAC, 2011).

Quantifying the cost reduction market driver can be realized by a percentaged decrease in operating and maintenance costs, although the scale for this decrease depends to a large extent on the specific case, its current and future conditions and the business environment. Therefore, setting a range for future scenarios or objectives should consequently be conducted by expert opinions, supported by findings in literature. In its last control period, starting in 2009 and ending in 2014, Network Rail (2014a) followed the objective to lower maintenance and operating costs for railways in England and Wales by 20%. In review, a total reduction of 23% was achieved, leading to a target for the next control period until 2019 of another 20% decrease in maintenance and

<table>
<thead>
<tr>
<th>Market drivers</th>
<th>Scenario-based technology roadmap</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1 - Optimized system capacity</td>
<td>D2 - Energy efficiency</td>
</tr>
<tr>
<td>D3 - Passenger satisfaction</td>
<td>D4 - Cost reduction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Link</th>
<th>Input</th>
<th>Weight</th>
<th>Max.</th>
<th>Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>1.44</td>
<td>4</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>D2</td>
<td>1.44</td>
<td>6</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>D3</td>
<td>3.83</td>
<td>2</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>D4</td>
<td>1.87</td>
<td>4</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 5. Quantitative technology roadmap, market drivers.

Fig. 6. Quantitative technology roadmap, systems and products.
operating costs. The ‘Rail Route 2050’ study (ERRAC, 2011) sets a target of reducing the maintenance costs of infrastructure by at least 50% until 2050.

4.1.6. Business drivers

In addition to the identified market drivers, Siemens identified three business drivers in a previous workshop, namely (1) Set standards, (2) Miniaturization and (3) Achieve cost leadership. These business drivers represent key conditions or processes for a sustainable success and a leading market position and are included in the constructed roadmap for the sake of completeness. In fact, in the constructed roadmap, these business drivers have been assigned a code for simplification, as illustrated below (Table 4). Further analysis of the roadmap will concentrate more on the market drivers identified before.

4.1.7. Products

Following identification of the market and business drivers, a further analysis of the studies and reports presented in Section 3.3 Rail Automation generated several suggestions for systems and products that support achieving the vision created by the drivers. Listing the recommended systems and products from different studies and reports, followed by combining and summarizing them, resulted in eleven systems and products presented in Table 5. The identified set of systems and products has been further clustered by grouping them according to their respective application area into five groups, namely (1) Control, (2) Signaling, (3) On-board systems, (4) Infrastructure and (5) Passengers.

The ‘Control’ group comprises systems and products supporting traffic management and control of the system. Intelligent traffic management and control systems, intelligent asset management as well as route operational control systems, such as ETCS, lay the foundations for a centralized control of the whole system, allowing intelligent and automated techniques to be benefited from. Wireless connectivity as well as communications-based train control enable data flow between the train and the centralized control system. The ‘Signaling’ group comprises systems and products redefining the signaling process. Train-centric signaling systems as well as standardized modular on-board equipment allow a reduction in wayside equipment and thus a

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**Fig. 7.** Quantitative technology roadmap, technology.
reduction in costs. Furthermore, the new signaling systems enable the introduction of even more efficient moving-block signaling which allows shorter headways and hence offers higher capacity than fixed-block signaling. The ‘On-board systems’ group comprises systems and products concentrating on the control, management and observation of trains. Remote condition monitoring and intelligent maintenance observe the conditions of trains and optimize the maintenance process. Driver advisory systems (DAS) ensure the realization of signal instructions. Both reliability and availability can be improved and especially maintenance costs can be reduced. The ‘Infrastructure’ group comprises systems and products concentrating on maintenance of the track and wayside equipment. Intelligent rail infrastructure and intelligent maintenance optimize the maintenance process of the infrastructure. Maintenance and repair services can be executed preventively and when needed. The ‘Passengers’ group comprises systems and products supporting passengers’ travel experiences. Passenger guidance information systems provide accurate, real-time timetable data to the passenger. A more advanced system also provides personalized journey information on a real-time basis or even coordinates processes such as entering the train by giving passengers customized information, spreading them along the whole train where seats are available.

4.1.8. Link between drivers and products

Based on expert opinions, linkages between market drivers and systems or products were analyzed. A distinction was made between no link (0), a weak (1), medium–strong (2) and strong (3) relationship. The results of a questionnaire are presented in Table 6. Both strong and medium–strong relationships between market drivers and systems or products will be used for the scenario-based approach and therefore are also presented in the final roadmap.

4.1.9. Technologies

Similar to the analysis of systems and products, recommendations for the new or further development of technologies were identified from the studies and reports presented in Section 3.3 Rail automation development. Combining and summarizing the suggestions of the different reports and studies resulted in a list of fifteen technologies, presented in Table 7, that facilitate the development of the named systems and products. As most of the identified technologies are related with data processing, they were clustered into the four groups: (1) Data collection, (2) Data transfer, (3) Data management and (4) Devices.

The ‘Data collection’ group comprises technologies developed for the process of data logging. Included are sensors, such as obstacle detection, satellite-based real-time train positioning and monitoring sensors for both trains and infrastructure. Besides these, also new and existing communication standards as well as a cloud environment, an open network and the internet of things make lots of data available that can be used by, for example, intelligent control systems. The ‘Data transfer’ group comprises technologies developed for data transmission. New technologies are optimized interfaces between trains, track and control systems as well as high-capacity voice and data communication systems, allowing the transmission of the increased amount of collected data. The ‘Data management’ group comprises technologies analyzing the collected and transferred data. Data management systems for railway application need to store a big amount of data and selected data over a longer time. For analyzing the data, forecasting methods, appropriate safety and security mechanisms and mixed-traffic capabilities are required. Software-defined radio systems enable receiving and analyzing data on the train sent in different communication standards. The final group, ‘Devices’, comprises technologies not related to data processing but developed for machines and devices for the railway industry. Automated maintenance and inspection machines perform both preventive and required repair tasks.

4.1.10. Link between products and technologies

Similar to the linkages between market drivers and products, linkages between products and technologies were also analyzed based on expert opinions. Again, a distinction was made between no link (0), a weak (1), medium–strong (2) and strong (3) relationship. The results of a questionnaire are presented in Table 8. Just like the strong and medium–strong relationships between market drivers and products will be used for the scenario-based approach, the strong and medium–strong linkages between systems or products and technologies will also be used for this approach and thus are also presented in the final roadmap.

4.1.11. 5.1.7 Roadmap for rail automation market

Combining the identified market and business drivers, systems and products, technologies as well as the linkages between them allows construction of the qualitative technology roadmap for rail automation in mainline and mass transit systems. The complete roadmap is shown in Fig. 4. Drivers, products and technologies are included in the roadmap with their respective code and links are only shown for strong (thick line) and medium–strong (thin line) relationships.

4.1.12. Scenario identification for quantitative roadmap

On the basis of the findings on quantified scenarios from the market driver analysis in the section above, a range for possible future scenarios and an expected scenario for all four market drivers can be defined. The range is given in the form of an optimistic scenario, representing the maximum value for the quantifying variables, and a pessimistic scenario, representing the minimum value. The expected scenario is fixed as an average and most likely scenario in between the defined range, named most by the set of sources available. Referring to the results for the quantifying variables and their values, specific ranges and expected scenarios for all four market drivers are given in Table 9.

For the capacity demand driver (D1), scenarios for increasing demand are selected for the year 2020, as most projections are given for this time horizon and the results of the remaining study can be lead back to this year (Table 2). The resulting range shows a broad diversity between a minimum value for the increase of 21% and a maximum value of 222%. Due to this wide range, the expected scenario is set, in consultation with rail automation experts, to an increase of 50% in capacity demand until 2020. For the energy efficiency driver (D2), scenarios for the decrease in carbon dioxide emissions are selected for the year 2030, as the available data is spread over different projection horizons and can be best compared for this year (Table 3). The resulting range is spanned by a minimum value of 20% and a maximum value of 50% decrease in carbon dioxide emissions caused by railways until 2030 and the expected scenario is set to 30%. For the passenger satisfaction driver (D3), scenarios for the targets for 5-minute punctuality show a range of between 90% and 95% and a most named target of 92% in the available literature. For the cost reduction driver (D4), data for maintenance and operating cost reduction targets until 2020 is available directly in the literature, resulting in the presented values.

4.1.13. Evaluation of relevance

The quantitative technology roadmap for the case of rail automation mainline results from the combination of the qualitative roadmap and the identified scenarios from the previous section. Including data for the relevance inputs of each system, product and technology block, generated by expert opinions, allows calculation of the respective product and technology relevance, as described in Section 4. Methodology. The resulting values are presented in the final quantitative roadmap (Figs. 5, 6 and 7).

4.1.14. Sensitivity analysis

For a further analytical analysis of the quantitative technology roadmap, a sensitivity analysis is executed. As proposed in Section 4. Methodology, the scenario for each market driver is set first to its
maximum value and afterwards to its minimum value, keeping the sce-
narios for the remaining market drivers at their expected value. The
resulting relevance values are summarized in Table 10 for systems and
products and in Table 11 for technologies.
Filtering the maximum and minimum values for each system,
product and technology allows an average variance of the expected
relevance to be calculated. This variance is an indicator for poten-
tial changes of the relevance for each system, product or technol-
ogy under changing and unexpected future conditions. Although the
maximum and minimum relevance values do not represent the
absolute extremes, these are chosen for calculations, as a scenario
where all market drivers are at their minimum or maximum
value is considered to be highly unlikely.
For the identified systems, products and technologies, it is con-
spicuous that in general the expected relevance is relatively high
and the average variance relatively low (Tables 10, 11). For systems
and products, this effect is mainly due to the fact that the resulting
suggestions from literature research are the most important ones.
Irrelevant systems and products are either not mentioned in the
available studies and reports or not extracted in the review process.
For technologies, the definition for the relevance calculation further
enhances high-relevance values, in addition to the previously men-
tioned impact of literature research. Setting a lower boundary in a
first step makes low values improbable. Nevertheless, the resulting
values of the sensitivity analysis show a perceptible distribution,
allowing further analysis and interpretation in the following
section.
5. Discussion and recommendation
5.1. Graphical representation of results
As proposed in the four-step methodology, the resulting values from
the sensitivity analysis can be represented in a two-axis diagram for sys-
tems and products, presented in Fig. 8, and for technologies, presented
in Fig. 9. For both diagrams, the horizontal axis shows the expected rel-
EVance of the respective system, product or technology under the ex-
pected future conditions. The vertical axis shows their robustness,
defined as the variance of relevance under changing future conditions
as calculated in the sensitivity analysis. The arrangement with respect
to these two axes allows four groups to be introduced by quartering
the diagram. In order to take adequate account of the previously de-
scribed effect of tendentiously higher relevance and lower variance,
the dividing lines are placed in consideration of the results. For systems
and products, the dividing relevance line is placed at a relevance value
of 6, while for technologies the trend is towards even higher relevance
and thus the dividing line is placed at a value of 7.5. Accordingly, the di-
viding lines for robustness are placed at 1.25 for systems and products
and at 0.75 for technologies.
Table 11
Sensitivity analysis, technologies.
As a result of the introduction of the dividing lines, a distinction between four clusters can be made, namely the relevant and robust, relevant and non-robust, minor relevant and robust, and minor relevant and non-robust clusters. The relevant and robust cluster is located in the top right of the diagram and the cluster of relevant and non-robust elements is located in the bottom right. Both clusters include elements that show particular importance. However, the elements in the upper cluster show only slight variations of this importance under different future conditions, while the elements in the lower cluster show greater variations. Accordingly, the minor relevant and robust cluster, located in the top left, and the minor relevant and non-robust cluster, located in the bottom-left, can be distinguished. Compared to elements in the clusters on the right side of the diagram, elements in these clusters are not as important.

The robustness value, defined as the average variance of the extreme values resulting from the sensitivity analysis, provides an indicator for clustering the respective elements; however, it causes a loss of separate information on the variance in the positive and negative directions. Especially for the lower part of the diagram, a statement on whether there is a high relevance in a positive or negative direction provides crucial additional information. To provide this information, the results of the sensitivity analysis are prepared in a second diagram, showing the expected as well as the maximum positive and negative relevance for each system, product and technology separately in the form of a bar along a relevance axis. For systems and products, the resulting diagram is shown in Fig. 10, while the results for technologies are presented in Fig. 11.

5.2. Recommendations

Based on the graphical representations and the clustering of the results, recommendations can be provided for further actions and
observations of the identified systems, products and technologies. Starting from general recommendations for each of the four groups, more individual suggestions for a single system, product or technology are derived by combining the information from both types of diagrams.

5.2.1. Relevant and robust
Systems, products and technologies in this group are of high relevance under the expected future conditions as well as in different scenarios. Therefore, a company should definitely consider developing them and prioritize them highest. Additional information on differences in variation in negative and positive directions from Figs. 10 or 11 does not provide further important information for this group. The results for the application case of rail automation show that there are four products in this group and eight technologies. All these products and technologies ranked high in a priority list.
5.2.2. Relevant and non-robust

Systems, products and technologies in this group are of high relevance under the expected future conditions, but might be minor relevant in different future scenarios. Therefore, a company could consider developing them, but should definitely observe their relevance on a regular basis by repeating the scenario-based roadmapping approach. The priority has to be considered for each of these systems, products and technologies separately, by also including information from the relevance variance diagram (Figs. 10 or 11). This diagram provides major additional information for this group, showing whether the variance is higher in a positive or negative direction. A high variance in a positive direction combined with a low variance in a negative direction leads to an increase in priority, while variances the other way around lead to a decrease. These differences in prioritization also influence the decision about whether a company should develop the respective system, product or technology. The results show a single product, namely intelligent automated asset management (P5), and one technology, namely appropriate safety and security mechanism (P12) located in this group. Including the information of (Figs. 10 and 11) mainly shows a variation towards higher values for both and, in particular, not minimum values below the limit. Therefore, the products and the technology in this group can be prioritized as high.

5.2.3. Minor-relevant and robust

Systems, products and technologies in this group are of minor relevance under the expected future conditions as well as in different scenarios. Therefore, they generally should have a low priority for a company. As relevance is robust against different future scenarios, additional information is not necessary for this group. However, products or technologies from this group that show promising results in a profitability analysis could be just minor relevant for future market drivers, but important for the market or the whole railway system of today. Thus, they can be classified as classics.

The results for the application case of rail automation in passenger transport show that there are four technologies in this group and two technologies. For these technologies, there is a considerable distance to more relevant products and thus they can be prioritized low. For products however, even though they are under the limit, their relevance is close to product P8. Consequently, for prioritization and development decisions, a closer look should be taken at them.

5.2.4. Minor relevant and non-robust

Systems, products and technologies in this group are of minor relevance under the expected future conditions, but might be more relevant under different future scenarios.

In order to prioritize them, additional information is provided by the relevance variance diagram (Figs. 10 or 11). High variance in a positive direction implies that the relevance of the respective product or technology should be observed in an ongoing process by repeating the scenario-based technology roadmapping approach as future changes may have a significant impact on relevance. Lower variances in a positive direction imply that these products are of minor relevance and also have a lower priority.

The results for the application case of rail automation in passenger transport systems show that there are two products, namely wireless connectivity (P1) and standardized modular on-board equipment (P6), and three technologies, namely new and existing communication standards (T1), monitoring sensors for rolling stock (T4) and software-defined radio (T10) in this group. Evaluating the information from Figs. 10 and 11 allows the conclusion that all these products and technologies have the potential to be highly relevant under different future conditions. Therefore, it is recommended for all five to be further observed. Moreover, from today’s perspective, these products and technologies can be classified as risky investments.

6. Conclusion

This paper establishes an approach for a scenario-based technology roadmap. Applying this approach to the case of rail automation, demonstrated its applicability and the meaningfulness of its result. Regarding the case application, this thesis delivered two main outcomes. First, a qualitative technology roadmap was generated, including four market drivers, eleven products and fourteen technologies as well as significant links between them based on literature research and expert judgment. This roadmap on its own is well suited for communicating purposes both within the company and externally. Second, relevance and robustness values for products and technologies are presented in a graphical format using two types of diagrams. Classifying products and technologies into four groups, depending on their relevance and robustness, allowed recommendations to be given and furthermore provided a basis for prioritization, which companies can use as a basis for strategic decisions. From the resulting priority lists for future development activities of systems and products (Table 12) and technologies (Table 13), findings on the future of rail automation can be derived. Products and technologies related to the development of new traffic management and control systems in general have high priorities (P2, P3, P5, P8, T7, T2, T9, T11, and T13), leading to the conclusion that traffic management and control is a major area for future development. Route operational control for signaling (P4) has an exceptional character in this area, having a medium priority. Being already implemented into today’s railway systems along with its minor relevance but robustness for future development emphasizes that ETCS can be classified as a classic product. A second observation based on the priority lists is that the introduction of new communication standards shows only medium priority (P1, P6, T1 and T10). However, these products and technologies reveal a non-robust character and higher importance for changing future conditions. Therefore, this area can be classified as a risky area for future developments but might become necessary under changing conditions.
In addition to the conclusion on the priority and relevance of the identified systems, products and technologies, the impact of the market drivers on this relevance and thus the most influential and crucial drivers can be identified. The results of the sensitivity analysis show that most of the extreme values for product or technology relevance are caused by the cost reduction market driver (D4). Calculating the average variance caused by a change of future conditions for this driver supports this result. The cost reduction market driver exhibits an average value of 0.73 for products and 0.61 for technologies, which is in both cases around three times higher than for other market drivers. Changing conditions for the energy efficiency market driver exhibits the smallest influence on the relevance of products and technologies. In conclusion, the results of the application of the scenario-based roadmapping approach demonstrate that special attention should be paid to future requirements for operational and maintenance cost savings.

References


Christoph Hansen is a graduate student at Technical University of Hamburg, Harburg, Germany

Horst Ernst is an Engineering Manager at Siemens, Germany

Tugrul Daim is a Professor at the Engineering and Tech Mgmt Dept in Portland State University, USA

Cornelius Herstatt is a Professor at the Technology and Innovation Mgmt Institute at TUHH, Hamburg Germany