Structure of knowledge in the science and technology roadmaps

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Abstract

Science and technology (S&T) roadmaps are an attractive tool in R&D management, and have been widely used during the past decade. S&T roadmaps are typically described as a link among concepts such as product, technology, and science. However, it is still not clear what these concepts, especially, S&T, mean. In this work, we propose a framework describing engineering knowledge, and analyze two S&T roadmaps based on the framework. A distinct difference was seen between these roadmaps. According to our results, there are two types of roadmaps with respect to their description levels. One is entity-level description that is seen in environmental science and life science. Another is attribute-level description seen in the manufacturing industries including the semiconductor industry. We assume the attribute-level description of roadmap to be more effective because it enables us to set quantitative goals.

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1. Introduction

The rapid pace of science and technology (S&T) growth and globalization has substantially increased the complexity of S&T management [1–3]. Due to difficulty in technology forecasting under such circumstances, there is a growing need to clarify the direction of research and development (R&D), share future visions on technologies, and promote interdisciplinary collaborations among different participants.
both in industry and academia. In such circumstances, there is a growing need for S&T roadmaps to offer a means of communicating visions, attracting resources from business and government, stimulating investigations, and monitoring progress. In this context, Robert Galvin describes a roadmap as becoming an inventory of possibilities in a particular field, thus stimulating more targeted investigations [4,5].

Although there is no standard definition of an S&T roadmap, Lewis Branscomb gives the following brief definition [6]: “A consensus articulation of a scientifically informed vision of attractive technology futures.” Similarly, Robert Galvin states [4,5], “A ‘roadmap’ is an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field.” Roadmaps are both forecasts of what is possible or likely to happen, as well as plans that articulate a course of action [7]. In short, roadmaps are defined as the views of a group of stakeholders as to how to get where they want to go to achieve their desired objective [8].

This definition of S&T roadmap originates from that of a road map [9]. In everyday life, a road map is a layout of the paths or routes of some particular geographical space. They are used by travelers to select among alternative routes in determining how to arrive at a particular destination. Reflecting this, S&T roadmaps are typically illustrated as a time-directed representation among scientific and technological concepts.

The widely used framework of S&T roadmaps is relationships among markets, products, and technologies [10–12]. There are also other types of framework [9,13,14]. Examples are Market–Product–Technology–R&D project [13], and Market–Product–Technology–Science [9]. Fig. 1 is a summary of these frameworks. The aim of constructing S&T roadmaps is to realize products at a suitable time. This is driven by the external environment such as market trends, the conduct of suppliers and competitors and social change. It is also necessary to fit the internal resources and R&D project to the achievement. Roadmapping becomes an emerging research field, which is summarized in a special issue of the journal [15]. The roadmapping process involves a wide range of agents from firm, industry, to global level. A prominent example of industrial level roadmaps is International Technology Roadmap for Semiconductors (ITRS) [16]. In Japan, The New Energy and Industrial Technology Development Organization (NEDO) takes an initiative in the construction of industry level roadmaps [17]. There are a number of firm level roadmaps along with the other industry level roadmaps.

Fig. 1. Generic technology roadmap.
However, an examination of roadmaps shows that there is considerable variation among practitioners in the actual representation of S&T roadmaps. Previous works on roadmaps focus on the roadmapping process rather than the roadmap itself, and little effort is devoted to elucidating the structure of existing roadmaps. Therefore, the contents of roadmaps, especially the contents of the science and technology layer, are still obscure. What do these abstract categories mean? We feel that, as Phaal et al. insist, effective technology roadmaps should include activities to structurize the various layers and sub-layers within the map [18]. Therefore, it is worth discussing what science and technology mean and which terms are described as science or technology in current S&T roadmaps.

The aim of this paper is to investigate the content of S&T roadmaps and to offer a viewpoint for discussing the content of each roadmap. For this purpose, we assume a knowledge framework describing engineering knowledge. We analyze the content of roadmaps based on the framework. Two roadmaps are selected for case study: The International Technology Roadmap for Semiconductors (ITRS) and the Technology Strategic Roadmap (TSR) made by the New Energy and Industrial Technology Development Organization (NEDO) in Japan. Then, we discuss the difference and effectiveness of the roadmaps based on the proposed framework.

2. Model

The starting point of our model is to regard the engineering process as a sequential step where material is transformed into another material by process. It is common for R&D managers and researchers to divide technological innovation into product innovation and process innovation after a classical work by Abernathy [19]. Vojak also regards the engineering process as a transformation process from raw material, component, module, and finally to product [20]. In this paper, we collectively define these elements as material, because it is difficult to distinguish raw material, component, module, and product by a definite criterion. Adding to material and product, analysis is included into our framework, because in some cases, analysis is referred to as the key factor in maintaining their own competence. We call these three categories, i.e., material, process, and analysis, entity.

These entities have their own attribute-level concepts. Abernathy mentions that in process innovation, the major focus is cost reduction. Here, cost can be regarded as the attribute of process. Adding to processing cost, other factors such as yield and processability are important to supply the product into the market. We call these process performance, which is also controlled by operational conditions such as reactor geometry and temperature. Therefore, process performance and operating condition are attributes of process. Similar to process, the attributes of analysis, analytic condition and analytic performance, are added in our model.

In product innovation, products typically compete with predecessor products on the basis of their own superior functional performance [19]. Functional performance is the attribute of material. More strikingly, the functional performance of materials is realized by the physicochemical property of the material or a combination of properties [21]. The desired property is realized by the structure of the materials. For example, the strength of a steel depends on its inner structure such as grain size and carbon content. Structure is also called architecture where the structure of the material or product is a complex artefact. These two categories, material structure and material property, are set as attributes of material. These attributes, material structure, material property, and also process performance, are usually controlled by operational conditions [21–23].

In addition to entity and attribute, the final category of our framework, mechanism, is included in our model. A model based on this mechanism is sometimes referred to in roadmaps. In their classical
paper, Rosenblueth and Winner mention that the intention and the result of a scientific activity are to obtain an understanding and control of some part of the universe [24]. One may attribute the former to science and the latter to technology. An inevitable step in S&T is creating a certain level of model. Generally, models can be classified into empirical and mechanistic models [25]. An empirical model is based on the observable relationship between input and output data, trials or experiments. Direct relationships among attributes are regarded as empirical models. A straightforward manner of science is to elucidate the underlying mechanisms and create mechanistic models, which gives us a deeper understanding and, in turn, enables us to gain deeper control. We regard mechanistic models among operating conditions, process performance, and materials structure as process model [23]. Similarly, we call the mechanistic relationship between material structure and material property, and the relationship between analyzing condition and analyzing performance, material model and analysis model, respectively.

In materials science, it is generally considered that central to the materials design approach is a powerful logical structure connecting these elements [21–23]. By connecting adjacent pairs of these elements, a link chain representing a versatile materials paradigm emerges. The deductive, cause–effect logic of reductionist science flows from the process and operating conditions to the material and its properties. The inductive logic of systems engineering flows the other way, from the material and its properties to process and operating conditions, thereby enabling designers to arrive at specific procedures likely to yield materials with the desired sets of properties and performance. By studying the roadmap of the polymer industry, Baker et al. also conclude that processability, structure, and property relationships are important for the roadmap of polymers [13]. Fig. 2 is the entire structure of the proposed framework to describe and analyze S&T roadmaps. We analyze the following two roadmaps based on this framework.

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Fig. 2. Knowledge framework describing engineering knowledge. Entities are Pc (Process), Ma (Material), and An (Analysis). Attributes are OC (Operating Conditions), PP (Process Performance), MS (Material Structure), MP (Material Property), AC (Analytic Condition), and AP (Analytic Performance). Mechanisms are PM (Process Model), MM (Material Model), and AM (Analysis Model).
3. Data and methods

3.1. ITRS

The International Technology Roadmap for Semiconductors (ITRS) is regarded as the most famous and successful roadmap among a number of industrial roadmaps. The ITRS is edited on a regular basis every two years (with updates of the tables only in the years between). The mission of the ITRS is a definition of the near- and long-term technology requirements for the semiconductor industry as well as a description of potential technical solutions to meet these needs. The current ITRS has the following 15 categories: system drivers; design; test and test equipment; process integration, devices, and structures; radio frequency and analog/mixed-signal technologies for wireless communications; emerging research devices; front-end processes; lithography; interconnect; factory integration; assembly and packaging; environment, safety, and health; yield enhancement; metrology; modeling and simulation.

The organizations editing the ITRS are the Semiconductor Industry Associations of USA, Europe, Japan, Korea, and Taiwan. In addition to the semiconductor industry, which is the owner of the ITRS, there are also representatives from the equipment and materials supplier industry, research institutes and international research consortia participating in the roadmapping. In total, more than 800 experts are participating; 20% of them are from consortia, research institutes or universities, and most of the others are from industry. In our analysis, the ITRS 2003 edition was used.

3.2. Roadmap by NEDO

The New Energy and Industrial Technology Development Organization (NEDO) was established by the Japanese government in 1980 aiming to develop new oil-alternative energy technologies. Later, NEDO’s activities were expanded to include industrial technology research and development in addition to environmental technology research and development, the promotion of new energy and energy conservation technology. Currently, NEDO is responsible for R&D project planning and formation, project management and post-project technology evaluation functions.

The Technology Strategic Roadmap (TSR) was developed at the initiative of NEDO and published at 2005. TSR has the following four categories: information and communications technology (ICT); manufacturing; environment and energy; life science. Each category has its own sub-categories. ICT has 4 subcategories, i.e., semiconductors, storage and non-volatile memory, computer, network, software, and usability. However, we exclude usability from our analysis, because usability focuses on the cognitive and aesthetic aspects of users and is not adapted to the framework of engineering knowledge. Manufacturing includes 6 subcategories, i.e., robot, aircraft, microelectromechanical systems (MEMS), space, nanotechnology, and green biotechnology. Four subcategories are in environment and energy (E&E), i.e., fixation and effective use of CO$_2$, regulation of chlorofluorocarbons (CFC), pollutant release and transfer register (PRTR), and recycle–reuse–reduce (3R). Life science (LS) has 3 subcategories, i.e., drug discovery and diagnosis, diagnostics and therapeutic instruments, and tissue engineering. Participants of TSR are more than 300 experts in Japan. A total of 38% of them are from universities, 36% from national institutes, and 25% from industry. This constitution is determined by considering the balance among participants in university, industry, and government, which is in good contrast with ITRS where most roadmap constructors are from industry.
3.3. Analyzing procedure

In this work, we performed an archival analysis as a case study method [26,27]. At first, we check the validity of our proposed framework by the above two roadmaps. The confirmation of the validity is performed by matching the content of the roadmaps with the framework. When the framework matches the content of actual roadmaps, we can regard that the framework is adequate to express engineering knowledge, at least, represented in a roadmap. After briefly checking the validity, we discussed the structure of these two roadmaps. Our aim of this study is not to check the correctness of our proposed framework to represent engineering knowledge in a strict methodology but rather to discuss the structure of these two roadmaps based on the proposed framework. Because our study is based on a case study method, we cannot elucidate general characteristics of roadmaps. But it is plausible to generate a new hypothesis for effective roadmap. Because there has been little research on the content of roadmaps, i.e., roadmap itself, compared to roadmapping, our study meets the criteria to apply a case study method.

Our data source is published roadmaps itself. We downloaded these roadmaps from the web-sites [16,17]. These two roadmaps have a similar layout as shown in Table 1, i.e., the value of the evaluation parameter is described for each year. There are a number of layouts for S&T roadmaps, but this type of representation is the most popular among them [11]. For example, the value of the dielectric constant is set at less than 2.7 in 2005 and 2006, while it is reduced to less than 2.4 in 2007.

After obtaining these two roadmaps, we manually extracted and listed the evaluation parameters represented in each roadmap. A total of 1823 parameters are in ITRS and 3655 parameters are in TSR. Then, we assigned these parameters to 12 categories in our framework proposed in Section 2, i.e., 3 entity categories, 6 attribute categories, and 3 mechanism categories. For example, in the case of Table 1, ‘dielectric constant’ is assigned as material property, and ‘flatness of wafer’ is material structure. We classified evaluation parameters in this way and counted the number of parameters included in each category. The discrepancy in the assignment of evaluation parameters among authors was negligible. When we could not determine the category, we assigned it to others. Finally, we calculated the percentage of the parameters included in each category for each roadmap.

Unfortunately for us and also for the users of TSR, the evaluation parameters in TSR are sometimes vague and include multiple concepts in one evaluation parameter. For vague expressions, we interpreted the evaluation parameter with the information described in the time column. When the evaluation parameter includes multiple concepts, we assigned it to the corresponding multiple categories. For instance, in the memory roadmap of TSR, ‘new technology for FeRAM’ appears as evaluation parameter, which is difficult to understand regarding what the new technology means. In its time column, four concepts, ‘metal organic chemical vapor deposition (MOCVD),’ ‘polymer FeRAM,’ ‘three-dimensional (3D) capacitor,’ and ‘1T-FeRAM,’ are described as value. These four concepts should be categorized as

<table>
<thead>
<tr>
<th>Evaluation parameter</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2005</td>
</tr>
<tr>
<td><strong>Value</strong></td>
<td></td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>&lt;2.7</td>
</tr>
<tr>
<td>Flatness of wafer (nm)</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 1
An example of S&T roadmap
process, material, material structure, and material property, respectively. Therefore, we count ‘new technology for FeRAM’ as four concepts, i.e., we assigned it into four categories. This is an extreme case, but 7% of the evaluation parameters in TSR include multiple concepts.

4. Results and discussions

Fig. 3 shows the results of our analysis. The average percentages of the concepts classified into each category are in Fig. 3(a) for TRS and Fig. 3(b) for ITRS. In both roadmaps, most of the concepts could be categorized into the class of attributes of materials, i.e., material structure and property. In ITRS, material structure was the largest because parameters expressing device size such as ‘DRAM 1/2 Pitch (nm)’ were repeatedly referred to. For TRS, entity comprises a relatively large fraction, while fewer concepts were observed in entity for ITRS. Concepts not categorized into our model are 16% in TRS and 2% in ITRS. One reason for the large fraction of the others category in TRS is the vague expression as described in the previous section. Another reason is the existence of non-technological parameters such as market needs, development of R&D, and social change.

The pronounced difference between these roadmaps is the small amount of entity-level description in ITRS. This difference was also seen in each roadmap of TSR. Fig. 4 shows the results of TSR analyzed by category. ICT and manufacturing focus on attribute-level description, especially on material property. However, E&E and LS focus instead on entity-level description, i.e., process in E&E and material in LS. The difference in the focus of each roadmap reflects the current status in each domain. In ICT and some parts of manufacturing, a dominant design for process and product is established. Therefore, few items are described in product (in our analysis, material) and process, because they reach shared agreement. In these domains, priority is set to incrementally improve the attributes of process and material within the dominant design. For example, in complementary metal oxide semiconductor (CMOS) technology, the priority is to catch up with the continuous shrinkage of device size, i.e., material structure, expressed by

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Fig. 3. Average percentages of evaluation parameters in each category. (a) TSR and (b) ITRS. (I) Entities, (II) Attributes, and (III) Mechanisms.
Moore’s law. In the hard disk drive (HDD), the priority is the incremental development of recording density, i.e., material property.

In E&E and LS, there is no such dominant design. In E&E, discussions during roadmapping focus on how to develop a new process such as the production process of hydrogen and how to manage society to accept a new process such as materials recycling. Process is not yet existing or accepted. In LS, the bottleneck is to discover candidates for new materials, and the roadmap therefore includes many material-level descriptions such as the discovery of new drugs for cancer and the development of vaccines to control biophylaxis induction.

However, the entity-level description seen in E&E and LS has the shortcoming that it is difficult to manage. How can we control new drug discovery and monitor progress using a roadmap? On the other hand, attribute-level description reduces difficulty in management and monitoring, because it enables us
to set a quantitative value for each evaluation parameter for each year as seen in Table 1. This agrees with the argument by Zurcher and Kostoff [28]. They state that S&T roadmaps link the product, technology, and requirements expressed by a quantitative value. Quantitative target setting enables us to monitor the progress of projects. In addition to quantitative goal setting, attribute-level description sharpens the functional requirement. Suh describes the design process in engineering as a sequential step from the specification of the functional requirement of the customer to determining design parameters to realize the functional requirement [29]. Ingredients functionally required by the customer are not process and product but their attributes such as functional properties, structures and cost.

There are two alternatives for the roadmaps currently described at entity level. One is to modify the roadmap into attribute-level description. For example, it is desirable to replace entity-level description such as ‘development of new hydrogen production process’ with entity-level description such as ‘cost of hydrogen production’ and ‘rate of hydrogen production.’ However, it is not feasible in any case. The other is to explore another R&D management tool instead of a roadmap. For example, it is difficult to replace entity-level description such as ‘new drug discovery’ with attribute-level description. Another management tool such as pipeline management might be more effective in this case [30].

In previous research on the S&T roadmap, it is usually assumed that roadmapping is more important than the roadmap [7,11,18,31,32]. Phaal states that many of the benefits of roadmapping are derived from the roadmapping process, rather than the roadmap itself [11]. Indeed, the roadmapping process brings together people from different parts of the business, providing an opportunity for sharing information and perspectives and providing a vehicle for the holistic consideration of problems, opportunities and new ideas [11]. Definitely, roadmapping conveys us these fruitful outcome. Compared to roadmapping, little effort has been devoted to the content of roadmap, i.e., roadmap itself. On the contrary of it, our results suggest that the content of the roadmap is also an important element and the performance of the roadmap may depend on its structure.

On the assessment of the quality of roadmaps, researchers have also focused on the roadmapping. Kostoff and Schaller [9] proposed the following factors for high-quality roadmaps; 1) Senior management commitment; 2) Roadmap manager’s motivation to construct a technically credible and visionary roadmap; 3) Competence of roadmap participants/team; 4) Stakeholder-driven; 5) Normalization and standardization; 6) Reliability; 7) Cost; 8) Global data awareness. In addition to these criteria in roadmapping, they suggested the following two criteria for roadmap; 9) Roadmap criteria, i.e., criteria for selecting nodes and links in roadmap; 10) Relevance to future actions. But it is not clear what these criteria actually mean.

This work suggests a roadmap criterion. According to our analyzed results, we should select attribute-level elements as nodes. By taking attribute-level concept as evaluation parameters, we can sharpen the functional requirement. The attribute-level description also enables us to set a quantitative goal at each year, which stimulate the progress and monitor the current status of research. The generality of our proposed framework might be confirmed by more case studies. And it is open for future research. But our findings can help the practitioner to develop an effective roadmap, we believe. We hope that our results can offer to assess the quality of roadmaps and to improve and update roadmaps.

5. Conclusion

Science and technology (S&T) roadmaps are an attractive tool in R&D management, and have been widely used both in individual companies and entire industries over the past decade. In the current S&T roadmap as well as in roadmapping activities, the details of the roadmap contents are still obscure, while it
has been generally assumed that a link between product, technology, and science constitutes the basic elements of the roadmap.

In this work, we proposed a knowledge framework of engineering knowledge and analyzed the following two roadmaps, i.e., ITRS and the roadmap by NEDO. Over 90% of elements included in these roadmaps can be classified using the proposed framework. The generality of our proposed framework might be confirmed by more case studies, but the aim of this research is to propose the framework and discuss the current status of these roadmaps based on the proposed framework. Actually, a distinct difference was seen between these roadmaps and different industries. We assume that attribute-level description of the roadmap is effective because by doing so, we can sharpen the functional requirement and quantitatively set the goal as seen in ITRS.

As already mentioned, central to the materials design approach is a powerful logical structure connecting process, structure, property, and performance. We believe that such a view is also valid for roadmaps. To maximize the performance of a roadmap, the structure of a roadmap should be elucidated. Such an effort will lead to more effective processing, i.e., roadmapping. We hope that our findings in this research can help the practitioner to develop an effective roadmap.

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References

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