Toward integrated innovation roadmapping: Lessons from multiple functional roadmaps beyond technology R&D[1]

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Abstract

Originally developed for strategic planning and foresight of technological development, roadmapping techniques are increasingly being used to support strategy development for other functional activities of innovation systems (e.g., the development of skills, infrastructure, and standards). While conventional technology roadmaps focus on innovation pathways for technology development, considering other functions as contextual factors explored in less detail, the functional roadmaps dedicated to certain innovation functions (e.g., standardisation) give these functions centrality and greater granularity within the roadmapping architecture. Because different functional roadmaps are developed by different communities of stakeholders with different interests, often using different language, it is challenging to share information and manage knowledge between them. This can result in disconnected and misaligned strategies for complementary innovation efforts which, in turn, increase potential risks of inefficient use of resources and missed opportunities to capture greater value from technology R&D. In order to address these challenges, this paper introduces the concept of integrated innovation roadmapping, which is designed to support the systematic integration and alignment of multiple functional roadmaps. It does so by exploring recent efforts by multi-organisational networks to develop complementary roadmaps for diverse innovation functions beyond

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just technology R&D. By identifying challenges associated with their integration and practical steps to address them, the paper provides guidance on how integrated innovation roadmapping processes can be structured and organised to ensure effective knowledge management and alignment among multiple functional roadmaps.

Managerial relevance statement

This research provides significant managerial implications for strategic planning of innovation, by proposing a foundational concept of integrated innovation roadmapping. It is designed to support the systematic design, integration, and alignment of multiple roadmaps focusing on different functional activities and issues of innovation systems (e.g., technology R&D, workforce development, and standardisation). As these functional roadmaps are usually developed by different communities of innovation actors with different priorities and interests, there are significant challenges of knowledge management (i.e., transfer, translation, and transformation of knowledge) between them, even if they share broader innovation goals and objectives. This research not only identifies these challenges, but also suggests a number of practical steps to address them, by drawing on best practices and lessons learnt identified by the case studies. By supporting more effective information-sharing and increased understanding among a wide variety of participating stakeholders, these steps provide useful guidance for the systematic integration and alignment of diverse functional roadmaps, which, in turn, supports the overall functioning of broad innovation systems. Furthermore, the research highlights that efforts to develop and align various roadmaps themselves also provide useful platforms for networking among broad communities of stakeholders within complex innovation systems, facilitating their further collaboration.

I. Introduction

Roadmapping is one of the most widely used techniques for supporting strategic planning and management of technological innovation, by providing a structured platform that enables various perspectives and issues within an organisation to be aligned [1], [2]. Due to its flexibility and adaptability to suit many different strategic and innovation contexts, roadmapping has also been used for the planning and management of technology development in broader innovation systems, often at national-levels, but also sectoral- or regional-levels [3], [4]. Recently, there is an increasing use of roadmapping approaches to support strategic planning for different activities of innovation systems beyond just technology R&D; for example, roadmaps for standardisation, education and workforce development, and infrastructure development are developed [5], [6]. Many of these issues are partially discussed in conventional roadmaps, which mainly focus on the development, diffusion, and use of technology; however, they are typically framed as contextual factors influencing technology rather than the main focus of interest, thus considered in less detail. Consequently, these conventional technology roadmaps are often insufficient to anticipate the challenges with other 'functional' activities of broader innovation systems, even though these are key activities that are important for building up an innovation system beyond technological R&D [7], [8]. This is particularly the case for many important emerging technologies (e.g., additive manufacturing [9], synthetic biology [10], and smart technologies [6]), which require new workforce capabilities, new standards and regulations, and new infrastructure for effective development and use of overall innovation systems.

Hence, there are increasing developments of dedicated roadmaps that specifically focus on particular functional activities and issues of innovation systems (e.g., the development of skills, infrastructure, and standards). Because of the systemic, collaborative, and thus relatively public-good nature of these functional issues, relevant roadmaps are often developed by multi-organisational networks involving diverse public- and private-sector actors (e.g., [11]–[14]). Existing in diverse forms, such as membership-based intermediate R&D institutes, standards organisations, and public-private

partnerships, these networks are often formed from the partnership of multiple organisations to address innovation system challenges beyond just technology R&D (e.g., education, standardisation, and infrastructure development). As different networks engage different communities of stakeholders interested in particular system challenges when developing relevant specialised roadmaps, these roadmaps give certain functions (e.g., skills development) more centrality and greater granularity than conventional technology roadmaps. Different dedicated roadmaps thus have completely different dimensions and units of analysis within the roadmapping architecture, often using different terminologies and jargons.

These differences in roadmapping structure and language suggest that it may be difficult to effectively exchange and manage knowledge across multiple roadmaps that focus on different functional activities of innovation systems. This increases the challenges in the alignment and synchronisation between diverse functional activities in terms of their timing and approach, even if relevant communities involved share broader innovation goals and objectives. This, in turn, may result in significant coordination problems, such as duplicated investment of resources and misaligned activities between different communities of innovation actors, all of which weaken the overall functioning of the whole innovation system. Despite such challenges, there are limited studies exploring the issue of integrating and aligning multiple complementary roadmaps that focus on various functions of technological innovation systems.

In order to address this research gap, the current paper proposes the concept of 'integrated innovation roadmapping', by analysing the challenges associated with, and effective solutions of, the systematic integration of multiple dedicated roadmaps that focus on different innovation functions. A preliminary conceptualisation is first proposed in section II, by reviewing existing studies on roadmapping, which increasingly incorporates various innovation functions beyond technology R&D due to the progressively complex and systemic nature of innovation. In order to explore diverse challenges of managing knowledge across multiple roadmaps, case studies of recent roadmapping exercises

conducted by multi-organisational networks are carried out, based on document analyses and expert interviews introduced in section III. The case studies help identify various challenges associated with the systematic integration of multiple dedicated roadmaps (i.e., challenges in knowledge transfer, translation, and transformation), and also suggest practical steps that can be taken to address them, as discussed in section IV. So allowing further development of the concept of 'integrated innovation roadmapping' (as presented in section V), the current research provides theoretical implications for technology and innovation roadmapping literature, as well as practical contributions to effective foresight of various functional activities within broader innovation systems.

II. Literature Review

A. Recent trends towards innovation roadmapping

Technology roadmapping has become one of the most widely used management and foresight techniques for supporting technology and innovation strategy, by providing a platform that supports the dialogue necessary to develop and implement the desired innovation [1]. While there are various types of technology roadmaps with diverse purposes and in varying forms, they generally comprise visual time-based, multi-layered charts, enabling various functions and perspectives within an organisation to be mapped and aligned [2]. In particular, the general structure of roadmaps consists of three broad layers representing interests and concerns of key stakeholder groups participating in conventional technology roadmapping – i.e., marketing and sales groups concerning business environment (i.e., market), product development groups concerning products and systems to respond to market needs, and research groups concerning scientific and technological research required to develop them, respectively [15]. Because technology roadmapping allows effective visualisation and communication of how technological research can be aligned with product development and market opportunities, it provides a powerful technique for supporting technology management and innovation planning within corporate organisations.

As processes of technological innovation become more complex and depend on internal as well as external innovative activities and resources of firms and other actors, roadmaps are increasingly developed to focus on the broader contexts of innovation systems, involving various stakeholders from multiple organisations [16]. Flexibility and scalability of roadmaps allow them to overcome challenges introduced by multidimensional and complex characteristics of innovation, so enabling greater understanding of diverse contextual forces [17]. They thus include not only wider socio-economic elements that influence technological innovation beyond market drivers, including social institutions such as regulations and standards [18], but also underlying infrastructure that supports broad innovation activities, including financial and human resources [16]. Given the changing nature of innovation which depends on competing or complementary technology bases to meet converging or multiple market needs, extended perspectives of market and technology beyond the conventional scope may also be included [19]. Hence, such higher-level innovation roadmaps are increasingly being developed, incorporating broader perspectives representing diverse contextual aspects and functional issues of innovation systems than conventional technology roadmaps, as illustrated in Fig.1.

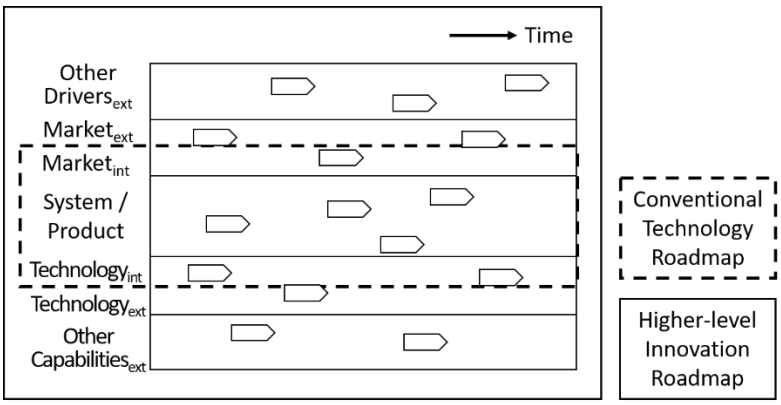

Fig. 1 Higher-level innovation roadmap focusing on broader contexts of innovation systems

B. Increasing development of specialised roadmaps focusing on certain innovation functions

As such broader innovation roadmaps are becoming increasingly complex with progressively complex modern technologies, it is significantly challenging for these roadmaps to be used by stakeholders who might only be interested in certain contextual issues of the innovation system. As a

result, specialised roadmaps are recently being developed, specifically focusing on particular functional activities and issues of innovation systems beyond just technology R&D. In particular, there are growing uses of roadmapping approaches to focus on innovation system issues such as regulations, standards, workforce, and infrastructure, as there are increasing challenges associated with these systemic issues that cannot be solved by a single organisation alone [5]. For example, with the increasing importance of standardisation in supporting innovation by facilitating interoperability within complex technological systems, some standards-related organisations have developed standardisation roadmaps to identify emerging standards needs and develop relevant strategies [6], [11], [20]. In emerging areas where there is a high level of complexity involved in underlying infrastructure, such as intelligent cities and smart transportation, roadmapping has also been widely adopted by relevant public-private partnerships for the planning of diverse physical, knowledge, and financial infrastructure development necessary to support innovation systems [12], [21]. In addition, a number of Manufacturing USA institutes (i.e., a network of research institutes formed through public-private partnerships among US industry, universities, and federal government agencies) have recently developed roadmaps to address increasing challenges with education and training required for radically changing innovation systems of manufacturing technologies [13], [14].

Although these specialised roadmaps share similar architectural characteristics and visual formats with those of conventional technology roadmaps, they are fundamentally different roadmaps with different emphases and scope of the issues being addressed [5]. While conventional technology roadmaps focus on exploring innovation pathways for technology development, framing other innovation activities as contextual factors to a limited extent, roadmaps focusing on particular innovation functions (e.g., skills development) give these functions centrality and greater granularity within the roadmapping architecture. The specialised roadmaps thus have different format, dimensions, and units of analysis, all of which are defined in terms of primary issues and perspectives (i.e., particular aspects or functions of innovation systems) that they focus on. Although some of these issues

overlap (e.g., issues regarding technology R&D are often discussed in other dedicated roadmaps to some extent), the level of detail included in specialised roadmaps are all different from each other, as they are developed by different networks involving different stakeholders with different interests and goals. Different roadmaps also tend to use different terminologies and vocabularies that are used by different communities of stakeholders developing them.

C. Needs for, and challenges associated with, integrated innovation roadmapping

The differences in roadmapping structure and terminology suggest potential challenges in sharing information between, and managing knowledge across, multiple dedicated roadmaps with highly complex boundaries between them. Because of the relational properties of knowledge at a boundary across specialised domains – i.e., difference, dependence, and novelty – actors participating in these roadmapping exercises might need to develop adequate common knowledge to share and assess each other's domain-specific knowledge [22]. The integrated framework for managing knowledge across boundaries (as shown in Fig. 2) identifies progressively more complex processes (i.e., transfer, translation, and transformation) of knowledge management required for increasingly complex (i.e., syntactic, semantic, and pragmatic) boundaries [23]. At the bottom of the inverted triangle, domain-specific knowledge can be efficiently transferred across a syntactic boundary using a common lexicon. As novelty arises at a semantic boundary, a process of translating domain-specific knowledge establishes common meanings that are adequate for the actors to share and assess their knowledge. When a pragmatic boundary is faced with the increasing novelty, negotiating and transforming knowledge is required to develop common interests that allow actors to address the consequences, differences, and dependencies of each other's domain-specific knowledge. Increasing efforts to develop an adequate level of common knowledge may thus be required to ensure the effective knowledge management across multiple specialised roadmaps developed by different multi-organisational networks with different terminology and interests.

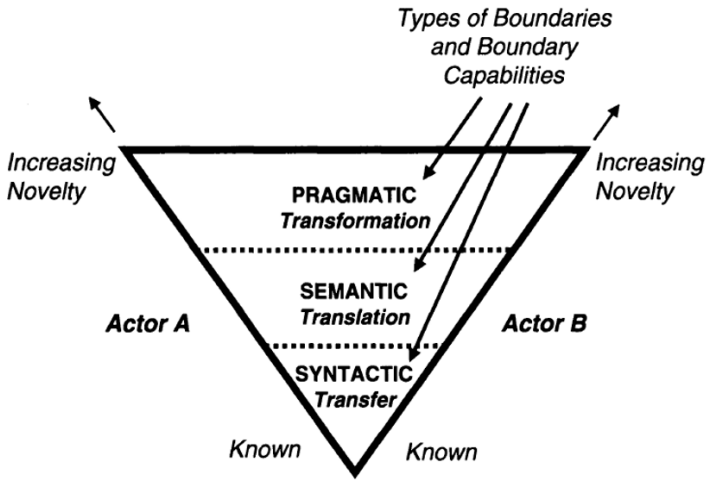

Fig. 2 Integrated framework for managing knowledge across boundaries [23]

Despite such challenges, it is important to ensure the effective knowledge management across multiple specialised roadmaps, as this can potentially enhance the performance of the overall innovation system. Existing literature on knowledge management advocate rich information exchange across organisational boundaries as important sources of innovation, as it generates synergy and leveragability [24], and also provides a basis of timely decision making and conflict resolution [25]. It can further allow the systematic integration and alignment between multiple roadmaps, ensuring that different activities across broader innovation systems are aligned and synchronised with each other in terms of timing and approach [26]. So allowing more coordinated and coherent strategic plans, where differing roles and responsibilities among diverse stakeholders are established and the timing of their activities are managed to avoid any gaps or overlaps, it can lead to efficient investment with minimum duplication of resources (including capital, human, knowledge, and other infrastructure).

Nevertheless, there are limited research on the systematic integration of multiple roadmaps focusing on diverse innovation functions and associated challenges in knowledge management. While some studies highlight the needs for roadmapping in broader innovation networks as progressively complex technological systems require networked partners to align their innovation activities [24], [27], [28], they are still mostly focused on the collaboration around technology R&D across networks of supply chains, rather than coordinating diverse innovation functions beyond just technology R&D. Possibly

due to such research gap, a wide variety of incompatible strategic documents and associated roadmaps, developed independently by different groups of stakeholders, are increasingly being observed in practice (e.g., [29]). Significant coordination problems may thus arise from such disconnected and misaligned roadmapping exercises. For example, the lack of appropriate workforces with new skills and knowledge to exploit novel technologies newly developed from R&D will result in structural and temporal mismatches between the stocks of physical and human capital, weakening the overall functioning of innovation systems [30]. In order to address such problems, the current paper proposes the concept of integrated innovation roadmapping, which supports the systematic integration and alignment of multiple specialised roadmaps focusing on diverse innovation functions, through effective management of knowledge across them.

D. Preliminary conceptualisation of integrated innovation roadmapping

Drawing on existing literature on technology roadmapping as well as recent practices of innovation roadmapping (as discussed in previous sections), Fig. 3 represents the preliminary conceptualisation of integrated innovation roadmapping. These complementary roadmaps, also called *(dedicated) functional roadmaps*, focus on particular systemic issues or themes that are usually represented as a single layer in the higher-level, *(integrated) innovation roadmap* incorporating broad contexts of innovation systems. A bidirectional arrow indicates the systematic integration and alignment between them, allowing the harmonisation of diverse functional activities and synchronising their timing across multiple roadmaps, so facilitating overall innovation systems.

In order to further develop this conceptualisation, the current study aims to investigate diverse challenges associated with the systematic integration of multiple functional roadmaps, with particular focus on sharing and management of knowledge across them. By analysing what challenges exist and what practical steps can be taken to address them, effective practices of integrated innovation roadmapping may be proposed. It can then provide more informed guidance on how to systematically

design, integrate, and align multiple roadmaps focusing on different innovation functions, so enhancing the overall functioning of innovation systems.

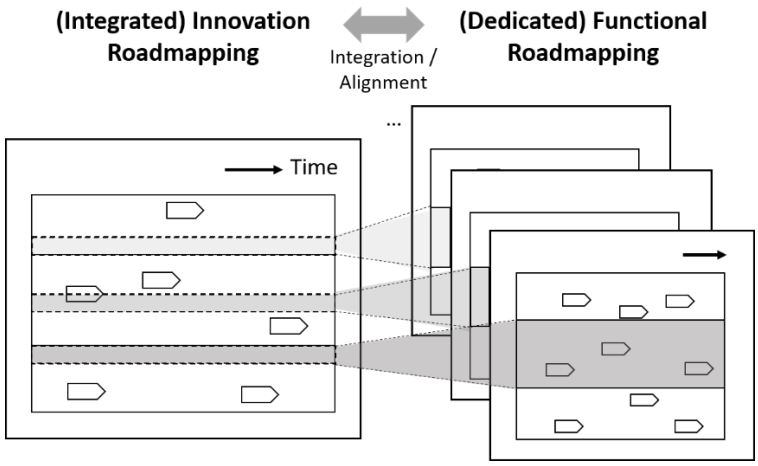

Fig. 3 Preliminary conceptualisation of integrated innovation roadmapping

III. Research Methods

A case study approach was used to develop the novel concept of integrated innovation roadmapping, as it allows the researcher to develop clearer and richer insights into a relatively new phenomena based on multiple sources of data [31]. A variety of roadmaps published online are first explored to identify appropriate cases for analysing various knowledge management challenges associated with the systematic integration of multiple functional roadmaps, along with practical steps that can be taken to address them. Seven cases of recently conducted roadmapping exercises that focus on diverse systemic issues beyond just technology R&D (such as education and workforce development, infrastructure development, and standardisation) have been finally selected for case studies (see Table 1 for detailed case profiles). Developed by various types of multi-organisational networks and spanning across diverse industries and innovation functions, these cases provide rich variations in terms of functional issues, network characteristics, and industrial contexts, so allowing the researchers to explore diverse challenges associated with practices of integrated innovation roadmapping.

Table 1. Profile of roadmapping cases studied

Case #	Year of Roadmap Publication	Location of Networks	Type of Networks	Industry	Innovation Functions addressed (other than Technology R&D)	Purpose of Roadmapping	Roadmapping Methods	Participants of Roadmapping
1	2017	US	Intermediate R&D institute	Sensors / Digital Controls	Workforce Development, Platform Infrastructure, Business Practices	To accelerate the development and adoption of advanced sensors and controls to enable smart manufacturing	Interactive virtual workshops	Over 100 experts (from industry, academia, research institutes…)
2	2017-2018	US	Intermediate R&D institute, Standards organisation	Materials / Material Processing	Workforce Development, Standardisation	To facilitate the development of additive manufacturing technology through aligned and collaborative projects and initiatives	Multi-phased workshops (online & face-to-face)	Over 180 member organisations (industry, academia, federal agencies…)
3	2018	US	Intermediate R&D institute	Biotechnology / Material Processing	Workforce Development, Regulatory Science & Standards	To accelerate biopharmaceutical manufacturing innovation, support the development of standards, and educate a world-leading workforce	Series of workshops (online & face-to-face)	Over 200 experts (from industry, academia, federal agencies…)
4	2017	US	Intermediate R&D institute	Chemical Processing	Education & Workforce Development	To establish high impact project portfolio & education programs for effective deployment of modular chemical process intensification	Series of workshops (online & face-to-face)	Over 100 experts (from industry, academia, federal agencies…)
5	2014-2015	UK	Public-private partnership	Transportation	Infrastructure	To provide a framework to help plan and coordinate technology developments that meet the goal of decarbonising transport	Series of multi-phased workshops	Over 200 members (manufacturers, suppliers, public organisations…)
6	2012-2017	Europe	Public-private partnership	Transportation	Infrastructure	To explore opportunities and challenges in the move of Europe towards the electrification of road transport	Series of workshops & plenary meetings	Over 200 experts (from industry, academia, public organisations…_
7	2009-2016	US	Standards organisation	Energy	Interoperability Standards	To coordinate development of a framework and standardisation activities to achieve interoperability of smart grid devices and systems	Series of workshops & plenary meetings	Over 1000 experts (from industry, academia, standards organisations…)

Case studies have been performed in two rounds of iteration for increased validity; cases 1 through 4 were first studied in-depth, then cases 5 through 7 were explored using mainly secondary sources and phone interviews for the purpose of verification. For both rounds of case studies, mostly qualitative data were collected through desk research and expert interviews. Many of documents, such as roadmaps, official reports, and brochures, were collected from online, but some documents that are accessible to members only were also obtained from interviewees. They provided detailed and accurate information about the roadmap outputs. Triangulation using multiple sources of data also enhanced the credibility of case study research.

Interviews, on the other hand, helped understand the background and details of roadmapping procedures, which may be difficult to access through document sources. Twenty experts, who either managed the roadmapping exercises in responsible networks, or helped facilitate the roadmapping processes as external consultants, participated in semi-structured interviews (see Table 2 for details of these interviews and interviewees' profiles). They were asked to remark on their roadmapping exercises, needs for integrating multiple roadmaps, associated challenges and issues, and any useful practices to help address them. Focus group, face-to-face interviews were preferred wherever possible (as opposed to individual, or phone interviews), in order to benefit from rich insights generated from in-person interactions as well as triangulation of data obtained from interviewees.

Most interviews lasted about an hour; were recorded and subsequently transcribed for analysing natural language data. The first author read interview transcripts line-by-line to highlight the sentences that could add detailed information regarding challenges and issues with the systematic integration of multiple functional roadmaps, as well as practical steps to address them. Together with data obtained from desk research, they were first content-analysed using dimensions from the integrated framework for managing knowledge across boundaries developed by Carlile [23]. A more detailed coding scheme was created using emergent coding techniques, by moving back and forth between the coding rule and the data under examination. In order to increase the validity of case analyses, the authors held a series

of brainstorming and discussion meetings to triangulate multiple viewpoints in analysing the data and produce findings that accurately represent the data. The next section presents the findings that were repetitively identified across multiple cases investigated in the first round of case studies and also verified in the second round.

Table 2. Interviews conducted and interviewees' profiles

Case	Interview Type	Interviewee's Position
Case 1	Individual interview (phone)	Senior Manager
	Individual interview (face)	Senior Manager
	Individual interview (face)	Consultant
Case 2	Focus group (face)	Senior Manager, Senior Manager, Manager
	Focus group (face)	Consultant, Consultant
	Individual interview (face)	Senior Manager
Case 3	Individual interview (face)	Director
	Individual interview (phone)	Consultant
Case 4	Focus group (phone)	Manager, Manager
	Focus group (face)	Manager, Director
Case 5	Individual interview (phone)	Consultant
Case 6	Individual interview (phone)	Senior Manager
Case 7	Individual interview (face)	Deputy Director
	Individual interview (phone)	Senior Manager
	Individual interview (phone)	Consultant

IV. Results and Findings

A. Knowledge management challenges with the integration of multiple functional roadmaps

While there have been no explicit efforts specifically aimed for the systematic integration and alignment of multiple functional roadmaps, needs for such integration were increasingly being observed in recent roadmapping practices to ensure effective innovation systems. Managers in cases 2 and 4 highlighted the importance of adequate educational programmes aligned with the development of new technologies, in order to develop human resources equipped with the right set of knowledge

and skills to use them. The director of case 3 also noted an illustrative example of delayed opportunities for innovative products, when appropriate regulatory measures are not in place to give health authorities confidence regarding the quality of products.

Despite increasing needs for the systematic integration and alignment of multiple functional roadmaps, the case studies revealed that there are numerous challenges associated with managing knowledge across these roadmaps. Using the integrated framework for managing knowledge across boundaries developed by Carlile [23], these challenges can be grouped into three major categories (i.e., transfer, translation, and transformation of knowledge); these are summarised in Table 3.

Table 3. Challenges and issues with systematic integration/alignment of multiple functional roadmaps identified from case studies

Challenges / issues associated with	**Due to…**	**Reference (Case #)**						
		1	2	3	4	5	6	7
Knowledge transformation	Large number of participants from diverse backgrounds / organisations	X				X	X	X
	Different goals / objectives / motivations of different organisations represented by multiple participants	X			X		X	X
	Strategic orientations that prevent open communication / willingness to share information		X			X		X
Knowledge translation	Different terminology / jargon used by different community with different expertise / background	X	X				X	X
	Different understanding / perspective of the industry by different stakeholders		X			X		
Knowledge transfer	Narrow / specific focus of expertise / interests of individual participants of functional roadmapping	X		X	X			X
	Large amount of information collected from multiple roadmapping exercises		X			X	X	X
	Different structure / framework of functional roadmaps, resulting from different issues / characteristics of different innovation functions		X		X			
	Rapid development of technologies, compared to systemic functions of innovation			X			X	

The development of systematically integrated roadmaps requires transformation of knowledge to

effectively share and assess knowledge among roadmapping participants who may have different interests to be resolved. The challenges mainly arise from the high level of novelty across a large number of participants, who are engaged in overall processes of developing multiple roadmaps that focus on various functions of technological innovation systems (e.g., technology R&D, education, regulation, and standardisation). An interviewee from case 6 noted that "it's a huge challenge… when you have challenges that are systemic, you have to bring together different kinds of expertise. And those people have such different perspectives on [these] challenge[s]." As they are from different organisations and backgrounds, they also have different self-serving interests and motivations, which may create tensions or even competitions between stakeholders trying "to steer a roadmap in a particular direction," as noted by a manager in case 7. In the context of multi-organisational networks, participants from different organisations may also be reluctant to share sufficient information due to strategic reasons. These all add to the challenges of knowledge transformation to negotiate diverse interests of participants and create common interests among them.

Such diverse participants from different backgrounds may also result in challenges of knowledge translation to establish common meanings, as they may have different interpretations of the same terminologies, based on different perspectives and understandings. A manager in case 7 recalled "because you would have one group that would be talking about something and using a particular term, but the term might have a completely different meaning to another group… you weren't really communicating. You were talking at each other but there wasn't a common understanding of what you were saying." The problem of different vocabularies spoken by different groups of experts are particularly significant, as modern technological systems are becoming increasingly complex and convergent in nature, requiring a high level of collaboration among experts that used to work in completely different technical domains (e.g., network developers and automobile manufacturers working together to develop infrastructure for smart transportation).

In addition, there are challenges of knowledge transfer to create a common lexicon, which is essential

for the coordination and harmonisation of diverse innovation activities across multiple roadmaps. In order to enable efficient transfer of outputs, it is important to establish differing roles and responsibilities among participating organisations and manage the timing of their activities to avoid any gaps and overlaps in assigned work. However, it is challenging for participants to have such discussions, as they are often confined in their narrow and specific areas of expertise, rather than being able to connect with other relevant topics and issues. Additional issues of knowledge transfer exist due to a large amount of information collected from multiple roadmapping workshops, and thus organised in different roadmap structure and format; much of these information also become quickly outdated, due to the rapid development of modern technologies.

B. Practical steps to address the identified challenges of knowledge management

The case studies also revealed how these challenges of knowledge management can be addressed, allowing the systematic integration and alignment of multiple functional roadmaps developed by various multi-organisational networks. By closely examining specific activities undertaken in existing roadmapping exercises, as well as drawing on lesson learnt from interviewees' experiences, eight practical steps for the integrated innovation roadmapping are suggested. Grouped into four main stages of overall roadmapping processes (i.e., exploratory high-level roadmapping, dedicated functional roadmapping, combined innovation roadmapping, and overall project management), these are summarised in Table 4. Table 4 also highlights how each of these practical steps address specific challenges of knowledge management (i.e., transfer, translation, and transformation of knowledge), using the integrated framework for managing knowledge across boundaries developed by Carlile [23]. Although they do not completely address all associated challenges and issues, they provide further insights and implications for how such integrated innovation roadmapping can be designed and structured for effective foresight of increasingly complex technological systems.

Table 4. Practical steps for integrated innovation roadmapping suggested from case studies

Stage	Practical steps	To address challenges / issues mainly associated with…			Reference (Case #)						
		Knowledge transformation	Knowledge translation	Knowledge transfer	1	2	3	4	5	6	7
(Exploratory) High-Level Roadmapping	1) Define overall vision / impact objectives	X			X	X		X	X		X
	2) Develop a high-level roadmap as a reference point			X	X	X	X				X
	3) Define common terminology / system architecture		X		X	X				X	X
(Dedicated) Functional Roadmapping	4) Use consistent roadmap structure / format			X	X	X	X	X			
	5) Develop linking taxonomy / typology as appropriate		X		X			X			X
(Combined) Innovation Roadmapping	6) Cross-check to identify interrelationships / linkages		X		X	X	X	X		X	
Overall Project Management	7) Keep living documents through continuous revision / update	X	X	X		X	X	X	X	X	X
	8) Engage professional facilitators / field experts in management teams	X			X	X	X	X	X	X	

1) Define overall vision and impact objectives

From early stages of the roadmapping exercise, it is important to clearly define the overall vision and impact objectives of what diverse stakeholders want to achieve in common, in order to ensure a shared understanding of where this is going to and how it will influence the overall innovation system. As the

majority of stakeholders participate in developing a particular functional roadmap only, they tend to pursue the interests of promoting certain innovation functions. There are thus potential risks of roadmapping exercises heavily driven by particular interests of certain stakeholder groups, resulting in significant challenges of knowledge transformation during the collaboration and alignment of multiple functional roadmaps.

Identifying the common vision and impact objectives helps create common interests to develop more aligned and integrated roadmaps, so ensuring initial buy-in to the collaboration from stakeholders with diverse interests. "By emphasising that only the collective group can come up with a collaborative strategy that is more effective than what one organisation can accomplish alone (consultant, case 1)", participants have clear understanding of the value of, and their roles in, developing a cohesive roadmap. Such understandings not only encourage their active participation, but also keep them on track of coherent discussions. So facilitating knowledge sharing across boundaries between multiple roadmaps, identifying the overall shared vision helps address the challenges associated with the transformation of knowledge across diverse stakeholders involved.

Preliminary activities may be required to define preliminary vision and objectives, as it may be challenging to reach a consensus among diverse participants with different expertise and interests from scratch. In case 5, the manager prepared diverse materials that lead to a starting point for the discussion where people can bring their own ideas into and build on a more concrete vision, instead of having too open questions from the beginning. Various activities, such as literature review, survey, and expert interviews, can be conducted to develop such preliminary vision and objectives in advance.

Defining performance metrics to measure the impact and effectiveness of the roadmapping exercise may also be helpful in defining clear targets to achieve the overall vision and objectives. In cases 1 and 2, metrics were used for effective prioritisation and sequencing of diverse activities on multiple roadmaps, as well as their appropriate revision and update through relevant assessment and evaluation

of the progress made over time. A consultant also noted that this increases the long-term sustainability of roadmaps, by allowing participants to see the value and impacts of their contribution, so encouraging their continued engagement, which is a significant challenge in the context of multi-organisational networks. According to the manger in case 5, quantitative metrics based on modelling were particularly useful, providing clarity and objectivity.

2) Develop a high-level roadmap as a reference point

Drawing a high-level roadmap for the overall technological system can be useful to achieve the identified vision and impact objectives of the industry, by helping participants of individual functional roadmapping see how their interests fit within the larger whole. While they tend to narrowly focus on issues relevant to their own specialty or expertise in particular functional roadmaps, the high-level roadmap provides them a broad overall picture of how diverse innovation functions and relevant issues may be related to each other. Hence, it becomes a useful reference point of communication, where individual participants can continually refer back to position the topics of their interests within broader contexts, helping them to visually connect the dots, noted the manager in case 3. The consultant involved in case 3 also highlighted that "without that [broad] landscape, the scope of the topic [for each team] would be very difficult to control, and they'd lose similarities between themselves… so the wide industry-level landscape was essential [to achieve coordinated and coherent outputs]." So guiding overall project management through more effective communication, alignment of diverse interests, and coordination of their activities, the development of a high-level roadmap helps address the challenges associated with knowledge transfer among participants from diverse backgrounds.

Such a high-level roadmap may be developed and revised at any stages of the roadmapping exercise as necessary, embracing both future and any existing roadmaps that have already embarked on. But it is often suggested to be drawn in early stages, where small groups like the most senior executives are gathered for high-level visioning and goal setting; it can then be followed by multiple roadmapping

activities that pull in more people to contribute, confirm, add, and ultimately act upon individual roadmaps, each dedicated to particular functional activities or issues of innovation systems (consultant, case 1). In fact, most of the cases studied often started by drawing some types of high-level roadmaps that provide a broader picture of how functional roadmaps may fit within an overall industry. For example, managers in case 2 highlighted that the development of an education and workforce development roadmap actually started by developing the relevant technology roadmap, where a small number of education and workforce-relevant elements were initially incorporated in a single layer at the bottom (as a contextual factor), before growing into a separate roadmap.

3) Define common terminology and system architecture

In order to address the challenges of knowledge translation among participants from diverse organisations, backgrounds, and technical domains, it is important to define common vocabulary and terminology at early stages of roadmapping. This is because ontologies are developed very specific to the particular organisation or industry sector, often requiring these wide varieties of participants to possess the contextual knowledge to adequately interpret and communicate with each other [24]. A manager in case 6 noted that "when we started that roadmap, [participants were] speaking about using the same word but meaning really different things. And the roadmap started really by agreeing [on] a common definition. [It was] the first chapter and first task... and then you can develop everybody to understand in the same way." Interviewees from cases 1, 2, and 7 also identified a wide variety of technical language and jargons used in multiple functional roadmaps as significant barriers to communication, leading to disconnected and uncoordinated roadmapping activities. Common definitions would reduce potential risks of such misalignment between multiple roadmaps, by creating shared meanings between diverse groups of experts and thus facilitating their communication.

Defining an architectural framework of the system can also support the communication and knowledge translation among various stakeholders from different disciplines, as adopted in case 7. As

modern technological systems increasingly consist of a wide variety of entities and subsystems from diverse technical domains, such system architecture provides a useful reference model describing the overall structure of, and interrelationships within, complex systems. Thus allowing diverse activities and elements of the system to be described with reference to common architectural frameworks, it promotes cross-domain communication and knowledge exchange, both of which facilitate the systematic alignment and integration across multiple roadmaps.

In addition to such technical issues, a consultant involved in case 1 also highlighted needs to define key terminologies often used in roadmapping exercises, such as goals, objectives, targets, and pathways, which might be interpreted in slightly different ways by different participants, adding additional confusion and ambiguities.

4) Use consistent roadmap structure and format

Informed by the common architectural framework of the systems, using consistent format and structure during the roadmapping workshops can help promote the systematic integration of multiple functional roadmaps. By facilitating structured discussions where participants with diverse interests can share information and other resources in a collaborative manner, it helps address challenges of knowledge transfer across various stakeholders, as well as associated communication between them. This is shown in cases 2 and 3, where consistent topics and themes for discussion across multiple roadmapping workshops assisted the process of collecting diversity of information sources in a systematic way.

Coherent structure and format of roadmaps were also helpful to manage chains of activities across diverse innovation functions and streamline cross-functional collaborations, by developing a common lexicon for transferring knowledge across multiple roadmaps. Helping organise, synthesise, and consolidate a large amount of information integrated into a cohesive framework, they facilitate the coordination between diverse activities and issues dispersed across multiple functional roadmaps. As

noted by a manager in case 2 "as long as you collect information in a standardised way, then you are able to better [put it back], and align with [other] elements of the roadmap." According to a manager in case 4, "people were thinking a lot around these categories, and it [the categories] helped them develop [coherent] roadmaps… it may also be useful when we present all the materials together [later on]."

On the other hand, inconsistent structure and format between early roadmaps developed in cases 2 and 6 were major challenges for their alignment and synchronisation, as it was difficult to integrate, or even identify potential linkages between, diverse information organised in different ways in different functional roadmaps. A manager in case 2 noted how they couldn't "utilise the [consistent] structure as much as [they] would have liked to… [partly] because it was difficult to get people agree on terminology," highlighting the importance of common terminology in achieving consistent structure and format across multiple roadmaps.

5) Develop linking taxonomy and typology as appropriate

Despite its usefulness, it is not always feasible to have identical structure and format across various functional roadmaps, as detailed categories and layers of each roadmap framework may need to vary to suit their different functional characteristics and needs. For example, the technology roadmap and the standardisation roadmap in case 2 required slightly different formats, as they addressed different topical areas, focusing on different issues of relevance. Sometimes, different structure and format may result when certain roadmaps evolve faster than others, as new knowledge is soon gained to revise the premature roadmaps that were initially developed without thorough knowledge of the field. For instance, managers in case 2 and 3 noted that structure and format of technology roadmaps tend to evolve at faster rates than those of regulatory science or education and workforce development roadmaps, both of which usually have longer lifecycles of revision.

In such instances, developing appropriate typology or taxonomy that help link different categories or

layers of different functional roadmaps may be useful, as suggested by interviewees in cases 4 and 7. By clearly identifying any potential relationships and interactions between them, such typology or taxonomy can facilitate the knowledge translation between multiple roadmaps having different structure or format, so supporting their systematic integration and alignment. They can also be more easily revised or updated than entire roadmaps, facilitating the overall knowledge management across multiple functional roadmaps, even when the structure and format of certain roadmaps are revised with the accumulation of new knowledge of the field. Consultants involved in cases 1 and 4 noted that preliminary activities to gather information about state-of-the-art of technology and industry landscapes (e.g., literature review, survey, and interviews) may be useful in developing appropriate structure and format of functional roadmaps, as well as taxonomy and typology that link them.

6) Cross-check to identify interrelationships and linkages

In order to integrate diverse activities and issues that are scattered across multiple functional roadmaps in a systematic way, the interrelationships and linkages among them need to be identified during the combined innovation roadmapping. Consistent format and structure across multiple roadmaps would be useful for such cross-checking, by providing a standardised way of collecting, organising, and overlaying information during individual roadmapping exercises. However, an additional cross-checking session is also needed to identify any unobvious linkages and interdependencies that could have been overlooked during individual functional roadmapping. By allowing additional communication and knowledge translation across diverse participants involved in individual roadmapping, it not only helps avoid any gaps and overlaps in planned activities, but also ensures their effective coordination and knowledge management across diverse functional roadmaps.

This cross-checking can be done by a small group of representatives from each working group of individual roadmapping (as in cases 1 and 4), but additional inputs from experts at more senior levels, who can really understand connections between diverse functional issues within broader innovation

systems, can also provide valuable information (as in case 4). On the other hand, consolidation workshops with a larger group of participants from all roadmapping sessions can be helpful to identify any unexpected linkages or cross-cutting issues, by facilitating wider communications across interfaces between different functional issues (as in cases 3 and 6). Either way, in-person meetings or workshops are strongly suggested; a consultant involved in case 3 noted that "face-to-face meeting allows enormous progress within a couple of days, compared to tele-conference… it can get through works much quicker effectively." By promoting active discussion and interaction among participants, these meetings nurture the culture of open communication and information sharing, which are critical for the success of roadmapping. When such in-person workshops are not feasible due to a large number of stakeholders, surveys might be useful to complement smaller meetings with key representatives only, helping gather additional feedback from wider stakeholders involved.

Case studies also identified a number of techniques and tools that can be used during the cross-checking session to facilitate the identification of linkages and interdependences among diverse functional issues within broader innovation systems. A manager involved in case 1 noted how colour-coding of elements in functional roadmaps was an effective tool "to identify complex interactions and linkages, and also to manage and coordinate those [diverse functional] activities" that are closely related with each other. Consultants in case 2 emphasised how the visual analytic approach of roadmapping (as opposed to text-based approach) was helpful to explore additional interfaces and linkages, by allowing effective representation of how different pieces may actually be aligned with each other. In case 4, providing participants with more information (e.g., completed individual functional roadmaps) before consolidation workshops led to more productive discussions, by engaging their thinking in advance rather than thinking on their feet.

7) Keep living documents through continuous revision and update

Both individual functional roadmaps as well as the combined innovation roadmap need to be

continuously revised and updated, in order for them to be kept as living documents that are not outdated. As noted by a consultant in case 1, "it doesn't necessarily need to be a full process to be done from scratch, but assessing what still applies, what has been done, what still needs to be done, [and] how interdependencies have changed… [can make sure] that it [roadmap] can continue being the tool that's used, not just something that just sits on a shelf." Nevertheless, iterating the whole process of roadmapping not only allows the incorporation of more recent information, but also helps build consensus among participants, as they learn more about other stakeholders through discussion, according to the managers in cases 5 and 7. By allowing constant communication and knowledge exchange across diverse stakeholders, it helps them develop an adequate common knowledge for sharing and assessing each other's knowledge, so facilitating effective alignment and synchronisation of their activities in terms of timing and approach. Presenting the most up-to-date status of the relevant roadmaps at the beginning of each roadmapping is helpful for their efficient iteration, so that participants do not reiterate the same discussion (as in case 5). Consultants involved in cases 2 and 4 reemphasised needs to share these with participants prior to workshops, along with the agenda of the day, so that people have time to think about the questions beforehand rather than thinking on their feet.

The revision of roadmaps through iteration, however, requires significant efforts and resources, hence their updates are often conducted through follow-up activities in real practices of roadmapping (as in cases 4 and 5). Publishing the roadmaps to obtain feedback and comments through various channels – such as workshops, conferences, forums, and online survey – would be an efficient way to incorporate any changes and updates from a wider community of relevant stakeholders. These are particularly useful for the revision of certain functional roadmaps focusing on issues and topics that develop at a much faster pace, where another roadmapping exercises will only produce outdated roadmaps after time-consuming activities, noted the manager of case 3. Such follow-up activities also support continued communication and discussion among relevant stakeholders, so enhancing the collaboration and coordination of broader networks within the complex technological systems. The manager of case

2 highlighted the benefits of having a designated organisation responsible for such follow-up activities in ensuring the continuous revision and update of developed roadmaps.

8) Engage professional facilitators and field experts in management teams

As these processes of developing and integrating multiple roadmaps require substantial efforts and time, management teams play critical roles in project management by overseeing the overall processes from initial high-level roadmapping to individual functional roadmapping and their integration. By attending all sessions of individual roadmapping workshops, they play particularly important roles in cross-checking, as evidenced in cases 1, 2, and 4. Being able to connect diverse activities and elements across multiple functional roadmaps that other participants may find difficult if they had not participated in relevant roadmapping workshops, they support effective communication and knowledge exchange, so facilitating the systematic integration and alignment across the roadmaps.

Engaging professional facilitators in the management teams can be helpful, as they assist the management and organisation of roadmapping workshops by guiding structured discussions, managing time, and making participants focus on key agenda. Interviewees from all cases except case 7 noted that such facilitation skills are particularly useful when diverse organisations need to collaborate and coordinate with each other, as participants often tend to focus on particular topics of their expertise or pursue self-serving interests. By making participants focus on the overall vision and common objectives to achieve, experienced facilitators ensure that all key perspectives are addressed and no particular interests are necessarily dominating, noted the managers in cases 2 and 6. Hence, they facilitate negotiation processes to reach consensus, and also make participants feel that they are included and their opinions are valued. Thus promoting a pleasant and relaxed atmosphere where people are more inclined to open communication, these professional facilitators can help address the challenges associated with making trade-offs and transforming knowledge among diverse stakeholders with different interests.

Nevertheless, it is noted that such management teams must engage or closely interact with field experts, who can manage the highly technical inputs relevant to the topic area, because professional facilitators may not have capabilities to fully understand all the technical details and nuances. Managers of cases 1 and 6 also highlighted the importance of adequate leadership who understands both technical aspects and diverse functional issues in achieving coordination and collaboration among multiple roadmapping.

V. Discussion

A. The conceptualisation of integrated innovation roadmapping

Drawing on the practical steps for addressing the challenges of managing knowledge at boundaries, the preliminary conceptualisation of integrated innovation roadmapping has been further developed, as shown in Fig. 4. It summarises key points of the eight practical steps suggested from the case studies into a cohesive framework that acknowledges different stages of the development and systematic integration of multiple functional roadmaps.

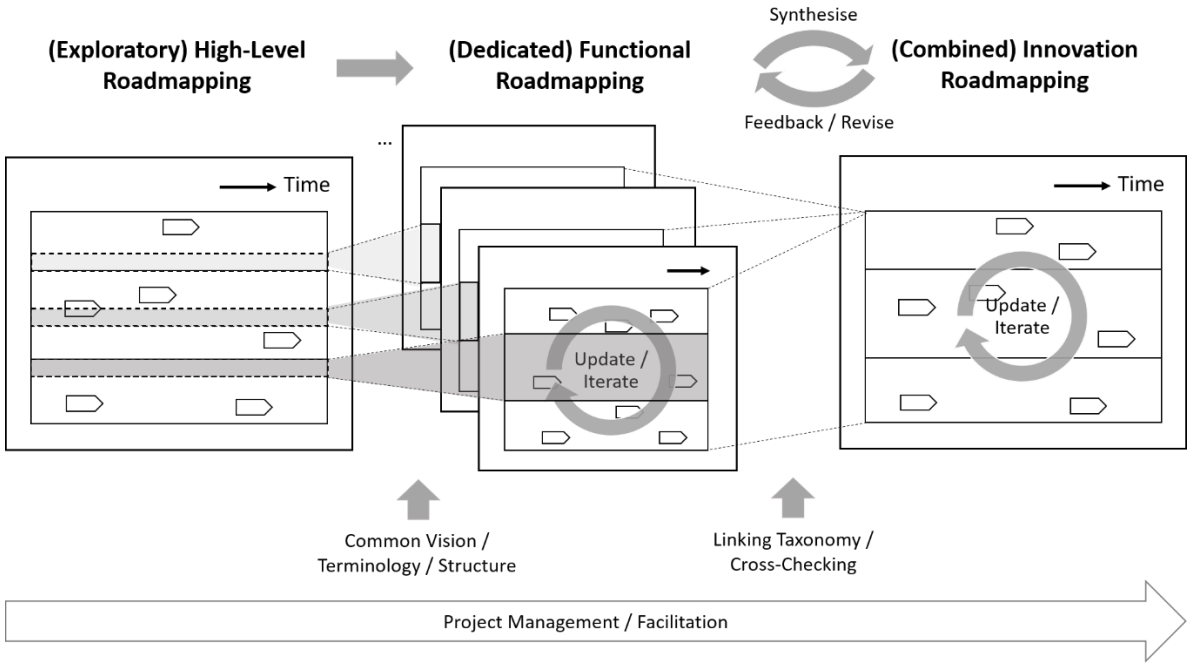

Fig. 4 Re-conceptualisation of integrated innovation roadmapping

The first stage is to develop an exploratory high-level roadmap of the overall technological system, in order to provide a broad picture of how diverse innovation functions may be related to each other, so helping participants of individual functional roadmapping see how their interests fit within the larger whole. This can be done in parallel with defining overall vision and impact objectives, as well as common terminology and system architecture, all of which help address challenges associated with translation and transformation of knowledge among diverse stakeholders with different backgrounds and expertise. These can inform the development of consistent format and structure for dedicated functional roadmaps, which are essential during individual roadmapping sessions for efficient knowledge transfer and alignment between multiple complementary roadmaps. Linking taxonomy or typology may also need to be developed to enhance compatibility between multiple functional roadmaps, facilitating the cross-checking step during the combined innovation roadmapping. The synthesised roadmap is then better informed by details of functional roadmaps than the previous high-level roadmap. It also supports revision and alignment of functional roadmaps by providing feedback into, and synchronising with, appropriate layers of individual roadmaps. Both combined innovation roadmap and multiple functional roadmaps need to be kept up-to-date through an iterative approach of continuous revision and update, as well as follow-up activities. All these procedures can be managed in a more effective manner, by engaging professional facilitators and appropriate field experts in management teams supporting the overall roadmapping project.

B. Practical implications

Drawing on the best practices and lessons learnt from recent roadmapping exercises, the revised concept of integrated innovation roadmapping can be used to inform practitioners for the systematic design, integration, and alignment of multiple roadmaps focusing on different functional activities of innovation systems (e.g., technology R&D, workforce development, and standardisation). Eight practical steps have been identified, in order to support more aligned and coordinated activities of broader innovation systems through effective communication and increased understanding among

diverse stakeholders involved. While these are mostly consistent with existing literature emphasising the importance of social interactions between roadmapping participants through engagement and communication [32], they are significantly more challenging for roadmapping in the context of multi-organisational networks, where participants are from different organisations with different interests and goals. These challenges are even exacerbated due to increasingly complex innovation systems, requiring strategic roadmaps to incorporate broader perspectives representing diverse contextual factors and functional issues than conventional technology roadmaps. More systematic and carefully structured procedures of roadmapping are thus needed to address such increased challenges. The current research fills this gap by providing useful guidance of practical steps for systematic integration and alignment of multiple functional roadmaps.

C. Theoretical implications for roadmapping literature

The findings of this research also have theoretical implications for literature on technology and innovation roadmapping, which have not been discussed much from knowledge management perspectives. Although the communication benefit of roadmapping has been widely acclaimed in existing roadmapping research (e.g., [1]), only limited studies highlight it as a vehicle to support effective inter-organisational collaborations through sharing knowledge and information (e.g., [6], [27], [28]). The current study demonstrates that the efforts involved in the development and alignment of multiple functional roadmaps, as well as associated communication, provide useful platforms themselves for networking among broader innovation stakeholders, so facilitating their collaboration and leading to further innovation. Helping diverse innovation actors have increased understanding of others' interests and perspectives, such mutual learning effect from the process of roadmapping is increasingly important, as modern technological systems are increasingly complex, so requiring diverse stakeholders to share knowledge, expertise, and information across organisational boundaries [24], [28]. Hence, the proposed integrated innovation roadmapping is suggested to facilitate high levels of collaboration and coordination required in increasingly complex technological systems, by helping

communication and knowledge sharing among diverse innovation actors involved.

However, complex boundaries between diverse innovation functions and relevant roadmaps present significant challenges for adequate knowledge management required to support such inter-organisational collaborations. Using the integrated framework for managing knowledge across boundaries developed by Carlile [23], our case studies demonstrate that there are diverse challenges and issues associated with transfer, translation, and transformation of knowledge, in developing common knowledge required for the systematic integration of multiple functional roadmaps. This is due to high levels of novelty (in terms of technical expertise, innovation functions, as well as organisational backgrounds) across pragmatic boundaries between the specialised roadmaps. As they impede relevant actors' ability to share and assess knowledge across the boundaries, common interests need to be developed in addition to common meanings and lexicons [23].

The findings of current case studies not only demonstrate diverse challenges of knowledge management at such boundaries, but also suggest practical ways of addressing these complex challenges in the context of integrating and aligning diverse functional roadmaps. These can be grouped into four characteristics that describe the capability required for effective knowledge sharing at a pragmatic boundary, as proposed by Carlile [23]. First, to develop a common lexicon for transferring knowledge across diverse functional roadmaps, practical steps of developing a high-level roadmap as a reference point, as well as using consistent roadmap structure and format are suggested. Second, to translate different knowledge and develop shared meanings beyond cross-functional boundaries, practical steps such as defining common terminology and system architecture, developing linking taxonomy and typology, and cross-checking to identify linkages are suggested. Third, to develop common interests for making trade-offs and transforming knowledge, practical steps of defining overall vision and impact objectives, and engaging professional facilitators in management teams are suggested. Last but not least, the practical step of continuous revision and update is suggested to support an iterative approach, where actors get better at developing an adequate common knowledge

for sharing and assessing each other's knowledge.

Hence, the current study provides greater understandings of how roadmapping can be structured and organised to support more effective knowledge management required for the alignment of multiple functional roadmaps, using the integrated framework for managing knowledge across boundaries developed by Carlile [23]. By combining insights from knowledge management literature, it identifies various knowledge management challenges associated with the inter-organisational collaborations required for such integrated innovation roadmapping, as well as practical steps to address them. The current research thus contributes to technology and innovation roadmapping literature, by providing knowledge management perspectives that have not been discussed much in previous roadmapping studies. Such knowledge management perspectives are becoming ever more important as roadmaps are increasingly developed in the context of multi-organisational networks, where diverse participants collaborate and exchange knowledge across different organisations within broader innovation systems.

VI. Conclusion

With the ever-growing complexity of innovation systems of modern technologies, roadmapping techniques are increasingly used to support strategic planning of diverse innovation functions beyond just technology R&D (e.g., standardisation, education and workforce development, and infrastructure development). While conventional technology roadmaps usually consider these functions as contextual factors explored in less detail, these dedicated functional roadmaps give other key innovation activities centrality and greater granularity within the roadmapping architecture. The differences in structure, however, as well as different vocabulary and technical terminology used by different communities, make it challenging to share knowledge and develop coherent strategies among multiple functional roadmapping exercises. This can lead to potential risks of misaligned activities, leading to problems such as inefficient use of resources within the broader innovation system and missed opportunities to

capture greater value from technology innovation.

In order to address these challenges, this paper introduces the concept of integrated innovation roadmapping, which is designed to support the systematic integration and alignment of multiple roadmaps focusing on diverse functional activities and issues of innovation systems. The concept is developed through case studies of recent roadmapping exercises, which are carried out by various multi-organisational networks to develop complementary and compatible strategies for different innovation functions. By using an analytical framework from knowledge management literature, they highlight the challenges associated with transfer, translation, and transformation of knowledge across these multiple functional roadmaps, so providing theoretical implications for technology and innovation roadmapping literature. The case studies also offer a number of practical steps to address these challenges, categorised into four main stages of overall roadmapping processes (i.e., exploratory high-level roadmapping, dedicated functional roadmapping, combined innovation roadmapping, and overall project management). These steps support more effective knowledge management and thus increased understanding among a wide variety of participating stakeholders, so allowing effective coordination of diverse functional activities and synchronising their timing across multiple roadmaps. Hence, they provide useful guidance for the systematic integration and alignment of diverse functional roadmaps, which, in turn, enhance the overall functioning of broad innovation systems. Furthermore, the research highlights that efforts to develop and align various roadmaps themselves also provide useful platforms for networking among broad communities of stakeholders within complex innovation systems, supporting their future collaboration.

Despite such contributions in both theory and practice, the current research is not without limitations, and there are areas of further research for more effective practices of integrated innovation roadmapping. While the suggested practical steps incorporate best practices and lessons learnt from existing roadmapping exercises, their performance have not yet been tested in a rigorous manner. Further research is thus needed to evaluate the effectiveness of the proposed integrated innovation

roadmapping for systematic integration and alignment of multiple functional roadmaps. Action-based research comparing procedures of general innovation roadmapping and those of the integrated innovation roadmapping, together with interviews or surveys on experts' perception, can help validate the effectiveness of the proposed approach. Such research may also benefit from the development of appropriate metrics to evaluate the performance of integrated innovation roadmapping. It can help identify critical factors for the success of integrated roadmapping projects, and which practical steps might be more important than others in leading to the success.

Another area of future research is to develop effective tools and techniques that support virtual roadmapping activities, which are increasingly being used in practice, yet found to be less productive than face-to-face interactions. With the expansion of modern innovation systems in terms of geographical regions, interviewees highlighted the increasing challenges of gathering diverse participants spread across different cities together in a single location. Such challenges are even more significant when participants are coming from different countries, as in case 6. There is thus recently increasing use of virtual platforms for roadmapping instead of, or complemented with, in-person workshops, as demonstrated from many cases (see Table 1).

In conclusion, this paper proposes a foundational concept of integrated innovation roadmapping to support the systematic design, integration, and alignment of roadmaps that are developed by different communities focusing on different innovation functions. By identifying diverse challenges of knowledge management at cross-functional boundaries and offering practical steps to address them, it provides practitioners with informed guidance on effective planning and management of diverse functional activities within broader innovation systems. The research thus provides an initial stepping stone for developing and operationalising the concept of 'innovation system foresight', which is increasingly important as modern innovation processes are becoming more complex, contextual, and systemic in nature [33].

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