A SYSTEMATIC PROCESS FOR STRUCTURING SUCCESSIVE ROADMAPPING EXERCISES FOR EMERGING TECHNOLOGIES: LESSONS FROM ADDITIVE MANUFACTURING IN THE US

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Abstract

While strategic roadmapping is an increasingly widely adopted tool to support public-level strategy processes, there remain significant challenges for policymakers and government agencies in terms of how to structure and manage roadmapping exercises. This paper proposes a systematic process for structuring successive roadmapping exercises that help develop strategies to support emerging technologies, taking full advantages of previous foresight analyses. Using a general guideline for roadmapping processes as baseline, the process has been developed through the study of what specific activities and steps have been carried out in a series of roadmapping exercises in the case study of additive manufacturing in the US. In particular, the paper explores how existing information from previous analyses with broader scopes can be gathered in advance, and used to effectively facilitate and accelerate the development process of a more detailed roadmap focusing on particular issues of collective interest, such as measurement science and standards in the case study. The findings of the research are expected to provide guidance on how roadmapping processes can be structured and managed to effectively support public strategy development for emerging technologies as they emerge over time.

Keywords: Strategy, Governmental Foresight, Roadmap, Roadmapping Process, Emerging Technologies

Introduction

Many governments are increasingly taking strategic approaches to promote key emerging technologies and their innovation (Willetts 2013; HLG KET 2011; NSTC 2011). Systematic foresight analyses are used to support their policy making and strategy processes (Da Costa et al. 2008; Popper 2008; Coates 1985); strategic roamdapping is one of the practices that are widely being used recently (TSB 2012; DKE 2010; NCPV 2003). Roadmapping helps gather information from various stakeholders to identify their common vision and strategic options to achieve that vision (Kostoff & Schaller 2001; Phaal & Muller 2009). It is a particularly useful tool for exploring the emergence of new technologies, a process which involves high levels of system complexity, significant uncertainties, and diverse stakeholders (Phaal et al. 2010).

At the early stages of technological innovation where there is significant uncertainty, government policies and strategies typically offer a general vision for the technology's development, with roadmapping efforts focused on better understanding of the market opportunities and general innovation needs (Badger et al. 2011; DKE 2010; DOE 2004). As technology evolves and more information becomes available, a series of roadmaps with particular attentions on key opportunities, barriers, or challenges of innovation are often developed, providing ever more detailed strategic action plans (NIST 2014; SIENA 2011; NCPV 2003). They also tend to focus on specific issues of collective interest with infrastructure characteristics, such as research and development, regulation, standards, and skills and education. The systematic approach of roadmapping particularly addressing these issues is an appropriate communication and strategy tool, due to its ability to deal with conflicting perspectives and motivations of multiple stakeholders involved (Phaal et al. 2010).

Despite its wide adoption, there remain significant challenges for policymakers and government agencies in terms of how to structure and manage public-domain roadmapping exercises. In particular, questions remain regarding how such exercises can effectively draw on previous roadmapping or other similar foresight exercises, in order to access current information and state-of-the-art research. Although it is recognised that foresight exercises should gain more benefits from previous learning and analyses (Barré 2001), limited studies have been carried out regarding roadmapping practices in this context. Therefore, more research is needed on a systematic and comprehensive approach of roadmapping, incorporating relevant findings from previous analyses to refine the roadmap's structure and ensure effective planning and management of the roadmapping exercise.

In this regard, this paper proposes a more systematic and structured process of successive roadmapping exercises that help develop public-level strategies to support emerging technologies, effectively building on information from previous foresight analyses. Using the general roadmapping process framework as a baseline, it identifies potential effective practices from a series of roadmapping exercises explored in the case study. Additive manufacturing in the US is selected for detailed case study analysis, as it is an important emerging technology with a variety of complexities involved, so illustrating systematic strategic approaches adopted to enable its successful emergence. In particular, the paper explores how previous roadmapping exercises with broader scopes have been built on for the successive development of more focused and detailed roadmaps in the field. The findings of the research have implications for how roadmapping processes can be structured and managed to effectively support public strategy development for emerging technologies as they emerge over time.

Methodological Approach

Developing a Baseline Model

First, a 'baseline' model for the strategic roadmapping process is developed, based on a review of various literatures on roadmapping exercises (for example, see Phaal et al. 2010; Phaal & Muller 2009; EIRMA 1997; Garcia & Bray 1997); the following phases are presented as a general guideline for roadmapping processes.

1) Initiation and planning: to define scope, objectives, and boundaries of the roadmap, and identify participants, structure, and process of developing the roadmap
2) Input and analysis: to capture structure and share relevant knowledge.
3) Synthesis and output: to create the roadmap through convergence and synthesis, and implement to fulfill the objectives.
4) Follow-up: to review and update the roadmap.

Although detailed procedures of each phase differ depending on various factors such as the purpose and type of the roadmap, they generally follow a process of strategy development. To develop a model that is more generic, the following steps from a generalised strategy process model developed by Phaal et al. (2010) are adopted as the baseline process of strategic roadmapping.

1. Vision and goals
2. Appraisal of current position
3a. Assessment of external environments
3b. Assessment of internal environments
4. Generation and assessment of strategic options
5. Implementation
6. Evaluation and learning

Case Study Selection – Additive Manufacturing in the US

A case study of strategy processes used in actual roadmapping exercises is then conducted against the baseline model, providing information on what activities have been undertaken in each step. The case study focuses on additive manufacturing (AM)[1], the adding of material, often layer-by-layer, to build a three-dimensional part. While a number of production processes would by this definition qualify as AM, it typically refers to processes that progressively build parts in very thin layers. These processes include stereolithography, selective laser sintering, electron beam melting, inkjet or binder jetting, fused deposition moulding, and laminated object manufacturing. They use various raw materials and different application processes, such as liquid that is either in a vat or propelled, power that is either in a ‘bed’ or propelled, or solid material that is melted and extruded[2]. These processes are also employed in a number of different sectors, including jewellery, toys, manufacturing tools, parts for aerospace applications, and bio-inert parts (for example, prosthesis) for biomedical applications.

Due to such wide variety of applications and multiplicity of technological approaches, processes, and materials associated with it, systematic approaches are needed to help the AM community coalesce and coordinate around strategy development for supporting this emerging technology. A number of supra-firm strategic roadmaps are recently developed around the world, identifying priority actions to accelerate the deployment of AM in various applications as well as technical focus areas (Gausemeier et al. 2013; NIST 2013; Wohlers Associates Inc. 2011; Bourell et al. 2009). For the purpose of this paper, a set of AM-focused roadmaps developed in the US has been chosen for the case study, as a series of roadmapping exercises has been conducted, with varying scopes and levels of analysis, incorporating relevant findings from each other’s previous work. In particular, a recent roadmap developed by NIST (2013) focuses on issues of measurement science and standards, which are very consensus in nature, building on established understanding of various stakeholders to achieve coherence in their technical activities. Hence, AM offers an example of how a series of roadmapping practices can help focus on specific issues of collective interest, taking full advantage of previous foresight analyses. Table 1 lists five roadmaps selected for this case study, from the earliest application of RP to more recent, research and science oriented roadmaps.

[1] Also known as 3-dimensional printing, direct digital manufacturing (DDM), and, rapid prototyping (RP), the last of these because this was one of its earliest applications.
[2] For more information see Gibson et al. (Gibson et al. 2010).

Table 1. AM Roadmaps Reviewed in the Case Study (adopted from NIST 2013; Bourell 2012; Frazier 2010; Bourell et al. 2009)

Case No.	Title	Year	Author / Developing Organisation	Evolving Objective / Focus of Roadmap with Emergence of AM
1	En Route to the Future: A Roadmap from Rapid Prototyping to Advanced Rapid Manufacturing	1994	Advanced Manufacturing Roadmap Working Group of the Department of Energy Laboratories	To map out the future of three critical sectors in the broad area of advanced rapid manufacturing: RP / additive processes, product design, and high-speed machining
2	The Road to Manufacturing: Industrial Roadmap for the Rapid Prototyping Industry	1998	National Center for Manufacturing Sciences	To map out the industry future with focus on RP/AM, for advancing the use and development of RP technologies
3	Roadmap for Additive Manufacturing (RAM): Identifying the Future of Freeform Processing	2009	Bourell et al., funded by National Science Foundation & Office of Naval Research	To identify priority research topics in fruitful areas of AM, for accelerating integration of AM into the marketplace
4	Direct Digital Manufacturing of Metallic Components: Affordable, Durable, and Structurally Efficient Airframes	2010	Naval Air Systems Command & Office of Naval Research	To help the Navy formulate a robust R&D program required to implement DDM of metallic components
5	Measurement Science Roadmap for Metal-Based Additive Manufacturing	2013	National Institute of Standards and Technology (NIST)	To identify measurement / standards challenges & associated R&D needs for the development of metal-based AM systems

Data Collection and Analysis Methods

Qualitative and some semi-quantitative data are systematically collected through archival documents complemented by expert interviews. Documents such as roadmaps and official reports published by developing organisations or governments provide reliable and detailed information on contents and structure of roadmapping practices. Interviews with experts who were involved in roadmapping exercises are carried out to help understand the background which may be difficult to access through document sources alone. Collected information on the practices they employed is then mapped against the baseline model, adding details to each step of the roadmapping process. Throughout the analyses, particular attention has been paid to how existing knowledge is reviewed and used to inform the structure of current roadmapping practices, and the flow of activities to collect, organise, and synthesise relevant information to generate strategies for supporting emerging technologies.

Results, Discussion and Implications

Results from the study of five roadmaps have implications for how roadmapping processes can be structured and managed to support public-level strategy development for emerging technologies as they emerge over time. Based on lessons learnt from the case study, a more systematic and structured process of successive roadmapping exercises is developed, incorporating useful steps and activities adopted in the actual roadmapping practice. This process is summarised in Figure 1; although it appears linear, the actual roadmapping process would be more complex, dynamic, and iterative in nature. However, it is helpful to begin with a structured and rational view based on systems and process thinking (Phaal et al. 2010), hence the following process is proposed, followed by a step-by-step description with examples from the case study.

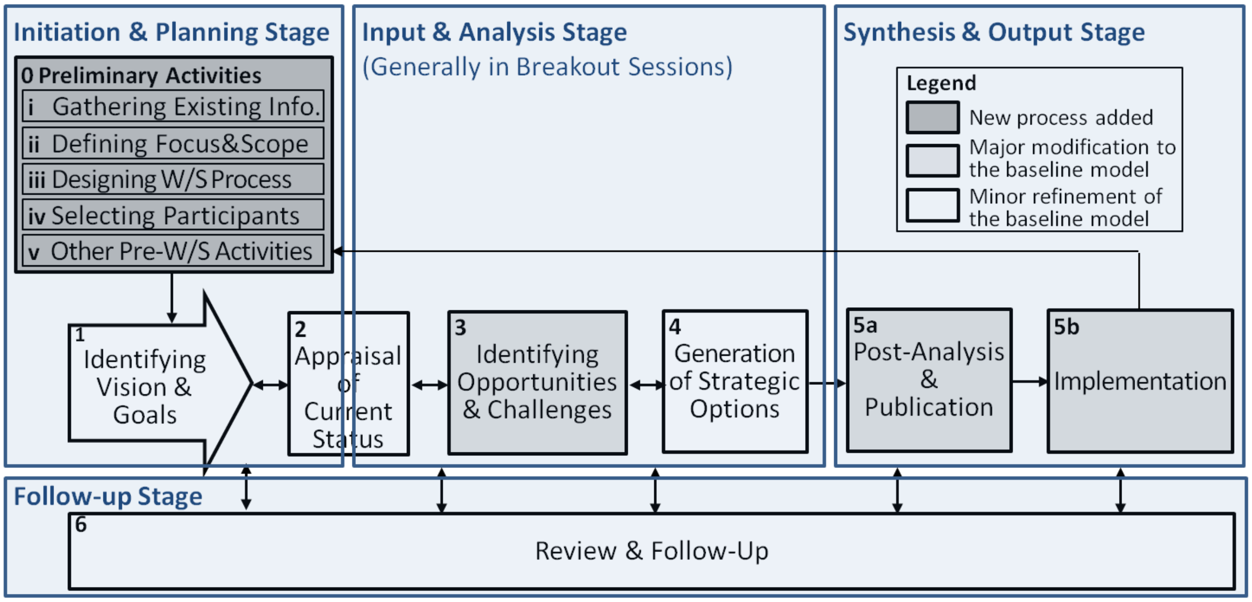

Figure 1. Proposed Process for Structuring Successive Roadmapping Exercises (adopted from Phaal et al. 2010)

Step 0. Preliminary Activities

Although not identified as a separate step in the general strategy process model developed by Phaal et al. (2010), preliminary activities during the planning and initiation phase is repeatedly highlighted in case study analyses as an important first step of developing a roadmap. As workshops often play a key role in the roadmapping process, preliminary activities usually involve planning and preparing for the workshop.

Step 0-i. Gathering Existing Information

Once the objectives and needs for a roadmap are identified, gathering existing information is one of the first activities that need to be done by the organisers, in order to access as much current knowledge and state-of-the-art understanding of the subject as possible. Information is collected from relevant industry reports and previous foresight exercises, and prior roadmapping activities are often used as important basis of the current roadmapping practice. For example, the 1998 roadmap in Case 2 was built on the 1994 roadmap in Case 1 by updating it and adding an industry perspective (Bourell 2012), whereas it, along with reports from World Technology Evaluation Center (WTEC) studies, provided key data points and served as the basis for developing the RAM roadmap in Case 3 (Bourell et al. 2009). The RAM roadmap later became an important source of information for subsequent roadmapping practices in Case 4 and Case 5.

Step 0-ii. Defining Focus & Scope of the Roadmap

The focus and scope of the roadmap is defined, typically highlighting more specific factors for exploration by contrast with previous exercises; findings from previous roadmapping analyses may help refine this focus. One of the first roadmaps developed in the field of AM (in Case 1) focused on three critical sectors of the broad area of advanced rapid manufacturing, one of which was the specific focus of the 1998 roadmap (in Case 2), the RP/AM industry (Bourell 2012). The focus of the roadmap continued to narrow down from broad AM (in Case 3) to metal-based systems of AM (in Case 4) and then to their measurement standards-related issues (in Case 5), of which the importance was repetitively highlighted over several topic areas of the RAM roadmap (Bourell et al. 2014). According to an interviewee who was involved in organising the roadmapping workshop in Case 5, metal-based AM was chosen to focus their efforts and best allocate available resources.

Step 0-iii. Designing Workshop Processes

Designing how the roadmapping workshop is going to be run and executed is an important step during the planning and initiation phase. Workshops with a large number of participants (as in Case 3 through Case 5) adopted breakout sessions, where participants are grouped into different topics depending on their experiences and interests; discussion topics vary depending on purpose of developing a roadmap, but are generally designed according to the themes that appeared to be significant in previous roadmapping exercises, and are later used to structure and organise the final roadmap report. For instance, Case 3 had five discussion groups: design and analysis, processes and machines, materials and materials processing, biotechnology, and energy and sustainability, which became main headings of the final report (Bourell et al. 2009). In each breakout session, information is collected and organised through various methods of brainstorming, discussion, and decision-making. More specific techniques can be utilised to facilitate the discussion; for example, Case 5 employed a tool called storyboarding – the use of boards and index cards to capture and organise thoughts and ideas to quickly identify priorities and pathways for action (NIST 2012).

Step 0-iv. Selecting Participants

The importance of selecting the right mix of participants representing a variety of perspectives has been emphasised by various practitioners (Ho 2014). Roadmapping exercises in this case study also gathered a diverse set of experts from the industry, university, and government. Whereas early roadmaps developed by high-level government initiatives (in Case 1 and Case 2) engaged only a small number of key experts, recent roadmaps in the field of AM were developed based on inputs of a large number of stakeholders involved: 65, 72, and 75 workshop participants in Case 3, Case 4, and Case 5, respectively (NIST 2013; Bourell 2012; Bourell et al. 2009). This may be due to the increased confidence of the community that it is worth to invest their time and resources for mapping out future directions, reflecting the maturity of the emerging technology hence reduced uncertainties, according to an interviewee who has participated in a number of these workshops. It is also noteworthy that the composition of participants varies depending on the focus and purpose of the roadmap; majority of participants in Case 2 were from the industry, whereas more engagement from the research community – though not dominant – was evident in both Case 3 and Case 5, where the purpose of roadmapping was to identify research priorities (NIST 2013; Bourell 2012).

Step 0-v. Other Pre-Workshop Activities

Other preparatory works are needed before holding workshops, including setting agenda, assigning plenary talks, and preparing handouts for workshop information. In addition, participants may be invited to submit 'white papers' prior to the workshop; they were found to be effective throughout the case study, in not only stimulating participants' thinking in advance, but also helping organise workshop processes, such as designing discussion topic areas and refining the roadmap's structure (NIST 2013; Bourell et al. 2009). An organiser of the roadmapping workshop in Case 5 notes that it was also a useful tool of gathering ideas and insights from experts who could not attend the workshop.

Step 1. Identifying Vision and Goals

At the beginning of actual roadmapping workshops, a future vision and goals need to be agreed among participants to establish a common sense of direction of the field. They are often pre-outlined by organisers of the workshop based on findings from previous analyses, then presented as keynote presentations during plenary sessions, followed by discussions among participants (NIST 2013; Frazier 2010; Bourell et al. 2009). Participants may also be asked to validate and, if necessary, amend the goals and objectives of working groups during their breakout discussion sessions, as was the case in Case 4 (Frazier 2010). For more recent roadmaps focusing on particular issues, scopes of the roadmapping activities are also presented at this stage, helping participants focus on specific issues of interest; for example, organisers of the roadmapping workshop in Case 5 recalled giving introductory remarks regarding the roadmap's focus on measurement science and metals-based AM.

Step 2. Appraisal of Current Status

Currently available information is then reviewed to broadly cover present landscape of the field. It can be conducted during plenary sessions where pre-collected data are presented to set the stage for a forum to broadly discuss the current status of the issue (as in most cases), or through discussions during breakout sessions where participants identify current trends and significant milestones in each topic area (as in Case 3) (NIST 2013; Frazier 2010; Bourell et al. 2009). In addition, defining key terminology and vocabulary may help articulate current understanding of the fundamental concepts, so reducing confusion and ambiguity associated with emerging technologies (Bourell et al. 2009).

Step 3. Identifying Opportunities and Challenges

This is the step where significant input is gathered by participants in each working group to analyse external and internal environments of particular topic area. The vision and goals of the subject are revisited if necessary, in order to identify detailed needs and objectives of specific areas in terms of technology, process, performance, or capability of AM (NIST 2013; Frazier 2010). Based on this and information on current status, external factors and internal capabilities are assessed to identify opportunities as well as any challenges, barriers, and gaps associated with achieving the objectives; they tend to focus on particular issues of interest, for example, research agenda in Case 3 (Bourell et al. 2009), or measurement and standards concerns in Case 5 (NIST 2013). These identified opportunities and challenges may be reviewed, clarified, and voted on the priority according to the order of importance and urgency, when appropriate (NIST 2013; Frazier 2010).

Step 4. Generation of Strategic Options

Viable approaches to solve the challenges identified are then discussed during breakout sessions drawing on collective experiences and information; sometimes existing working groups for each topic area are divided into smaller discussion groups to address each priority challenge (NIST 2013). Early roadmaps tend to suggest only high level recommendations and guidelines (Bourell 2012; Bourell et al. 2009); whereas in recent roadmapping exercises, more focused and detailed action plans for future efforts, along with important milestones, results, pathways, potential stakeholders, and their responsibilities, are generated and prioritised, possibly with broad timeframes (NIST 2013; Frazier 2010). Organisers of the roadmapping workshop in Case 5 noted that a smaller scope made generation of detailed action plans possible, focusing on particular issues of interest, such as standards in the case study.

Step 5a. Post-Analysis and Publication

Discussion results of each working group may be summarised and briefed-out before concluding the workshop (Frazier 2010). A post workshop analysis is then performed, so that salient information is packaged in a format suitable for dissemination: a graphical roadmap showing an evolutionary path of the industry in Case 2 (Bourell 2012), a tree model and a list of recommendations for future research in Case 3 (Bourell et al. 2009), time-based layers with action plans for each focus area in Case 4 (Frazier 2010), or lists of action plans for priority challenges in Case 5 (NIST 2013). Final reports may be published and distributed in various forms, including hard copies, CDs, and files uploaded on websites.

Step 5b. Implementation

Strategies developed through roadmapping exercises can be implemented at various levels by different organisations. The 1998 roadmap in Case 2 served a multitude of organisations in the field of AM as an indispensable tool for strategic planning of R&D and technology investments (RPMI 1999). The RAM roadmap in Case 3 was also used by various governmental agencies to guide their own agendas for technology development, including NAMII (National AM Innovation Institute) initiative and DARPA's (Defense Advanced Research Projects Agency) open manufacturing program (Bourell et al. 2014). In addition, the measurement science roadmap in Case 5 not only influenced the selection, prioritising, and timing of standards development at relevant standards committees, but also triggered various activities of both public and private decision makers in furthering the capabilities of AM and accelerating its widespread use in the industry, according to an interviewee. As syntheses of iterative collection of up-to-date knowledge representing various perspectives, they have been also serving as critical sources of information for subsequent roadmapping exercises.

Step 6. Review and Follow-Up

Review and update of the roadmap is very important, as roadmapping is an ongoing learning process, rather than a single, one-off activity. An interviewee noted that once the roadmap is published, participants – and sometimes even non-participants – are given opportunities to review the roadmap for additional input regarding both the contents and process of the roadmapping activities, to support ongoing knowledge management. Organisers of roadmapping workshops often take responsibilities for maintaining and updating the roadmap on a regular basis, but sometimes other relevant organisations are specially assigned these roles, as was the case in Case 2 (Cooper 2001).

Conclusions

A systematic process of successive roadmapping exercises has been presented, that may help develop public-level strategies to support emerging technologies and their innovation. Using a combination of generalised strategy process model and general guideline for roadmapping processes as baseline, the process has been developed through the study of actual strategy processes against this baseline model. A series of roadmapping exercises conducted in the US in the context of AM is selected for this case study, providing information on what specific activities have been undertaken in each step of the roadmapping process. Based on these findings, a more structured process is proposed, introducing effective new process steps, incorporating other useful practices within existing steps, and modifying and refining some of the activities and techniques adopted within existing steps of the baseline model. The study also illustrates evolving trends and patterns of characteristics of these roadmapping processes as technologies emerge, such as the scope and focus being narrowed down, changes in roadmapping participants, and the development of more detailed strategies. These are all important aspects to be considered when designing roadmapping exercises, hence reflected in the proposed process for structuring successive roadmapping.

The proposed process particularly highlights how existing information from previous analyses can be incorporated to inform the development of a more detailed roadmap focusing on particular issues. Information from prior roadmapping exercises and similar foresight analyses may be gathered in advance, providing useful information for structuring and managing the roadmapping workshop, including: identifying scope and focus of the roadmap, anticipating key topic areas, targeted selection of participants, and structuring the workshop and report formats. They can also provide important inputs for analyses, which are necessary for the generation of adequate strategic options. As previous roadmapping analyses are syntheses of collective experiences and state-of-the-art information representing various perspectives, using them systematically and comprehensively can potentially facilitate the current roadmapping process, by significantly enhancing efficiency of the process, confidence of participants, and quality of outputs. Hence, building on existing information from previous works, roadmaps focusing on specific aspects of innovation can be effectively generated with more detailed strategic plans, as emerging technologies develop over time.

In order to provide more practical and generalised guiding principles for successive roadmapping practices, the proposed process needs to be tested and demonstrated in a variety of technical domains. Future research could also involve a close study of roadmapping exercises focusing on particular issues of collective interest, such as standards and regulation.

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